Development of a Real-time Thermal Hydrodynamic Model Using EFDC as Decision Support Tool for Compliance and Operations

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Abstract

A real-time three dimensional hydrothermal model was developed for Coosa River, AL, between Logan Martin Dam and Lay Dam using Environmental Fluid Dynamics Code (EFDC) and pre/post processor EFDC_Explorer (EE). The model's external forcing factors include flow releases from Logan Martin and Lay Dam, flows from tributaries, power plant withdrawal and temperature rise, and atmospheric conditions. The real-time model was calibrated against the field measurements of flows, water level, and water temperature. The model was developed to serve as a decision-making tool for Alabama Power Company (APC) electricity generation and assist in efficient operation of Logan Martin, Lay and Plant Gaston in order to meet generation needs while staying in thermal compliance at the monitoring buoy below Gaston. An online web interface was designed to visualize the results of the real-time EFDC model and provide quantitative comparisons to the thermal standard to help in real-time decision making. The web interface allows users to perform various scenario analyses that help to understand the possible changes in the water temperature in the waterbody under different environmental scenarios.

Introduction

The Coosa River is in Alabama with primary uses such as recreation, drinking water, power generation, agriculture, and timber. Lay Lake in Coosa River is a man-made reservoir approximately 47 miles long impounded by one of the earliest concrete dams in the US (Figure 1). The reservoir is bounded by Logan Martin Dam at the upstream end and Lay Dam at the downstream end, with installed hydropower capacities of 128 MW and 177 MW, respectively. Approximately 22 miles downstream of Logan Martin Dam, Alabama Power Company operates the E.C. Gaston coal-fired electricity generating plant. Gaston has four units that utilize once through cooling water drawn from a tributary of Lay Lake. Thermal structure and hydrodynamics of this lake are influenced by the flow release patterns at Logan Martin and Lay dams and electricity generation at Plant Gaston. The operation of these generation facilities can result in significant seiching within the reservoir.

Dynamic Solutions International, LLC (DSI) has been conducting numerical modeling and investigations of thermal and hydrodynamics of the lake using the Environmental Fluid Dynamics Model (EFDC) (Hamrick, 1992). This EFDC model has been thoroughly calibrated and validated against several years of data. The final goal for the model is to provide a system that would serve as a decision-making tool for APC power generation to assist in determining optimal generation schedules for Logan Martin, Lay, and Gaston in order to meet generation needs while staying in thermal compliance at the monitoring buoy below Gaston. This paper discusses the development of a real-time simulation system that reproduces the current conditions in the reservoir and the development of a predictive model which helps to understand the response on the reservoir if certain generation schedules are implemented.

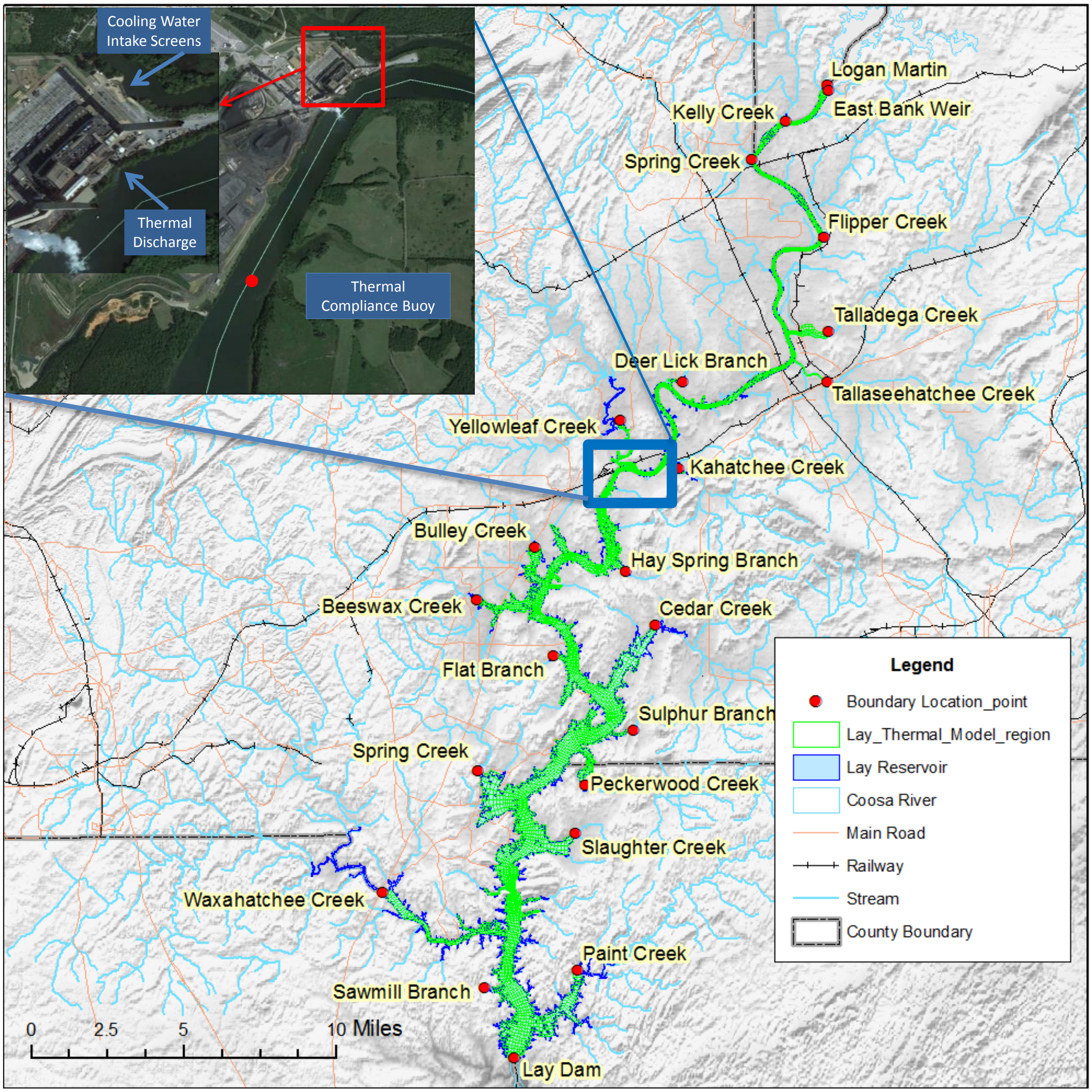


Figure 1 Map of the Lay Lake, local basins and measurement stations

Lay Reservoir Hydrothermal Model Setup

The Lay-thermal model was developed to conduct hydrodynamic and thermal analysis of the Lay Reservoir on the Coosa River between Logan Martin and Lay Dams using EFDC (Hamrick 1992) and EFDC_Explorer (EE) (Craig 2015). EFDC employs a finite-difference method to solve Navier-Stokes equations, continuity equation, and transport equations for salt, temperature, water quality parameters, turbulent kinetic energy, and macroscale turbulence. The governing equations are solved horizontally on a curvilinear, orthogonal grid, and vertically on a stretched sigma-grid. Vertical diffusion coefficients for momentum, mass, and temperature are determined by the turbulent closure scheme of Mellor and Yamada (1982) and Galperin et al. (1988). Horizontal mixing coefficients are parameterized using a Smagorinsky (1963) formulation.

The Lay-thermal model uses a curvilinear orthogonal grid and was developed based on shoreline of the Lay Reservoir. The model includes 9,872 horizontal grid cells and eight vertical layers to simulate the vertical temperature distribution. The model domain extends approximately 47 miles from Logan Martin Dam to Lay Dam. The model used the bathymetry that was compiled based on various surveyed data which included sounding data and LiDAR data.

Boundary Conditions

Flow and Temperature Boundary Conditions.

The two major boundaries that control the overall flow structure in the Lay reservoir are inflows from Logan Martin and outflows from Lay Dam (Figure 1). These boundaries used 1 minute flow data and 1 minute and 15 minute temperature data measured by APC. In addition to the flow releases from dams, 20 lateral inflows at various sections in the River were included in the model. The flow boundary conditions at these 20 locations were estimated based on hourly observations of flow at three USGS stations at Vincent, Alpine, and Westover using the drainage area ratios. The intake and discharge of cooling water for the EC Gaston Steam Plant were simulated using a withdrawal/return boundary in EFDC. The withdrawal/return boundary uses the flow and temperature rise to represent the flow that is withdrawn into the power plant from intake canal and the temperature rise is the difference between temperature at discharge point and intake point. 1 minute operational data of flow related to the generated power of the plant are used for these forcings at the cooling water intake (GAIC) and discharges for units 1 and 2 (GADCA) and units 3 and 4 (GADCB).

Meteorological Forcing.

The atmospheric parameters required to represent the heat exchange in the EFDC model are atmospheric pressure, air temperature, relative humidity, rainfall, cloud cover, solar radiation, evaporation, wind speed, and wind direction. The meteorological data were obtained from EC Gaston weather station, Shelby County Airport, and Birmingham Airport.

Model Calibration and Results

Lay Reservoir was initially developed using 2010 data sets and has been continuously improved over the years. Details about the model configuration and parameters can be found in (Craig et al. 2011). In the current study, the model was recalibrated for periods in 2011 and 2012. The calibration included comparison of measured and modeled water surface elevations (WSE) and temperature at various locations in the domain. Temperature calibration summary at the compliance buoy (Figure 1) is shown in Table 1. The summary of water surface calibration at various locations in model domain is presented in Table 2. Overall the results of water surface elevation and temperature indicate that the Lay Reservoir Hydrothermal model has been well calibrated. The calibrated model was then used for predictions of the hydrothermal structure in Lay Reservoir.

Table 1 Buoy temperature calibration for summer 2010-2012.

Month	Number of days	RMSE of Daily Averaged (°F)	Monthly Average (°F) Model	Data	Difference (Model-Data) (°F)
10-Jul	17	0.72	90.68	90.25	0.43
10-Aug	31	0.33	89.29	89.34	-0.05
10-Sep	30	0.62	86.01	86.41	-0.40
11-Jun	30	1.88	86.12	87.04	-0.92
11-Jul	31	0.85	89.75	89.32	0.43
11-Aug	31	0.64	89.78	89.50	0.28
11-Sep	13	0.58	84.88	84.48	0.40
12-May	24	0.58	79.39	79.49	-0.10
12-Jun	30	0.51	84.54	84.57	-0.03
12-Jul	30	0.53	88.88	88.58	0.30
12-Aug	30	0.49	86.11	85.86	0.25
All Periods	**297**	**0.82**	**86.86**	**86.80**	**0.02**

Table 2 Water surface elevation calibration summary at various locations in 2012.

Location	Starting Date	Ending Date	Pairs	RMSE (ft.)	Data Avg. (ft.)	Model Avg. (ft.)
Logan	May-08-2012	Aug-30-2012	165273	0.79	396.95	396.46
Lay	May-08-2012	Aug-30-2012	165010	0.19	396.01	396.03
Glover's	May-17-2012	Aug-30-2012	151536	0.16	396.12	396.15
Bowater	May-17-2012	Aug-30-2012	133467	0.79	396.72	396.10
Childersburg	May-08-2012	Aug-30-2012	161323	0.33	396.13	396.04
Gaston	May-08-2012	Aug-30-2012	164444	0.10	396.03	396.03
Overall			**941053**	**0.39**	**396.33**	**396.13**

The continual adjustment of the EFDC model led to excellent results in hindcasting temperature, water surface elevation, and flow rates. The high accuracy of the results produced by the EFDC model suggested automating this process could be of benefit to APC, i.e., using a real-time version of the model to predict future temperatures using load and weather forecasts. For this reason, APC decided to develop a real-time predictive tool using the Lay Reservoir EFDC model as a foundation.

For the real-time model setup, the model requires real-time data at key boundary locations. A number of real-time monitoring stations were added at key boundaries and telemetry was established so that the data could be automatically accessed for processing in real-time. The data and modeling system are operated through a web interface.

Real-time Prediction System

Based on the calibrated model described above, DSI developed the real-time prediction system to predict the hydrothermal discharges from the Gaston Power Plant and overall temperature distribution in the lake. The real-time model allows the user to investigate the effects of different release scenarios at Logan Martin and Lay Dams on the hydrodynamic and thermal characteristics of the Lay Lake.

There were three steps involved in the overall development of the prediction system.

a. Data collection: To support the program, APC started the real-time collection of 48 time series minute data (flow, temperature, elevation) which would serve as model input that is updated hourly.
b. Real-time Model: The model is run hourly with newly collected data. The model serves as a continually updated representation of the temperature distribution in the reservoir.
c. Predictive Model and Scenario Analysis: The model uses real-time status as a launch point to run various operational scenarios seven days into the future. Base Scenario runs three times daily using the most updated unit commitment data.

Development of Real-time Simulation System

The processes in the real-time modeling system are shown in Figure 2. The real-time system incorporates the measured real-time data from 48 stations/sensors, atmospheric data from APC sensor and the online resource www.wunderground.com to represent the realistic boundary conditions and weather scenarios. The input data is scanned and imported into the database and backed up in the archive folder. A Windows® service (i.e. APC service) was created to automate the pre/post processing for EFDC model (create *.inp file, run model, extract model output). The user may then extract the data from the database using the web portal which handles the visualization process. Automated messaging has been implemented to alert the operators of critical conditions and other warnings.

The interaction between server side and client side in the real-time simulation system is shown in Figure 3. On the server side, the data are managed in SQL database. Also on the server side, there are several folders such as incoming, input, output, restart, archive, model, and system to store incoming input data, output from EFDC model and system application, and scripts, etc. On the client side, the workstation folder is created daily that contains files for real-time and scenario data. APC services are called when EFDC model is running every hour.

- System files get *.inp files required for EFDC model from the server.
- Output files are copied to the server output folder.
- The restart files are copied to the server restart folder.

- The EFDC model results are imported into the database.

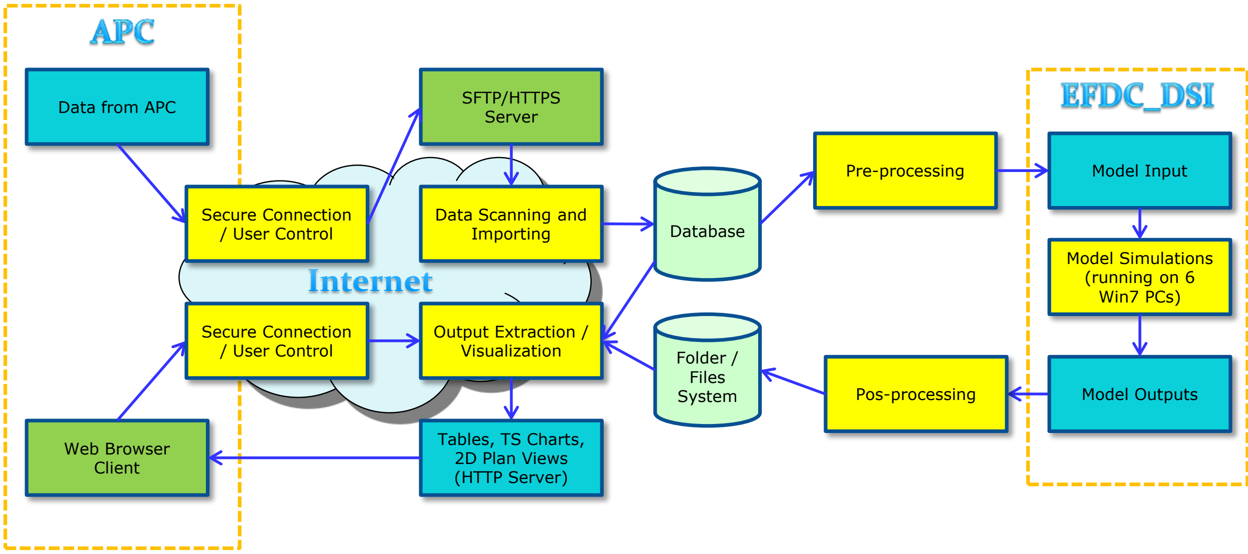


Figure 2 APC real-time modeling system processes

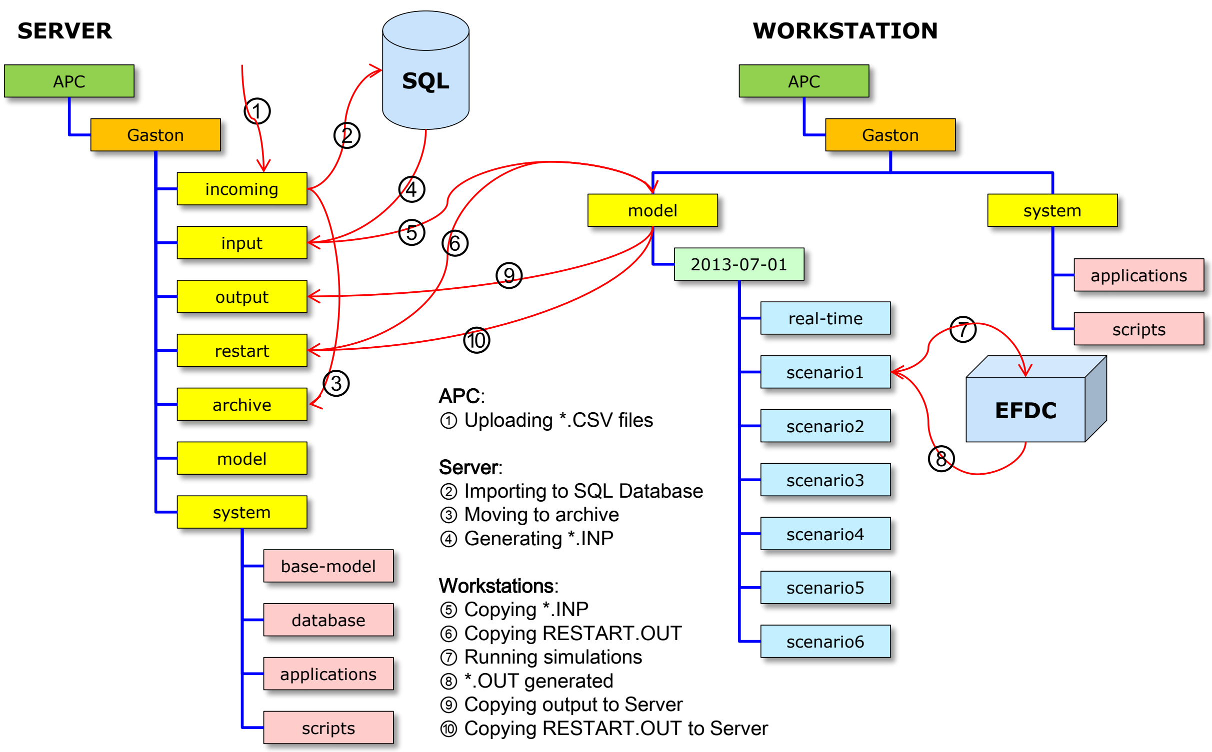
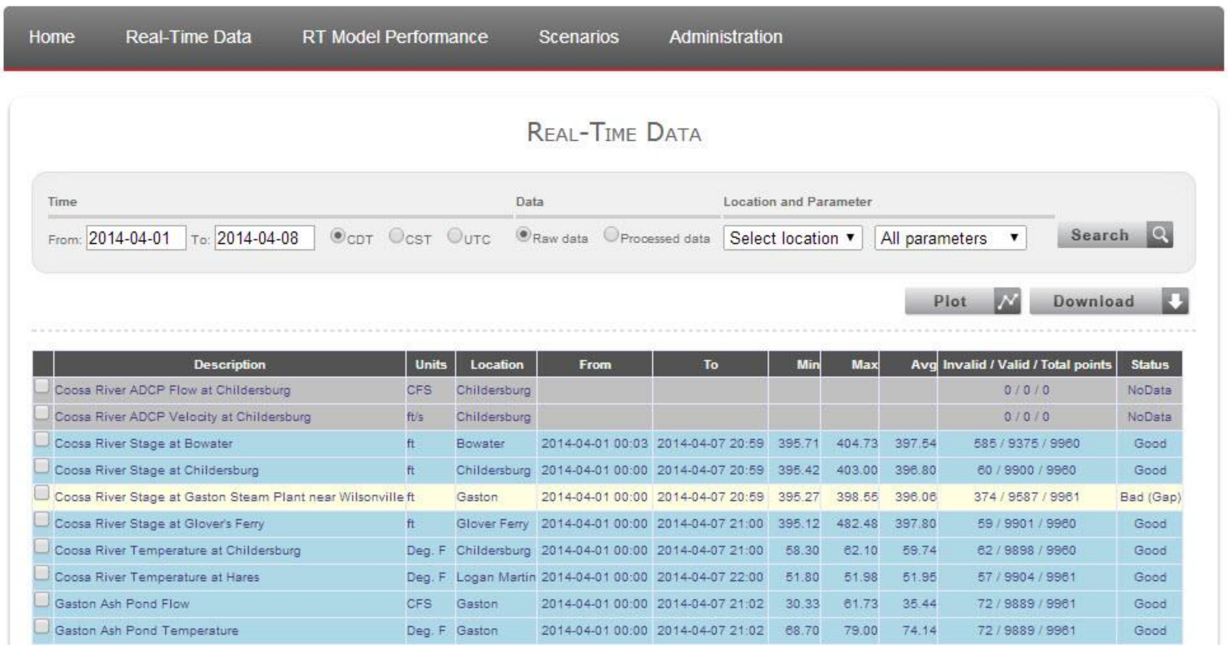


Figure 3 APC real-time modeling system overflow

Forecast Model Development

Each hour all of the boundary forcings are updated to the latest incoming data, i.e. the real-time existing conditions model. The real-time model is then updated with forecasted unit loads, hydro flows, atmospheric data, and reservoir inflow temperatures. Three times daily, a “base” scenario is automatically run for 7 days into the future based on daily APC unit commitments. The user can develop customized scenarios to evaluate generation options. These scenarios can be created, run, and evaluated through web interface.

Figure 4 shows the web interface for the APC real-time prediction system. The four main features in the web interface are real-time data, real-time model performance, scenarios, and administration. This system also includes visualization and editing features such as checking the real-time data for model input; setting the model scenarios, launching manual EFDC scenarios as well as visualization of key model results and data. Figure 4 shows the options available under the real-time data feature in the system. This allows viewing of data inputs for quality control (QC) and troubleshooting. This feature allows user to choose the start and end time of data collection based on three different time zones (CDT, CST, and UTC). Users may select parameters and locations where the data can be plotted and/or downloaded.

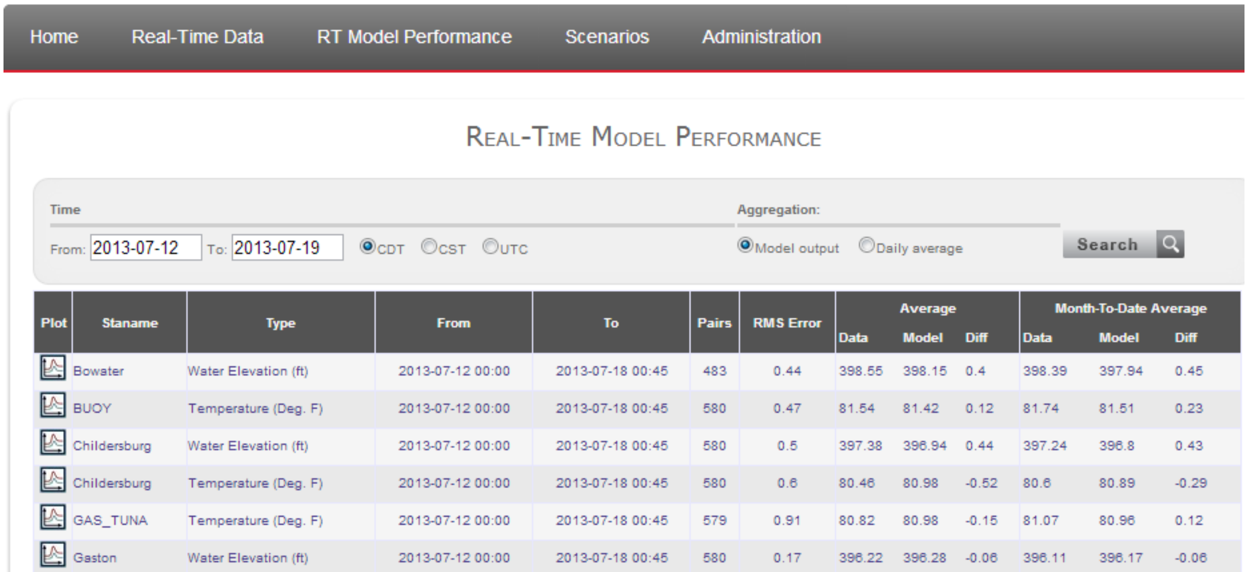


Description	Units	Location	From	To	Min	Max	Avg	Invalid / Valid / Total points	Status
Coosa River ADCP Flow at Childersburg	CFS	Childersburg						0 / 0 / 0	NoData
Coosa River ADCP Velocity at Childersburg	ft/s	Childersburg						0 / 0 / 0	NoData
Coosa River Stage at Bowater	ft	Bowater	2014-04-01 00:03	2014-04-07 20:59	395.71	404.73	397.54	585 / 9375 / 9960	Good
Coosa River Stage at Childersburg	ft	Childersburg	2014-04-01 00:00	2014-04-07 20:59	395.42	403.00	396.80	60 / 9900 / 9960	Good
Coosa River Stage at Gaston Steam Plant near Wilsonville	ft	Gaston	2014-04-01 00:00	2014-04-07 20:59	395.27	398.55	396.06	374 / 9587 / 9961	Bad (Gap)
Coosa River Stage at Glover's Ferry	ft	Glover Ferry	2014-04-01 00:00	2014-04-07 21:00	395.12	482.48	397.80	59 / 9901 / 9960	Good
Coosa River Temperature at Childersburg	Deg. F	Childersburg	2014-04-01 00:00	2014-04-07 21:00	58.30	62.10	59.74	62 / 9898 / 9960	Good
Coosa River Temperature at Hares	Deg. F	Logan Martin	2014-04-01 00:00	2014-04-07 22:00	51.80	51.98	51.95	57 / 9904 / 9961	Good
Gaston Ash Pond Flow	CFS	Gaston	2014-04-01 00:00	2014-04-07 21:02	30.33	61.73	35.44	72 / 9889 / 9961	Good
Gaston Ash Pond Temperature	Deg. F	Gaston	2014-04-01 00:00	2014-04-07 21:02	68.70	79.00	74.14	72 / 9889 / 9961	Good

Figure 4 Web user interface for real-time data

Real-time Model Performance

The real-time model performance feature is used to evaluate the real-time EFDC model simulation results by comparing model results to the real-time measured data sets. The plots and statistics are reported for daily averaged data.

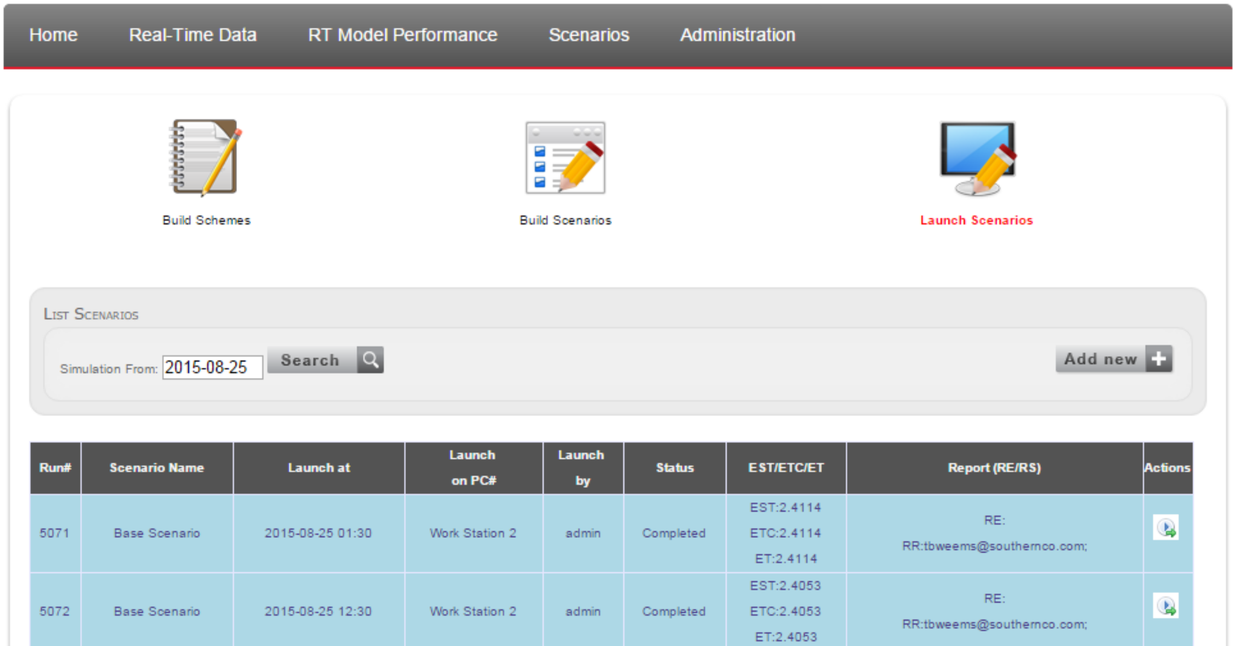


Plot	Staname	Type	From	To	Pairs	RMS Error	Average			Month-To-Date Average		
							Data	Model	Diff	Data	Model	Diff
	Bowater	Water Elevation (ft)	2013-07-12 00:00	2013-07-18 00:45	483	0.44	398.55	398.15	0.4	398.39	397.94	0.45
	BUOY	Temperature (Deg. F)	2013-07-12 00:00	2013-07-18 00:45	580	0.47	81.54	81.42	0.12	81.74	81.51	0.23
	Childersburg	Water Elevation (ft)	2013-07-12 00:00	2013-07-18 00:45	580	0.5	397.38	396.94	0.44	397.24	396.8	0.43
	Childersburg	Temperature (Deg. F)	2013-07-12 00:00	2013-07-18 00:45	580	0.6	80.46	80.98	-0.52	80.6	80.89	-0.29
	GAS_TUNA	Temperature (Deg. F)	2013-07-12 00:00	2013-07-18 00:45	579	0.91	80.82	80.98	-0.15	81.07	80.96	0.12
	Gaston	Water Elevation (ft)	2013-07-12 00:00	2013-07-18 00:45	580	0.17	396.22	396.28	-0.06	396.11	396.17	-0.06

Figure 5 Web user interface for real-time model performance.

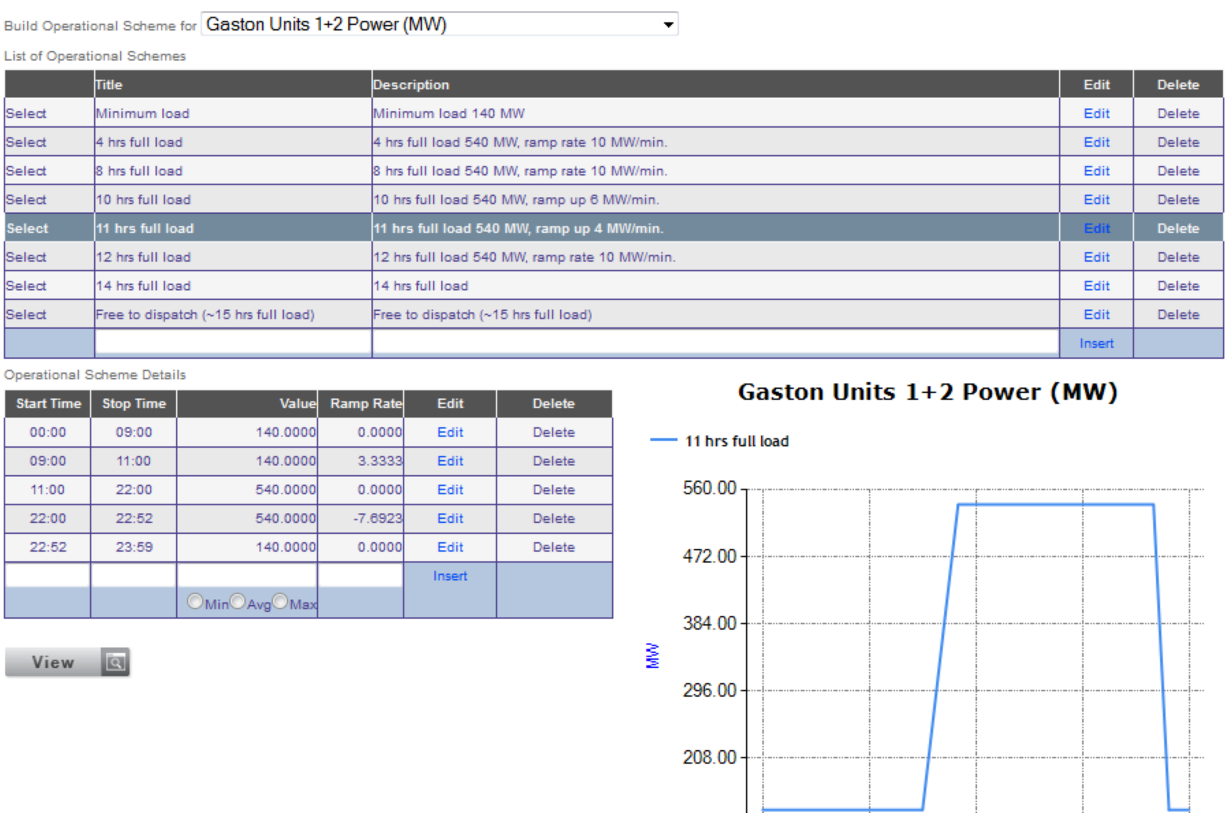
Building Scenarios

Scenarios representing generation at Logan Martin, Lay, and Gaston can be constructed for evaluation. Scenario Building is divided into three sub features: Load Dispatch Scenario (Build Schemes), Build Scenarios, and Launch Scenarios. . The user can build user defined scenarios based on the parameters selected by defining the operational schemes as a 24 hour block for each parameter. The user can also define generic operational scenarios for weekdays and weekends for all parameters based on their pre-defined schemes. Figure 6 shows scenarios that have been built for the analysis. Users can modify and/or list scenario parameters and properties such as name, site location, units, minimum / maximum / average values. Figure 7 shows the scenarios created for different Gaston unit load conditions such as minimum load, loading for certain time, ramp rate and full load, etc.



Run#	Scenario Name	Launch at	Launch on PC#	Launch by	Status	EST/ETC/ET	Report (RE/RS)	Actions
5071	Base Scenario	2015-08-25 01:30	Work Station 2	admin	Completed	EST:2.4114 ETC:2.4114 ET:2.4114	RE: RR:tbweems@southernco.com;	
5072	Base Scenario	2015-08-25 12:30	Work Station 2	admin	Completed	EST:2.4053 ETC:2.4053 ET:2.4053	RE: RR:tbweems@southernco.com;	

Figure 6 Web interface of Real-time prediction system showing scenarios options.



	Title	Description	Edit	Delete
Select	Minimum load	Minimum load 140 MW	Edit	Delete
Select	4 hrs full load	4 hrs full load 540 MW, ramp rate 10 MW/min.	Edit	Delete
Select	8 hrs full load	8 hrs full load 540 MW, ramp rate 10 MW/min.	Edit	Delete
Select	10 hrs full load	10 hrs full load 540 MW, ramp up 6 MW/min.	Edit	Delete
Select	11 hrs full load	11 hrs full load 540 MW, ramp up 4 MW/min.	Edit	Delete
Select	12 hrs full load	12 hrs full load 540 MW, ramp rate 10 MW/min.	Edit	Delete
Select	14 hrs full load	14 hrs full load	Edit	Delete
Select	Free to dispatch (~15 hrs full load)	Free to dispatch (~15 hrs full load)	Edit	Delete
			Insert	

Start Time	Stop Time	Value	Ramp Rate	Edit	Delete
00:00	09:00	140.0000	0.0000	Edit	Delete
09:00	11:00	140.0000	3.3333	Edit	Delete
11:00	22:00	540.0000	0.0000	Edit	Delete
22:00	22:52	540.0000	-7.6923	Edit	Delete
22:52	23:59	140.0000	0.0000	Edit	Delete
				Insert	

Figure 7 Management and building parameter scheme.

Analysis of Scenario Runs

After the scenarios have been built, the forecast system allows the user to analyze different scenario runs at the same time. Figure 8 shows the comparison of time series of observed, modeled, and predicted temperatures for different scenario runs. The observed data and real-time predicted series are plotted for the first seven days. The recent observed temperatures are compared to the real-time model predictions to help the user gauge the accuracy of the model and provide confidence for the forecasted temperatures. The second half of the scenario run plots show the seven day forecasted temperatures for each of the scenarios runs. This capability of analyzing different future scenarios ahead of time allows APC to assess their options for operation of Logan Martin Dam, Lay Dam and unit loads for Plant Gaston.

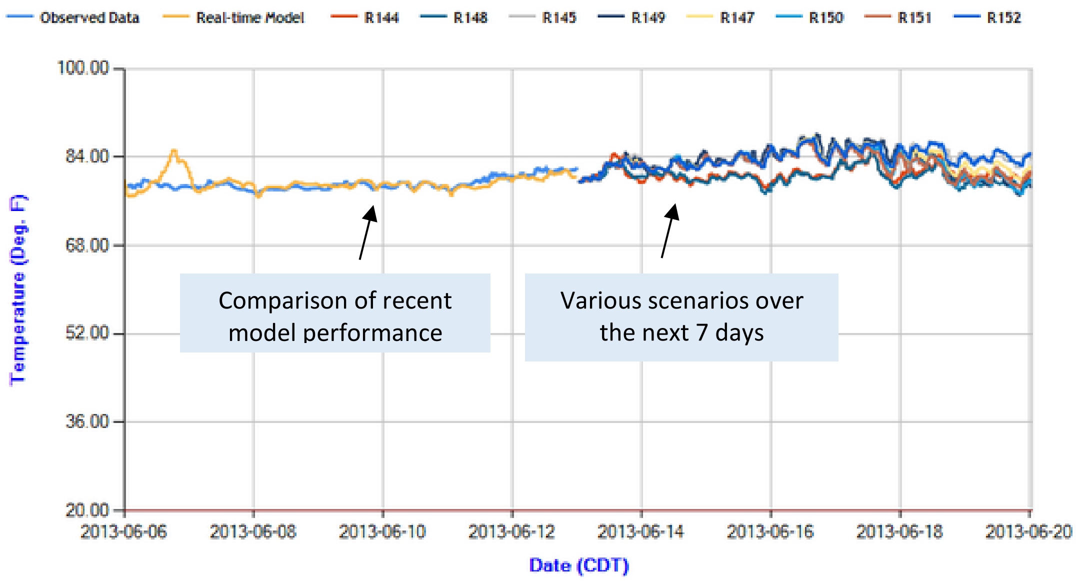
In the bottom panel of Figure 8, the daily average temperature values are displayed for the observed data, real-time model results, and scenarios. The statistics provided by the system can be directly compared to numeric thermal limits to help optimize operations and ensure compliance.

A study of the past two years of real-time model forecasted results compared to what actually occurred was conducted. It was found that the model forecast accuracy decreased by approximately 0.25 °F per day, on average. Forecast model accuracy is a function of the

It takes less than two hours to run the 7-day scenario. The real-time prediction system utilizes several PCs allowing up to six forecast scenarios to be simultaneously run without degredation of performance. OpenMP is also utilized in the EFDC model to allow for more efficient model runs.

Conclusions

A real-time hydro-thermal simulation system for Lay Reservoir has been successfully developed based on the calibrated eight-layer model. The real-time model and forecasting system has been used to investigate the effects of different release scenarios at Logan Martin and Lay Dams on the hydrodynamic and thermal characteristics of Lay Lake. The real-time system has an array of features for managing real-time data, analyzing real-time model performance, building operational scenarios, and forecasting operational impacts. The real-time system has been demonstrated to be powerful tool for efficient management of unit loads and dam releases. This system helps provide best practice for the operation of Logan Martin Dam, Lay Dam and Gaston Steam Plant to meet power generation needs while staying in compliance with regulatory requirements.



Date	Observed Data	Real-time Model	R144	R148	R145	R149	R147	R150	R151	R152
2013-06-06	78.96	80.49								
2013-06-07	78.71	79.06								
2013-06-08	78.33	78.74								
2013-06-09	78.91	79.08								
2013-06-10	78.85	78.99								
2013-06-11	79.8	79.03								
2013-06-12	81.38	80.67								
2013-06-13			81.35	81.06	82.11	82.03	81.85	81.76	81.81	81.77
2013-06-14			80.26	80.58	82.76	82.72	82.53	82.49	82.37	82.43
2013-06-15			80.4	79.95	83.78	83.97	83.51	83.56	83.45	83.55
2013-06-16			80.78	80.4	85.71	85.72	85.45	85.18	84.84	85.18
2013-06-17			82.17	81.99	85.96	85.89	85.24	84.64	84.17	85.21
2013-06-18			81.62	80.63	85.14	82.9	83.63	82.17	82.12	84.94
2013-06-19			80.59	79.31	83.67	79.43	81.69	79.56	80.24	83.88
2013-06-20			81.52	79.91	83.72	78.59	82.06	79.4	80.66	84.62
7 Day Average	79.61	79.64	81.09	80.48	84.11	82.66	83.24	82.35	82.46	83.95
Month-To-Date Average	78.87	78.66	79.56	79.33	80.67	80.13	80.35	80.02	80.06	80.61

Figure 8 Scenarios analysis of time series of temperature with observed data and model results under different scenarios. The columns starting with "R" refer to different model runs with different scenarios.

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