Influences of increased daily repeated upstream releases and varying meteorological conditions on temperature distributions in a river-reservoir system

G Chen [1] and X Fang [1, 2, 3]

[1] Department of Civil Engineering, Auburn University, Auburn, Alabama, USA
[2] Beijing Cooperative Innovation Research Center on Architectural Energy Saving and Emission Reduction, Beijing University of Civil Engineering and Architecture, Beijing, China

E-mail: xzf0001@auburn.edu

Abstract. Temperature distribution in a river-reservoir system was simulated using a calibrated three-dimensional Environmental Fluid Dynamics Code model under various hypothetical weather conditions and daily repeated large releases (DRLRs) from the upstream boundary. Both DRLRs and weather conditions affect and control the formation and spread of density currents and then affect the bottom-layer temperatures. The DRLRs with longer durations (e.g., 6 or 8 hours) can relatively quickly push cooler release water to the Gorgas upstream monitoring station (GOUS) and the river intake. With the air temperature drops in the first 6 days, simulated bottom temperatures at GOUS for 6- and 8-hr DRLRs are lower than one under 4-hr DRLR, but relatively larger bottom-layer temperature drops only primarily occur during the air-temperature drop and rise period. The release with larger flow rate can also maintain the cooler water temperature downstream. Releasing the same amounts of water, with different release durations and flow rates, has a very similar effect on the downstream water temperatures.

1. Introduction

Water temperature is one of the significant and important drivers of stream ecosystems. Water temperature affects all biological and chemical reactions and the density of water that influences the transport of water and pollutants in aquatic systems [1]. Human civilization and domination (through dam operation, industrial production, cropping, deforestation, etc.) would alter water temperatures in rivers [2]. Under the natural processes, many climate parameters can also possibly affect water temperature in streams/rivers, for example, solar radiation, relative humidity, wind speed [3]. Weather condition is one of the most important physical parameters that affects water temperature in aquatic systems. Harmeson and Schnepper [4] indicated graphically that water temperatures in rivers follow closely the pattern of variations in daily mean air temperatures.

The alteration of flow in the river can also be responsible for changes in river water temperature [5]. The reservoir release is a common operating procedure for regulated rivers to manage the water resources. The releases to meet hydro-electric power demands can affect the flow dynamics in downstream river. For the summer period or warm season, minimum release from upstream reservoir is typically required to maintain lower downstream temperature in relatively shallow rivers for environmental protection [6]. It is common that the upstream release results in rapid stage changes (such as more than 1 m) in the downstream river [7, 8]. The large release from a large dam results in wave propagations that exist more than 100 km downstream [9]. Besides the momentum and mixing effect from the upstream large release, atmospheric conditions will play an important role in the river temperature variations after the reservoir release.

The released temperature from stored water is much colder than the temperature in the shallow river downstream. Hence, many river-reservoir systems develop complex density currents in the downstream river/reservoir that has the large diurnal variations in atmospheric heating rates. A density current occurs when the density of the water flowing into a water body is greater than the density of the ambient water. For the traditional or classic gravity current, it's driven by the density difference. In the natural rivers and reservoirs, a density current is kept in motion by the force of gravity acting on differences in density, the slope of river and reservoir bottom (gravity), and the momentum effect from a large release that plays a role in density current propagation.

Several studies about density currents have been studied in situ [10]. The density currents are also investigated in the laboratory [11]. Using various simplifying assumptions, researchers dealt with sloping channels with rectangular cross sections to develop analytical models with laboratory data [12]. Recently, three-dimensional (3D) Environmental Fluid Dynamics Code (EFDC) [13] has been widely used in modelling hydrodynamics and transport processes in rivers, lakes, reservoirs, and estuaries. Hamrick and Mills [14] developed and used the EFDC model to simulate thermal transport and water temperature distributions in the Conowingo Pond that was influenced by thermal discharges from the Peach Bottom atomic power plant.

In this study, we focused on combined or integrated effects of variable weather conditions, and larger discharge of daily repeated large releases (DRLRs), on the downstream water temperatures. We examined simulated temperature distributions under different types of weather scenarios to evaluate site-specific correlation with weather conditions. The results of this study are important with regard to water quality modelling and management, and habitat assessment in rivers.

2. Study area

The study deals a river-reservoir system in Alabama (AL), USA, which is 124.2 river km long. For the modelling study of water temperature distributions in the system, the upstream boundary is the Smith Dam Tailrace (SDT), and the downstream boundary is Bankhead Lock& Dam (BLD). The system includes Sipsey Fork, the lower Mulberry Fork, and a reservoir segment of Bankhead Lake. Since Sipsey Fork and the lower Mulberry Fork are the riverine portions of Bankhead Lake, the study area is referred to as the Bankhead river-reservoir system (BRRS) in the paper. BRRS receives inflows from four tributaries: Upper Mulberry, Locust Fork, Lost Creek, and Blackwater Creek. A power plant is located at the bank of the upstream portion of BRRS and has a river intake that withdraws cooler water from two bottom layers in the Black Warrior River. One of the monitoring stations is called GOUS, 5.58 km upstream of the power plant or 64 km downstream from SDT. The average bottom slope of BRRS is 0.014% with bottom elevations changing from 65.8 to 77.2 m. The water surface elevation in BRRS depends on SDT's large water releases, flows from its tributaries, and the water surface elevation in BLD. The BLD elevation is typically influenced by outflow through hydro turbines, spillage through gates of BLD, and loss of water through the Bankhead navigation lock.

3. Model development and boundary conditions

The EFDC model is a general purpose modelling package that can be configured to simulate one-, two- and three-dimensional flow, transport, and biogeochemical processes in various surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions [15-17]. Details of governing equations and numerical schemes for EFDC hydrodynamic models are given by Hamrick [13]. The EFDC model for BRRS was designed to model or simulate temperature distributions along the Black Warrior River and along depth. Therefore, temperature model component in EFDC was activated to model thermal or heat budget for each computational cell. The heat input is from the upstream release water. It's the source of the lower water temperature which can make the downstream temperature lower. The measured upstream release temperatures varying with time directly link to the upstream computation cells. At the downstream boundary of the study area, water (heat) flux leaves the control volume. The model has the surface heat exchange between the atmosphere and the water surface. The heat exchange with the sediment is also applied around the river bed.

Using hydrographic bathymetry data, the EFDC model for the BRRS is developed. The simulation domain of the model has a total of 6974 horizontal grids and 10 horizontal layers along the depth direction for each grid. The grid size DX in transverse direction along the river ranged from 9.5 m to 189.8 m and DY in longitudinal flow direction ranged from 10.0 m to 277.1 m. Average grid sizes DX and DY are 25.7 m and 100.9 m, respectively.

The model of BRRS used the upstream boundary at the tailrace of Smith Dam and the downstream boundary at Bankhead L&D. There are two types of water releases from Smith Dam: (1) more or less constant continuous release (2.83 m^3/s) with almost 9.6 ^oC to support the downstream environment and ecosystem, (2) intermittent large releases from hydro-turbine units of Smith Dam in order to meet peak electric generation demand, which were about 4–5 ^oC higher than constant release temperature. For the downstream boundary, 15-minute water surface elevations are used for the BRRS. The typical water surface elevation at downstream is 77.6 m.

The atmospheric boundary condition was meteorological data from the Birmingham regional airport obtained from NOAA's Southeast Regional Climate Center (SERCC), which is about 40 km east of the study area. The data included hourly air temperature, atmospheric pressure, wind speed, wind direction, rainfall, and cloud cover. Required solar radiation data were obtained from Cleveland, AL, which is the closest Auburn Mesonet station from the study area.

4. Previous model application results

In the first study [7], a three-dimensional hydrodynamic and temperature EFDC model was calibrated with 2011 observed data to understand flow dynamics and temperature variations in BRRS under observed irregular upstream releases and varying meteorological conditions recorded in Birmingham. Comparing observed data, the simulation results show good performance for simulated water surface elevations, discharge, velocity, and temperatures at different locations. Especially for bottom temperature, the EFDC model predicted the magnitude and duration of these temperature drops with reasonable accuracy. It is essential that the EFDC model can predict the bottom temperatures because they are directly related to how the model simulates the density currents along the river bottom, which is the foundation for the next step.

Each flow release from SDT promoted and enhanced the movement of density currents moving from upstream towards downstream. In order to understand the cause/effect of upstream release on downstream bottom temperature in BRRS, all boundary conditions except the upstream release were fixed as constant in the second and third phases of the study [18]. Hourly varying climate variables under hypothetical constant weather condition were used as atmospheric boundary and based on data from a relatively warmer day in 2011, which have no cooling or warming trend, called as constant weather in this study, but have hourly variations in each day (Figure 1). Simulation results show that the density currents in BRRS are more complex than classic density currents and have discontinuous propagations. The density currents form at different reaches, and are destroyed at upstream locations due to the flow momentum of the releases, then form again due to solar heating. The propagation of density current is affected by the different durations of large releases and atmospheric conditions. Overall average surface and bottom temperatures are lower for longer duration of DRLRs [18].

5. Model scenarios

5.1. Durations of DRLR

After analyzing intermittent releases of 2010 and 2011 from SDT, and the statistical summary of the releases from SDT shows that both average and median releases were about 140 m^3/s and the releases typically started around 1:00 pm [7], additional data analysis was also performed to determine what possible durations of DRLRs from SDT could be. Table 1 shows calculated release durations of DRLRs from 2010 to 2014 if the release discharge at SDT is set at 140 m^3/s for each release. The available release data are about 184 days, mostly from May 1 to October 31 in each year. Calculated daily release duration ranges from 3.48 to 7.91 hours. Most release durations are from 4 to 6 hours, which will be used for the model scenario runs in this study. A few scenario runs will have the durations of 8-hr to generate comparative results, and the 8-hr DRLRs are highly possible in a relative warmer year, e.g., 2013 (table 1).

Table 1. Calculated daily upstream release durations of 140 m^3/s discharge based on 2010 to 2014 release data.

Year	Data period (Julian Day)	Recorded Total Release Volume (m^3)	Calculated Duration for DRLR (hr)
2010	151 to 333	359,557,358	3.48
2011	120 to 303	370,758,545	3.59
2012	121 to 304	443,569,903	4.39
2013	120 to 303	763,621,151	7.91
2014	120 to 303	631,369,260	6.45

5.2. Climate scenarios

Two types of meteorological scenarios were used in this study in order to identify weather impacts on density current movements: (1) constant weather (figure 1), and (2) hypothetical cooling and then warming weather (figure 2). For the constant weather scenario, the daily maximum and minimum air temperatures are 33.3 and 21.1 °C (figure 1). The hourly air temperatures were calculated from the daily maximum and minimum temperatures applying the sinusoidal wave function model [19]

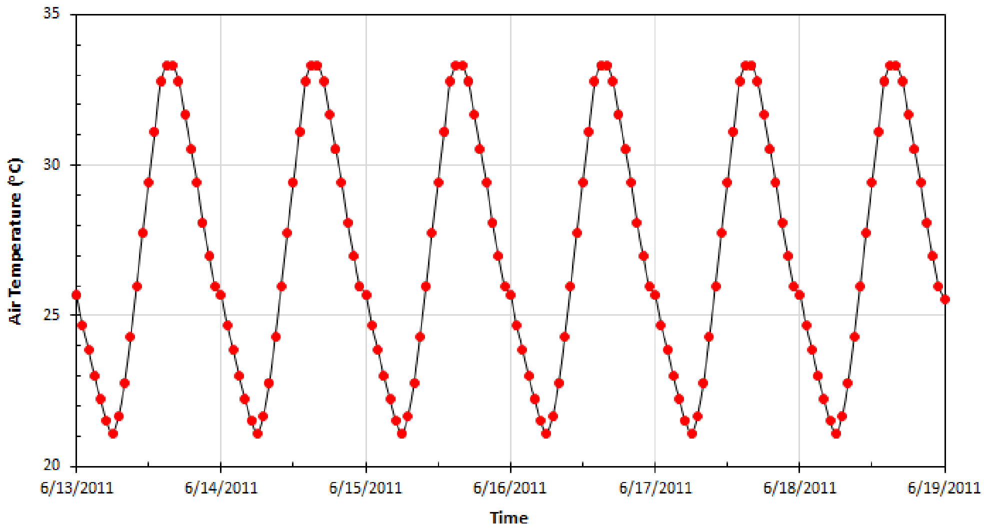

Figure 1. Six-day (June 13–18) example time-series of hourly varying air temperatures under hypothetical constant weather condition.

The calibrated EFDC model provided simulated water surface elevation in different cross sections and temperature, velocity and discharge in 10 layers (depths) for all grids. How do surface and bottom water temperatures at the downstream locations of BRRS drop or increase with the changes of weather conditions such as cooling and warming trend over a few days? To mimic typical weather variations in the Birmingham area [20], a new hypothetical weather scenario was proposed and developed: air temperature and solar radiation have a 6-day drop (June 13 – 18) and then a 6-day rise (June 18 – 23), and the constant weather (figure 1) was used before and after the drop and rise period (figure 2). This is an 11-day drop and rise period (June 13 – 23). During the drop and rise period, the air temperature has a drop or rise of 2 °C each day. The solar radiation has the same drop or rise pattern (trend) as the air temperature does, and it is assumed to be 10% change of the solar radiation under the constant weather condition each day.

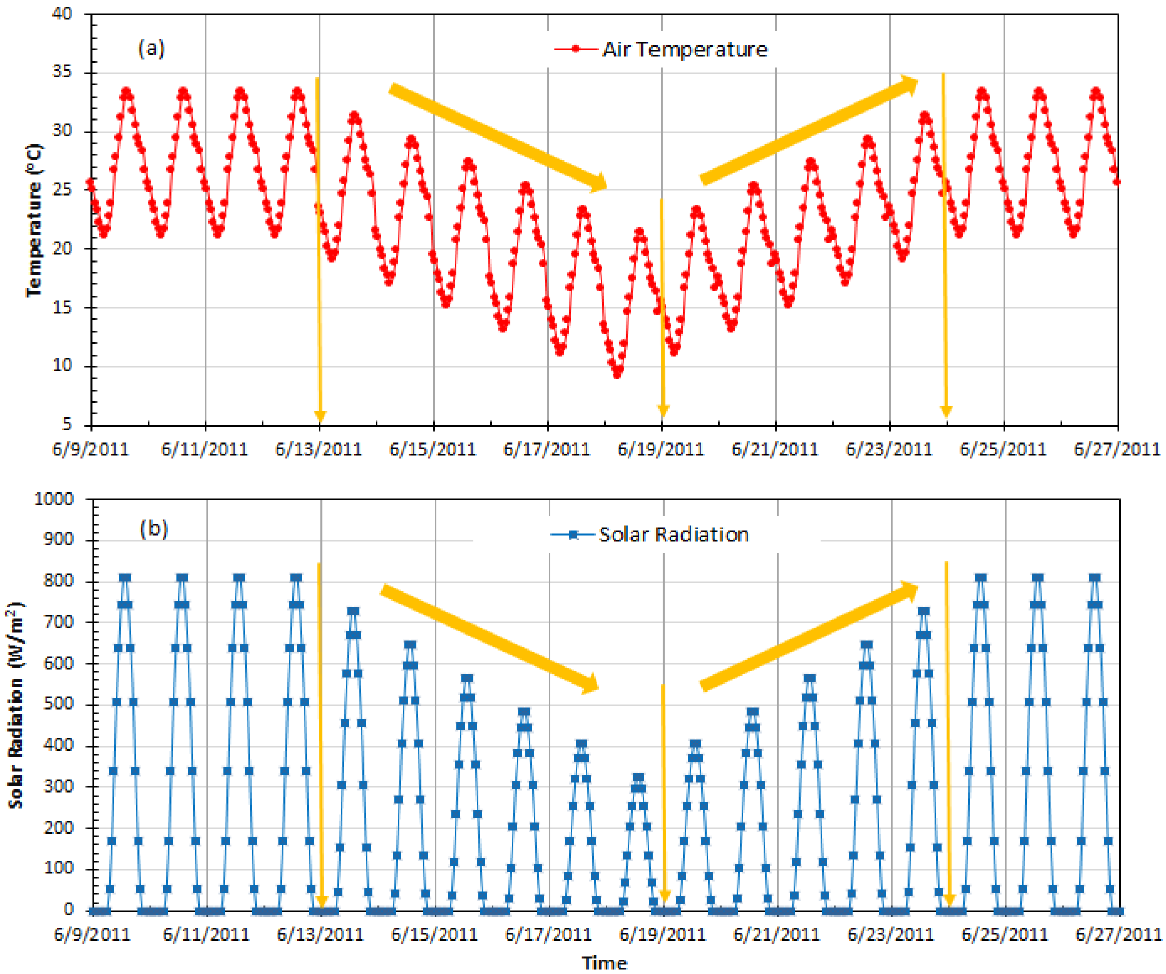

Figure 2. Weather scenario showing 6-day drop and then 6-day rise of air temperature and solar radiation from June 13 to 23 with the constant weather before and after the drop and rise period.

6. Results and discussion

6.1. Under two weather scenarios

Railsback (1997) concluded that significant saving can be realized using release patterns adapted to changing atmospheric conditions when the downstream river of the release is relatively shallow. Figure 3 shows time series of simulated surface- and bottom-layer water temperatures for 4-hr DRLR under two weather scenarios: the constant weather and the 11-day drop and rise. Under the constant weather, daily mean bottom and surface temperatures are almost constant for 4-hr DRLR from June 4 to July 18, and surface temperatures have 4.2 °C diurnal fluctuation when there is 12.2 °C variation of daily air temperature (figure 1).

For the first 6-day drop period, the surface temperature begins to drop quickly when the air temperature begins to drop from June 13. However, the bottom temperature shows a 3-day delay. After air temperature drops 4 days, the surface and bottom temperatures are well mixed for about 8 hours in each day (about 11 hr after the release) and continuously drop for 5 days. The surface temperature has much large diurnal variations that range from 3.8 to 9.0 °C (average of 6.9 °C and standard deviation of 1.8 °C) under the same 12.2 °C variation of daily air temperature. Under the 6-day rise period, when the air temperature starts to increase on June 19, the surface and bottom temperatures begin to increase with a 3-day delay. The surface temperature at GOUS rises quickly from 21.0 °C to 26.9 °C (constant daily-mean surface temperature under the constant weather condition) in 15 days. However, the bottom temperature takes much longer time to increase to the stable temperature simulated under the constant weather condition. Because of air temperature dropping and rising in 11 days, the bottom temperature can maintain a cooler temperature for about 32 (June 17 to July 19) days. Overall, water temperature at GOUS increases or drops corresponding to the air temperature change, but it can maintain the cooler condition for a longer period, especially for bottom layers.

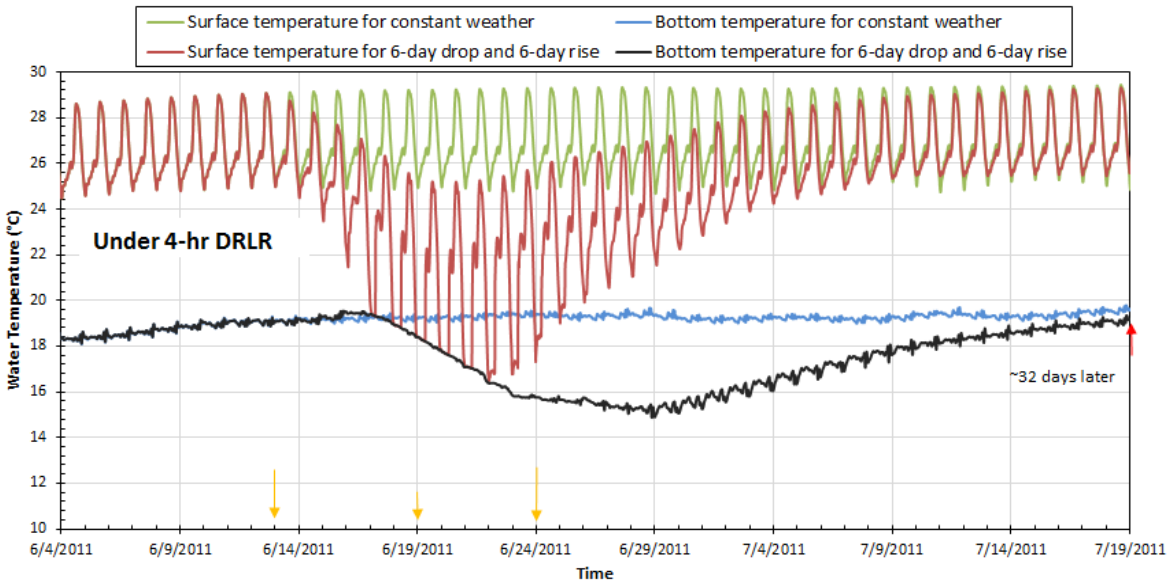

Figure 3. Time series of simulated surface and bottom water temperatures at GOUS for 4-hr DRLR under two weather scenarios: constant weather and the 11-day drop and rise.

6.2. DRLR duration changes during the drop and rise period

If more water is released during the cooler weather condition, could downstream temperatures become lower? Figure 4 shows time series of simulated bottom-layer water temperatures at the river intake under the 6-day drop and 6-day rise weather scenario when DRLRs with 140 m^3/s at SDT over the 11 days last for 4, 6, and 8 hours. The bottom-layer water temperatures at the river intake on June 13 (just before air temperature drop starts) are 19.3 °C. There are 4-hr DRLRs and the constant weather before and after the 11-day (June 13 to 23) air temperature drop and rise period. Comparing with the 4-hr DRLR for the whole period under constant weather, the scenario for 4-hr DRLR during 11-day drop and rise period has 12 °C air temperature drop, and solar radiation drops from June 13 to 19 (figure 2), and then increase on both parameters. The maximum and average daily mean differences during the cooler period (June 15 to July 9) between these two scenarios are 4.0 and 1.6 °C, respectively, which shows the benefit of air temperature drop on reducing the bottom-layer temperatures. For the 4-hr, 6-hr and 8-hr DRLRs during the drop and rise period, the bottom-layer temperature at the river intake begins to drop after 2 days of delay when it compares temperature time-series under the constant weather. The bottom-layer temperature drop is larger for longer DRLR. The lowest bottom-layer water temperatures at the river intake during the 11-day drop and rise period under 4-hr, 6-hr and 8-hr DRLRs are 15.4 ℃, 13.9 ℃ and 13.5 ℃ on June 24, 22 and 21 with the cooler duration 25 days (June 15 – July 9), 31 days (June 15 – July 15), and 31 days (June 15 – July 15), respectively.

To see the increased duration effects with cooler weather condition, the differences of daily mean temperatures for 6-hr, 8-hr DRLRs comparing with 4-hr DRLR were also calculated. The maximum daily mean differences for 6-hr and 8-hr DRLR scenarios are 2.23 °C and 3.13 °C, respectively. Over the cooler duration (June 15 – July 15), the average differences under 6-hr and 8-hr DRLRs are 0.6 °C and 0.9 °C in comparison to the 4-hr DRLR, respectively. Therefore, the large releases with longer durations (e.g., 6 or 8 hours) can relatively quickly push cooler release water to the river intake. With the air temperature drop in the first 6 days, simulated bottom temperatures at the river intake for 6-hr and 8-hr DRLRs are lower than ones under 4-hr DRLR, but relatively larger bottom-layer temperature drops primarily occur during the air-temperature drop and rise period. During or after the rise period, the bottom-layer temperatures are almost the same for 6-hr and 8-hr DRLRs and show similar patterns.

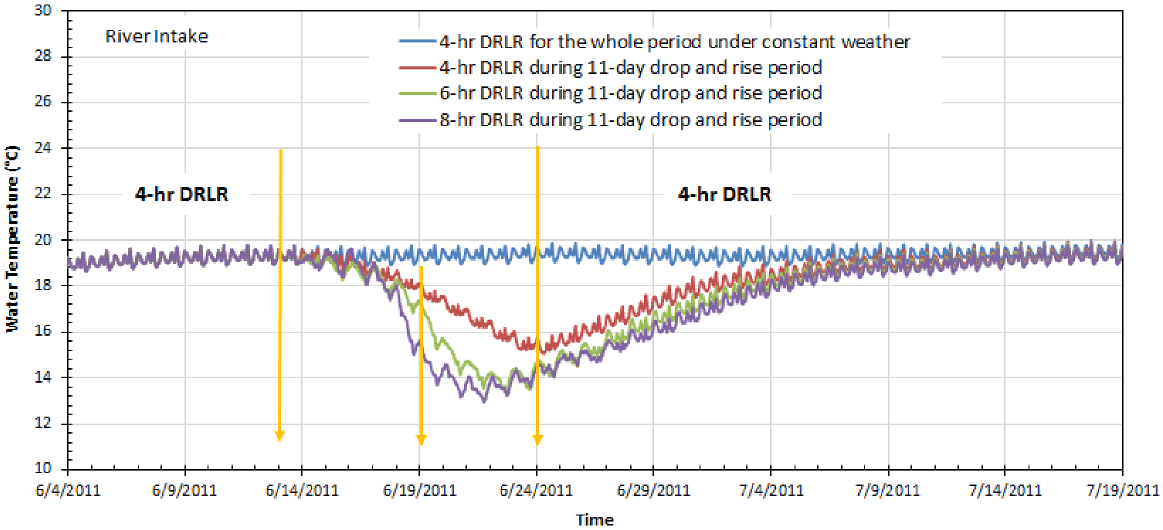

Figure 4. Time series of simulated bottom temperatures at the river intake when the DRLR release lasts for 4-hr, 6-hr and 8- from June 13 to 23 under 11-day drop and rise weather scenarios. There are 4-hr DRLRs and the constant weather before and after the air temperature drop and rise period.

6.3. Increase release flow rate scenario

6.3.1. Under constant weather. For the above scenario runs, the release flow rate from SDT is fixed as 140 m^3/s with different durations because, for example, 50% of 2011 recorded releases ranged from 137.3 to 142.1 m^3/s with a median of 138.8 m^3/s [7]. Under the actual release, there are some releases up to about 280 m^3/s in 2011. Figure 5 shows the time series of simulated bottom temperature at GOUS with increased release of 280 m^3/s starting from June 13 and lasting 2, 4 and 6 days under constant weather. The release duration is 4 hours each day. Due to the 280 m^3/s DRLR for 2, 4 and 6 days, simulated bottom temperature at GOUS increases from 19.1 °C to 20.2 °C in one day and keeps more or less constant for about 3 days due to the large flow momentum. Then, the bottom temperature decreases and maintains the cooler temperature from June 17 to July 13. It seems these 2, 4, and 6 days of larger release (280 m^3/s), push more cooler water to GOUS and have the cooler bottom temperatures for 26 days in comparison to temperatures for 4-hr 140 m^3/s DRLR. Although there are 4 days with higher bottom temperature immediately after the larger release (figure 5). The lowest bottom temperatures resulted from 280 m^3/s 4-hr DRLR for 2, 4, and 6 days are 16.8, 16.0, and 15.9 ^oC, respectively. The daily mean bottom temperatures from June 18 to July 8 for 2 days of 280 m^3/s 4-hr DRLRs are 0.2 to 1.4 ^oC higher than temperatures for 4 days of 280 m^3/s 4-hr DRLRs. Overall, simulated bottom temperatures at GOUS for 4 and 6 days of 280 m^3/s 4-hr DRLRs are very similar (figure 5).

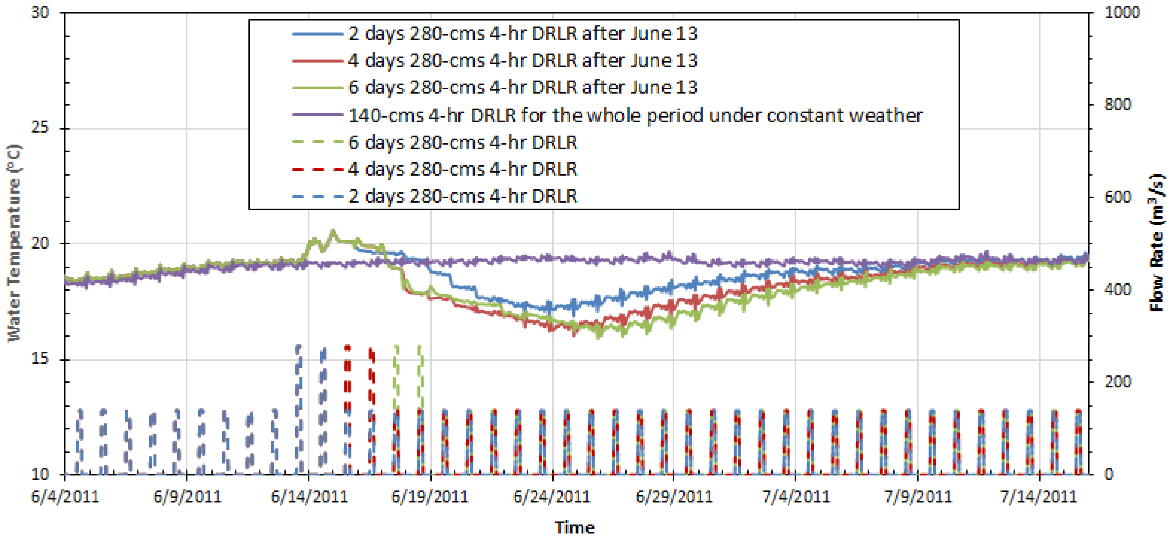

Figure 5. Time series of simulated bottom temperature at GOUS for 4-hr 140 m3/s DRLR with 4-hr 280 m^3/s DRLR starting from June 13 and lasting 2, 4 and 6 days under constant weather, including time series of release flow rate from upstream.

6.3.2. Simulation of release scenarios under drop and rise period. Can increased duration, or the flow rate, or both of the large releases make the downstream bottom temperature lower? Figure 6(a) shows time series of simulated bottom temperatures at GOUS under the 6-day drop and 6-day rise weather scenario under 4 release patterns, which are 4 combinations of DRLRs from two release flows (140 or 280 m^3/s) and two release durations (4 or 8 hours). There are 4-hr DRLRs and the constant weather before and after the air temperature drop and rise period (June 13 to 23). Same as Figure 4, longer and larger release will maintain the bottom temperature much longer and cooler. One interesting phenomenon is that the pattern of bottom temperatures is almost the same for 4-hr DRLR with 280 m^3/s and 8-hr DRLR with 140 m^3/s. It may be due to the same amount of water that was released for the two scenario runs. Due to the flow momentum, there are two days of the water temperature going up, which is an increase from about 19 to 20 ^oC. Afterwards, the bottom temperature decreases and maintains cooler temperatures for about 40 days. The scenario 1, 140 cms 4-hr DRLR, is a reference run because there is no change on the duration and the flow rate of the release before and after the drop and rise period. The minimum bottom temperature at GOUS is 15.2 ^oC occurring on June 29 under the scenario 1, and the bottom temperature increases to 19.2 ^oC on July 19.

For the other 3 scenarios, the minimum bottom temperatures at GOUS are 14.0, 13.8, and 12.9 ^oC occurring on June 20, June 20, and June 19, respectively. The bottom temperature gradually increases to 19.1, 19.1, and 18.9 ^oC on July 19, respectively. Figure 6(b) shows time series of differences of daily mean simulated bottom-layer temperatures between the reference scenario 1 and the other 3 scenarios. Figure 6(b) is derived from the data in figure 6(a). The positive differences indicate that the other 3 scenarios make the bottom-layer water temperatures at GOUS cool further. Although the bottom temperatures for 8-hr DRLR with 140 m^3/s are a little bit colder (on average -0.1 ^oC) than temperatures under the 4-hr DRLR with 280 m^3/s, overall, releasing the same amounts of water may have almost the same impact to maintain lower bottom-layer temperature downstream. Mean differences with standard deviations were calculated over the lower temperature periods (~35 days from June 15 to July 19), which are 0.7 (± 1.1) ^oC, 0.9 (± 1.0) ^oC and 2.0 (± 1.5) ^oC for the scenarios of 280 cms 4-hr, 140 cms 8-hr, and 280 cms 8-hr DRLRs. It should be mentioned that the scenario of 280 cms 8-hr DRLRs releases two times the amount of water in comparison to two scenarios of 280 cms 4-hr and 140 cms 8-hr DRLRs, and four times the amount of water in comparison to the reference scenario of 140 cms 4-hr DRLRs.

What is the optimal combination of release duration and flow rate? There is a maximum temperature at the river intake that we need to determine in order to meet downstream temperature constraints set by a regulatory agency. The releasing of more water during the drop and rise period has created a lower-bottom-temperature effect for ~35 days (figure 6(b)); it is still an efficient approach to make the bottom temperature at the river intake lower to compensate for potential temperature increase due to warmer weather after the air temperature drop period. More scenario runs and result analyses are still necessary to identify the optimal release pattern. Using weather forecasts and adjusted release schedules may be useful to the reservoir release management.

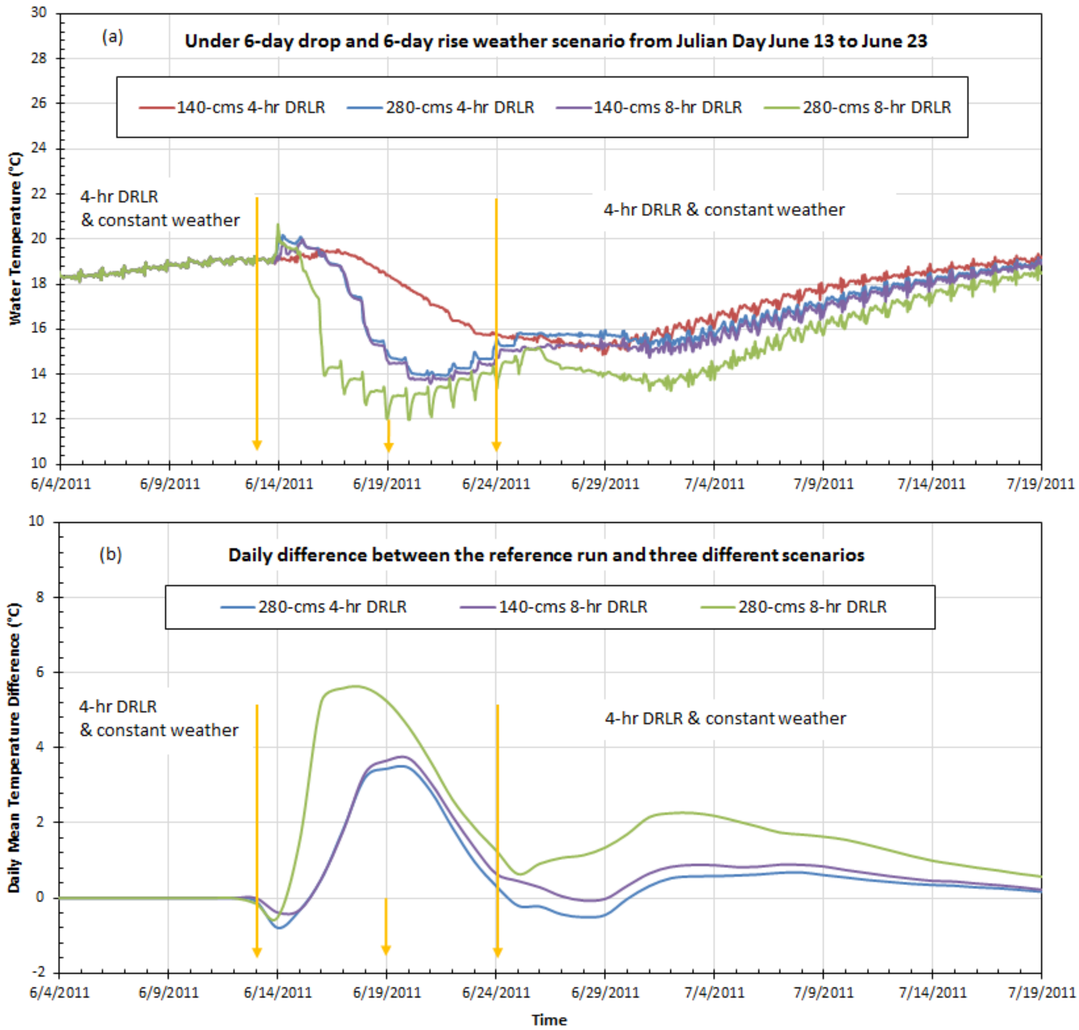

Figure 6. (a) Time series of simulated bottom temperatures at GOUS under the 6-day drop and 6-day rise weather scenario when 140-cms or 280-cms DRLRs last for 4 or 8 hrs (4 combinations). There are 4-hr DRLRs and the constant weather before and after the air temperature drop and rise period (June 13 to 23). (b) Difference of daily mean simulated bottom-layer temperatures between the reference scenario 1 and other 3 scenarios.

7. Conclusions

In this paper we applied a previously calibrated 3D EFDC model for a river-reservoir system to simulate temperature distributions under various hypothetical weather conditions and increased daily repeated large releases or DRLRs from upstream boundary. A series of model scenario runs were performed to further understand the bottom-layer water temperature changes at downstream locations of BRRS (e.g., GOUS and the river intake) corresponding to hypothetical meteorological changes under different release scenarios. All hypothetical weather and release scenarios were based on the data analysis of local weather conditions and actual release patterns.

Both the large releases and weather conditions affect the formation and spread of density currents and then bottom temperature distribution in BRRS. The large releases with longer durations (e.g., 6 or 8 hours) can relatively quickly push cooler release water to GOUS and the river intake. The air temperature drop of 12 ^{o}C in the first 6 days simulated maximum and average daily-mean differences during the cooler period (June 15 to July 9) in comparison to ones under the constant weather scenario are 4.0 and 1.6 °C, respectively. Daily mean simulated bottom temperatures at GOUS for 6- and 8-hr DRLRs are also on average 0.6 and 0.9 ^{o}C lower than ones under 4-hr DRLR, but relatively larger temperature drops only primarily occur during the air-temperature drop and rise period (figure 4). The release with larger flow rate can also maintain the cooler water temperature downstream. Releasing the same amounts of water have very similar effects to the downstream water temperatures (figure 6). More research is still necessary to identify the optimal release pattern.

References

[1] Thomann R V and Mueller J A 1987 *Principles of surface water quality modeling and control* (New York: Harper & Row)

[2] Caissie D 2006 The thermal regime of rivers: a review *Freshw. Biol.* **51** 1389-406

[3] Johnson A C, Acreman M C, Dunbar M J, Feist S W, Giacomello A M, Gozlan R E, Hinsley S A, Ibbotson A T, Jarvie H P and Jones J I 2009 The British river of the future: how climate change and human activity might affect two contrasting river ecosystems in England *Sci. Total Environ.* **407** 4787-98

[4] Harmeson R H and Schnepper V M 1965 Temperatures of surface waters in Illinois. In: *Illinois State Water Survey Report of Investigation* **49** p 45

[5] Sinokrot B A and Gulliver J S 2000 In-stream flow impact on river water temperatures *Journal of Hydraulic Research* **38** 339-49

[6] Consultants W-C 1986 *Stanislaus project instream temperature study* Pacific Gas and Electric Company, San Ramon, California

[7] Chen G, Fang X and Devkota J 2015 Understanding flow dynamics and density currents in a river-reservoir system under upstream reservoir releases *Hydrological Sciences Journal*

[8] Fang X, Weems T B, Devkota J and Chen G 2013 *Watershed modeling, water balance analysis, three-dimensional flow and thermal discharge modeling for the William C.* Gorgas Plant. Department of Civil Engineering, Auburn AL **368** p 124

[9] Petts G E 1984 Impounded rivers: perspectives for ecological management. Wiley, Chichester, UK **329** pp

[10] Dallimore C J, Imberger J and Ishikawa T 2001 Entrainment and turbulence in saline underflow in Lake Ogawara *Journal of Hydraulic Engineering* **127** 937-48

[11] Akiyama J and Stefan H G 1984 Plunging flow into a reservoir - Theory *Journal of Hydraulic Engineering ASCE* **110** 484-99

[12] Fernandez R L and Imberger J 2008 Time-varying underflow into a continuous stratification with bottom slope *Journal of Hydraulic Engineering* **134** 1191-8

[13] Hamrick J M 1992 A three-dimensional environmental fluid dynamics computer code: Theoretical and computational aspects. In: *Speical Report* **317** (Gloucester Point, VA: The College of William and Mary, Virginia Institute of Marine Science) p 63

[14] Hamrick J M and Mills W B 2000 Analysis of water temperatures in Conowingo Pond as

influenced by the Peach Bottom atomic power plant thermal discharge *Environmental Science & Policy* **3** 197-209

[15] Shen J and Lin J 2006 Modeling study of the influences of tide and stratification on age of water in the tidal James River *Estuarine, Coastal and Shelf Science* **68** 101-12

[16] Kim C-K and Park K 2012 A modeling study of water and salt exchange for a micro-tidal, stratified northern Gulf of Mexico estuary *Journal of Marine Systems* **96–97** 103-15

[17] Devkota J and Fang X 2014 Numerical simulation of flow dynamics in a tidal river under various upstream hydrologic conditions *Hydrological Sciences Journal*

[18] Chen G and Fang X 2015 Sensitivity analysis of flow and temperature distributions of density currents in a river-reservoir system under upstream releases with different durations *Water* **7** 6244-68

[19] Chen G and Fang X 2015b Accuracy of hourly water temperatures in rivers calculated from air temperatures *Water* **7** 1068-87

[20] Chen G and Fang X 2016 Influences of meteorological conditions and daily repeated upstream release on temperature distributions in a river-reservoir system *Journal of Hydro-environment Research*