Prepared in cooperation with the U.S. Environmental Protection Agency

Simulation of Discharge, Water-Surface Elevations, and Water Temperatures for the St. Louis River Estuary, Minnesota-Wisconsin, 2016–17

Scientific Investigations Report 2020–5028

U.S. Department of the Interior
U.S. Geological Survey

Full cover. Photograph showing the St. Louis River and St. Louis Bay, Duluth, Minnesota, taken June 6, 2015. Photograph courtesy of James St. John, licensed under the Creative Commons Attribution 2.0 Generic license.

Back cover. Photograph looking upstream towards the Oliver Bridge at the U.S. Geological Survey acoustic Doppler velocity meter installation, St. Louis River, Minnesota-Wisconsin. Photograph taken July 30, 2015, by hydrologist Joel Groten, U.S. Geological Survey.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	39.37	inches (in.)
kilometer (km)	0.6215	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	2.47	acre (ac)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F = (1.8 \times °C) + 32.$$

Datum

Vertical coordinate information is referenced to the International Great Lakes Datum of 1985 (IGLD 1985), unless otherwise indicated.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

A water year is the period from October 1 to September 30 and is designated by the year in which it ends; for example, water year 2016 was from October 1, 2015, to September 30, 2016.

Abbreviations

AOC	Area of Concern
EFDC	Environmental Fluid Dynamics Code
EPA	U.S. Environmental Protection Agency
GLRI	Great Lakes Restoration Initiative
MAE	mean absolute error
ME	mean error
MN DNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
NDBC	National Data Buoy Center
NSEC	Nash-Sutcliffe efficiency coefficient
RMSE	root mean square error
USAF	U.S. Air Force
USGS	U.S. Geological Survey

Simulation of Discharge, Water-Surface Elevations, and Water Temperatures for the St. Louis River Estuary, Minnesota-Wisconsin, 2016–17

By Erik A. Smith,[1] Richard L. Kiesling,[1] and Earl J. Hayter[2]

Abstract

The St. Louis River estuary is a large freshwater estuary, next to Duluth, Minnesota, that encompasses the headwaters of Lake Superior. The St. Louis River estuary is one of the most complex and compromised near-shore systems in the upper Great Lakes with a long history of environmental contamination caused by logging, mining, paper mills, and other heavy industrial activities. Presently (2020), a widely available, science-based assessment tool capable of evaluating ecosystem-level responses to remediation and restoration projects has not existed for the estuary. To address this need, the U.S. Geological Survey (USGS) built a predictive, mechanistic, three-dimensional hydrodynamic model for the estuary using the Environmental Fluid Dynamics Code framework. In the current version, the model can simulate continuous discharge, water-surface elevations, water temperature, and flow velocity, although the modular framework allows for future additions of water-quality modeling.

The model was calibrated using data collected from April 2016 through November 2016 and validated with data collected from April 2017 through November 2017. The four types of data used to evaluate model performance were water-surface elevations, discharge, water temperature, and flow velocities. Streamflow and temperature boundary condition data included a mixture of USGS streamgage data, Minnesota Department of Natural Resources gage data, and estimates derived from the gage data.

The model was able to simulate the water-surface elevations with generally good agreement between the simulated and measured values for both years at the daily time step. Specifically, the model was able to demonstrate excellent agreement with the measured data with Nash-Sutcliffe efficiency coefficients greater than 0.8 for all three locations; however, the model was unable to produce hourly water-surface elevations with such accuracy for 2016–17.

Discharge was more dynamic than the water-surface elevations, both for the measured and simulated data. Generally, most of the discharge ranged from −650 to 1,200 cubic meters per second, but the constantly changing flux exiting the estuary into Lake Superior (positive flows) and entering the estuary from Lake Superior (negative flows) occurred throughout the year. Even upstream at the St. Louis River at Oliver, Wisconsin, gage (USGS station 0402403250), the effect of flows into the estuary from Lake Superior did occur, demonstrating the strong effect of the Lake Superior seiche on flows for the estuary.

From a performance standpoint, the model was able to simulate discharge with generally good agreement in both years, although the 2017 validation was better than the 2016 calibration period. For the daily Nash-Sutcliffe efficiency coefficients, the simulated values were 0.98, 0.62, 0.49, and 0.71 for the Oliver gage; the Superior Bay entry channel at Superior, Wisc., (USGS station 464226092005600); the Superior Bay Duluth Ship Canal at Duluth, Minn., (USGS station 464646092052900); and total entries (combination of the Superior entry and Duluth entry), respectively. For the hourly evaluation criteria, the model performed poorly, with Nash-Sutcliffe efficiency coefficients less than 0 for the two entries into Lake Superior; therefore, as a predictor of discharge at the hourly scale, the model performed worse than using the measured data average. Similar to discharge, the model was a good predictor of flow velocity at the daily time scale but had difficulty matching the measured data at the hourly scale. For discharge and flow velocity, matching at subdaily time steps for a system as complicated as the St. Louis River estuary is considered difficult because the match is highly sensitive to coordinating the exact measurement location to the simulated value.

The final calibration target was water temperature, calibrated for the Oliver gage and the Duluth entry. For calibration purposes, the Duluth entry was the more important water temperature target because the Oliver gage was more of an internal check on the model. The Nash-Sutcliffe efficiency coefficients for the Duluth entry were high; hourly Nash-Sutcliffe efficiency coefficients at the Duluth entry were either at or greater than 0.7 for both years, and daily values were 0.84 and 0.82 for 2016 and 2017, respectively.

[1]U.S. Geological Survey.

[2]U.S. Army Corps of Engineers.

Introduction

The St. Louis River is the largest U.S. tributary to Lake Superior, flowing 323 kilometers (km) before discharging into Lake Superior between Duluth, Minnesota, and Superior, Wisconsin (Christensen and others, 2012). The last 38 km of the St. Louis River is a freshwater estuary that encloses several shallow bays, an 8-meter (m) dredged shipping channel, and an active shipping port. Also known as the St. Louis River estuary, the freshwater estuary is about 4,850 hectares in area and encompasses the headwaters of Lake Superior (St. Louis River Estuary, 2019).

The St. Louis River estuary also is one of the most complex and compromised near-shore systems in the upper Great Lakes with a long history of environmental contamination caused by logging, mining, paper mills, and other heavy industrial activities. For the past 200 years, the St. Louis River estuary has been an economic hub for northeast Minnesota and northwest Wisconsin (Christensen and others, 2012). All these economic activities have deposited large loads of suspended solids and nutrients directly into the estuary. The International Joint Commission designated the estuary as a Great Lakes Area of Concern (AOC) in 1989 (Christensen and others, 2012) because of severely degraded water quality.

In 2010, the Great Lakes Restoration Initiative (GLRI) was launched as a multiyear commitment to implement solutions to beneficial use impairments around the Great Lakes through monitoring, remediation, and restoration (Great Lakes Interagency Task Force, 2014). These monitoring and restoration efforts have moved forward on many fronts, often at the same time, with the stated objective of approaching or reaching previously established delisting targets for individual impairments. The estuary has been the recipient of multiple projects through the GLRI because there has been coordinated action by multiple partners in Minnesota and Wisconsin to delist the St. Louis River AOC (Anderson and others, 2013); however, one of the difficulties in delisting any AOC is how individual projects that have been implemented will produce a sustainable solution to the stressor gradients. This is particularly difficult for near-shore areas of the Great Lakes such as the St. Louis River, which itself is one of the largest and most complex tributary systems in the upper Great Lakes. For example, sediment and nutrient loading from this system dominates the near-shore nutrient economy of western Lake Superior (Robertson and Saad, 2011), so its effect on Lake Superior is substantial.

Presently (2020), a widely available science-based assessment tool capable of evaluating ecosystem-level responses to remediation and restoration projects that can consider the complex hydrodynamics of the St. Louis River estuary does not exist. A previous hydrodynamics model was completed in 2013 on behalf of the U.S. Environmental Protection Agency (EPA) to address the mercury total maximum daily load for the estuary. The modeling framework combined Environmental Fluid Dynamics Code (EFDC) and the Water Quality Analysis Simulation Program, but the model calibration period was for less than 1 month and only included the Nemadji River and the St. Louis River main branch (RTI International, 2013). A second model, also built with EFDC, was completed to understand sediment transport caused by dredging activities within a section of Saint Louis Bay around 21st Avenue West (Mausolf, 2014). However, this project was largely focused on a small area, so to help understand the cumulative effect of multiple, simultaneous aquatic restoration actions across the estuary, a new systems-level evaluation tool is required.

A first step in designing a new evaluation tool or modeling framework for the St. Louis River estuary is to incorporate all the hydrodynamics, including continuous discharge from the following sources: the main St. Louis River channel, Nemadji River, Pokegama River, Duluth-area (Minnesota) tributaries, northwest Wisconsin tributaries such as the Red River and Little Pokegama (not shown), and water treatment effluent. The new evaluation tools would need to also consider the effect of Lake Superior water-surface elevations because the lake causes frequent back flow into the estuary through storm surges and periodic seiche events (Mausolf, 2014; City of Superior, 2019). By incorporating all flow sources and Lake Superior water-surface elevations into the new model, the estuary water balance can be properly accounted for so that additional modeling of sediment, nutrients, and submerged aquatic vegetation can eventually be merged into this single modeling framework.

Starting in 2015, the U.S. Geological Survey (USGS) received GLRI funds from the EPA to collect new streamflow, stage, and water temperature datasets across the St. Louis River estuary, including the initiation of a new gaging and water-quality station near Oliver, Wisc. Funds also were provided to establish continuous velocity and discharge stations for the Superior and Duluth entries from the estuary into Lake Superior. These new datasets provided the necessary information for developing a three-dimensional hydrodynamic model of the St. Louis River estuary. Building on other data collected by multiple agencies across the estuary, including the Minnesota Department of Natural Resources (MN DNR); University of Minnesota-Duluth, Natural Resources Research Institute; and Minnesota Pollution Control Agency (MPCA), the USGS, in collaboration with the U.S. Army Corps of Engineers, Engineer Research and Development Center, and in cooperation with the EPA, developed a predictive, mechanistic, three-dimensional hydrodynamic model for the St. Louis River estuary, Minnesota-Wisconsin. This model was developed with EFDC, a grid-based, surface-water modeling package for simulating three-dimensional circulation, mass transport, sediments, and biogeochemical processes (Hamrick, 1992, 2007). The new model simulates continuous discharge, water-surface elevations, water temperature, and flow velocities across the estuary. Furthermore, this model can be used as a framework for simulating other biogeochemical processes once the appropriate datasets have been collected and processed. The long-term goal for the model is to serve as an integrated, science-based assessment tool capable of evaluating ecosystem-level responses to remediation and restoration projects for the St. Louis River estuary.

Purpose and Scope

The purpose of this report is to describe the initial development of the hydrodynamic component of a new model to simulate discharge, water-surface elevations, water temperature, and flow velocity for the St. Louis River Estuary, in Minnesota and Wisconsin. The model was calibrated using data collected from April 2016 through November 2016 and validated with data collected from April 2017 through November 2017. The report summarizes the development and calibration of the new model.

Study Area

The St. Louis River is the largest tributary to Lake Superior (fig. 1; Smith and others, 2017), flowing for 323 kilometers (km) (201 mi) towards Lake Superior before discharging into Lake Superior at Duluth, Minn. (fig. 1). The St. Louis River drainage basin is one of the largest in northern Minnesota. The drainage basin above the St. Louis River at Scanlon, Minn. (USGS station 04024000), streamgage (hereafter referred to as “gage”) is 8,884 square kilometers (km^2) (Smith and others, 2017). The drainage basin includes the main stem of the St. Louis River, in addition to the Whiteface River and the Cloquet River. The St. Louis River drainage basin is in a heavily forested region of northeastern Minnesota; most of the drainage basin is within the Northern Lakes and Forests ecoregion (Anderson and others, 2013). The climate in the basin is hemiboreal, a warm summer continental climate, and is characterized by long winters, moderate to heavy snow cover, and short summers. Precipitation in the area averages between 0.7 and 0.8 m per year (Lindholm and others, 1979; National Climatic Data Center, 2018).

The last 24 km (15 mi) of the St. Louis River is considered a freshwater estuary that forms part of the border between Minnesota and Wisconsin (fig. 2). The St. Louis River estuary includes several shallow bays, including Saint Louis Bay, Superior Bay, and Allouez Bay, as well as Spirit Lake and the lower Nemadji River (fig. 2). Additionally, the Nemadji River flows into the estuary, and the system is sometimes referred to as the St. Louis River/Nemadji River estuary. The estuary has been affected by heavy industry since the late 1800s, although water quality has steadily improved since the Western Lake Superior Sanitary District began treating industrial and domestic effluent in 1979 (Lindgren and others, 2006). The estuary still contains several potential sources of contaminants, including two Superfund sites (Blazer and others, 2014) and several impairments related to altered hydrology and total suspended solids, although these are all being addressed by multiple Federal, State, and local partners.

Previous Studies

A preliminary water budget was included as part of a characterization of the St. Louis River surface-water and groundwater resources by Lindholm and others (1979). Separately, the Fond du Lac Indian Reservation water resources were characterized by Ruhl (1989). The physical characteristics and comprehensive water-quality synopses for the St. Louis River were summarized by Lindgren and others (2006). In 2010, chemicals of emerging concern were sampled at selected sites in Saint Louis and Superior Bays (Christensen and others, 2012). After the severe flooding of the St. Louis River in 2012, Czuba and others (2012) characterized the high-water marks for several communities in and around the St. Louis River, also creating flood-peak inundation maps and water-surface profiles for several of the most affected communities.

Other studies have included the numerical modeling and sediment transport analysis to identify optimal dredged placement sites within the estuary around the 21st Avenue West site in Saint Louis Bay (Mausolf, 2014). Across the drainage basin, multiple partners led by the MPCA contributed to the St. Louis River Watershed Monitoring and Assessment report, a summary of load and discrete sampling across the St. Louis River drainage basin (Anderson and others, 2013), and the more recent Watershed Restoration and Protection Strategy Report (MPCA, 2018). Tetra Tech, in cooperation with the State of Minnesota, completed a series of Hydrologic Simulation Program-Fortran models for subwatersheds across the St. Louis River drainage basin, including the Duluth-area tributaries (Tetra Tech, 2016). Finally, the USGS characterized the relative and cumulative streamflow distributions for the St. Louis River drainage basin (Smith and others, 2017).

Methods

The St. Louis River estuary model was constructed using EFDC, a grid-based surface-water modeling package developed in the 1990s for estuarine and coastal applications (Hamrick, 1992, 2007). EFDC solves the vertically hydrostatic, free-surface, turbulent-averaged equations of motions for a variable-density fluid. Dynamically coupled transport equations for kinematic energy, turbulent length scale, salinity, and temperature also are solved. EFDC is a widely used modeling framework that has been applied in a variety of surface-water studies (Ji and others, 2004; Elçi and others, 2007; Dynamic Solutions, LLC, 2013; Ji, 2017). The new model discussed in this report simulates discharge, water-surface elevations. water temperature, and flow velocity.

The EFDC model structure used in this study required bathymetric data, bottom roughness coefficients, and tributary inflow locations. For all aspects of running the enhanced model, EFDC Explorer version 8.4 (compiled July 28, 2018),

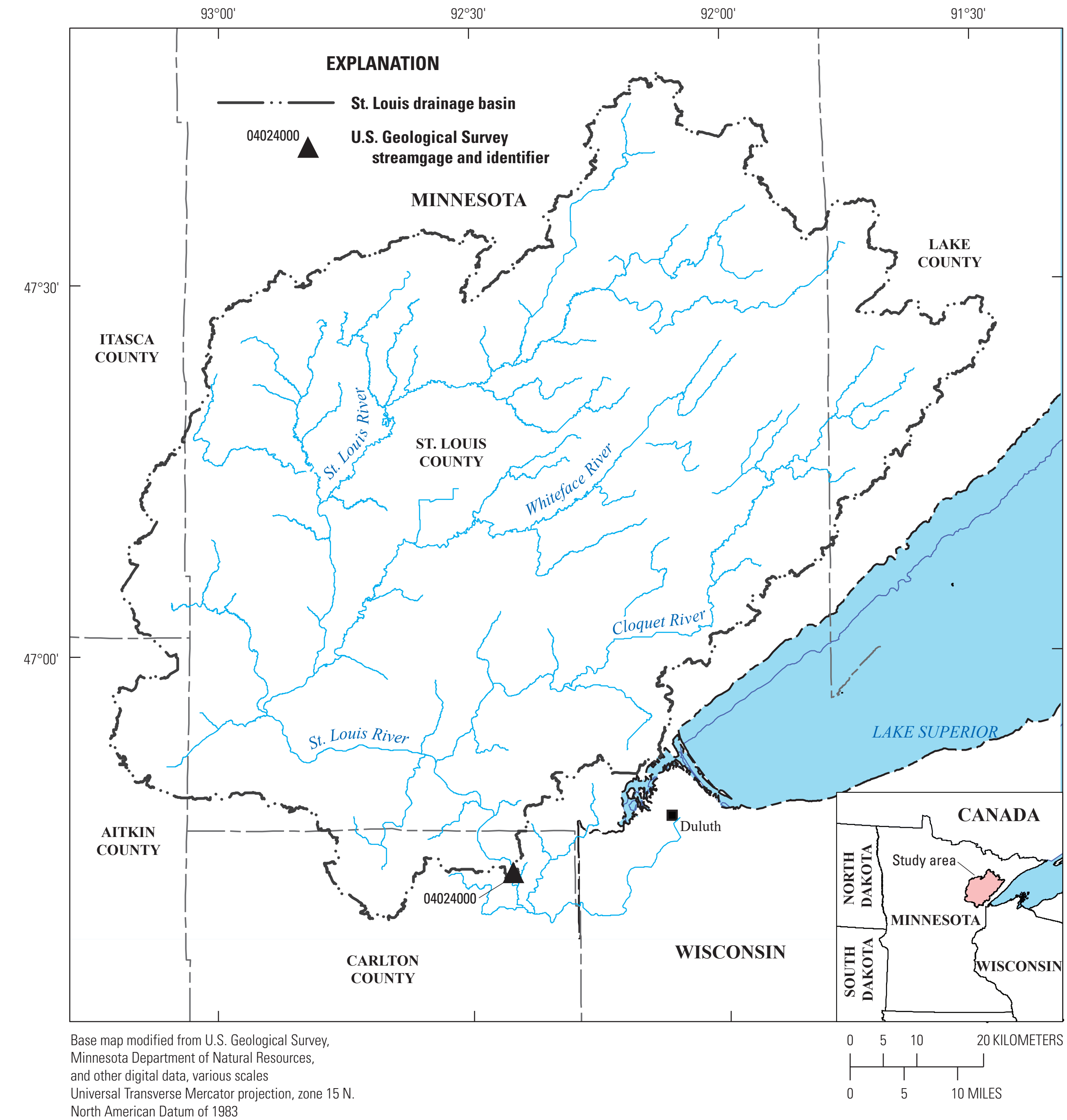

Figure 1. The St. Louis River drainage basin above the St. Louis River at Scanlon, Minnesota, streamgage (U.S. Geological Survey station 04024000), including the main stem of the St. Louis River, the Whiteface River, and the Cloquet River, major cities/towns, and other administrative boundaries.

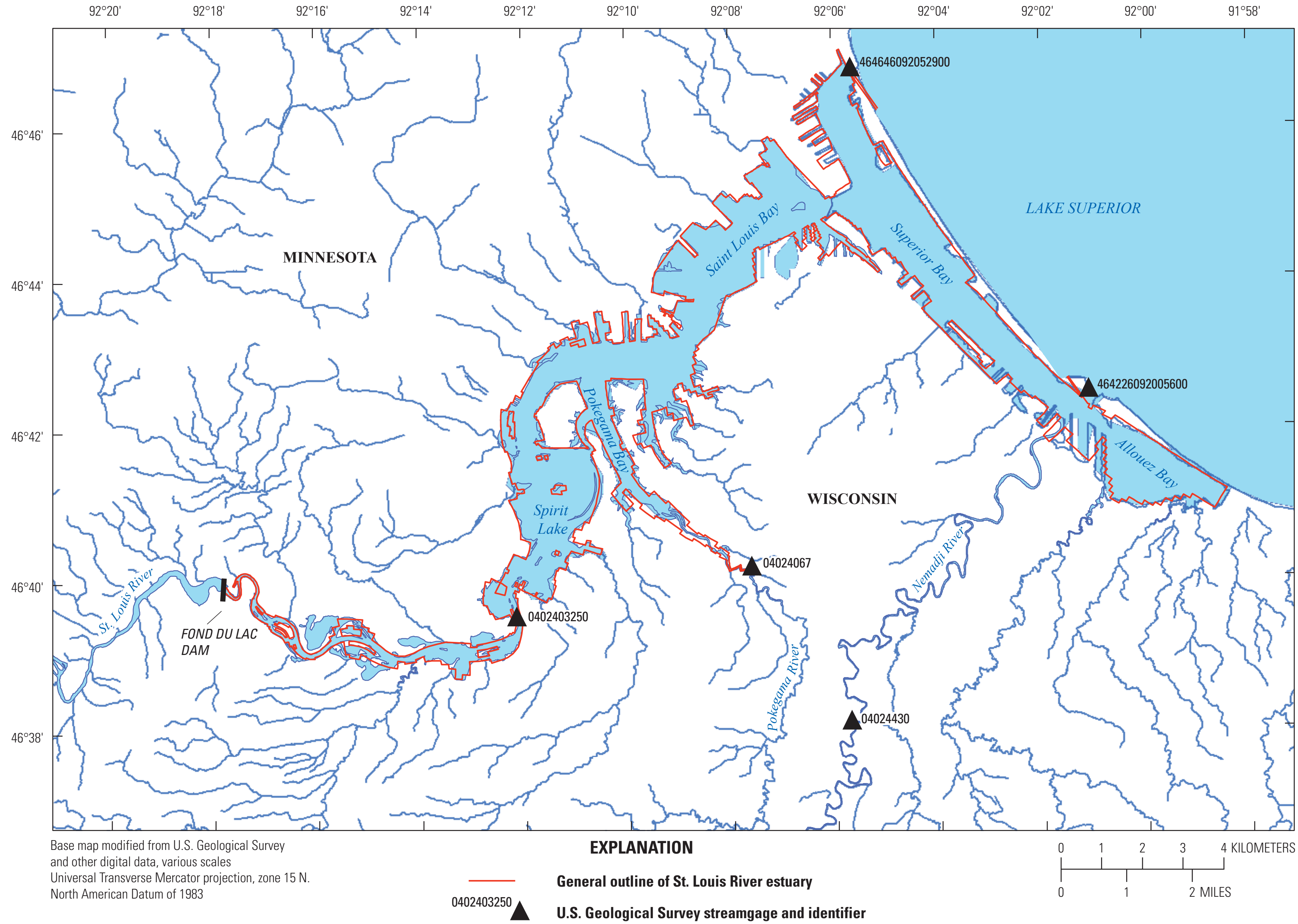

Figure 2. The St. Louis River estuary with bays, tributaries, and continuous measurement locations, Minnesota and Wisconsin.

which is a pre- and postprocessor for EFDC models (Craig, 2017), was selected. EFDC Explorer was used to enter the required input data into the model, control model parameters, manipulate run-time configurations, begin model runs, and complete postrun statistical comparisons. As previously noted, the model was calibrated for the period April–November 2016 and validated using the period April–November 2017. Four primary statistics, including mean error (ME), mean absolute error (MAE), root mean square error (RMSE), and the Nash-Sutcliffe efficiency coefficient (NSEC), were used to evaluate the degree of fit for the EFDC model.

The EFDC model was developed in several phases. First, data were collected and compiled to determine the hydrological and thermal boundary conditions. To prepare for running the model, these multiple datasets had to then be specially formatted for the EFDC model. A summary of the continuous datasets used for this study is shown in table 1. Next, the model grid was augmented, based on a previous EFDC model set-up (Mausolf, 2014). The final phase, which constitutes most of the second half of this report, was the calibration and validation of the model.

Bathymetric Data and Computational Grid

A curvilinear computational grid was developed based on a previous model set-up for the St. Louis River estuary, available from the U.S. Army Corps of Engineers (Mausolf, 2014). The grid was augmented to cover the domain of the new model using CVLGrid, a preprocessing software package for creating and editing EFDC model grids (Craig, 2017). To add areas that were missing from the previous model, information from an available 2014 bathymetric survey was used (EPA, 2014). The missing grid information was assigned using the bathymetry assignment option within EFDC Explorer. Because the previous model set-up and 2014 survey were in the 1985 International Great Lakes Datum, the new grid datum was preserved in the same datum. Areas missing in the original grid included more detailed bathymetry information for the Pokegama River arm of the model domain and the St. Louis River main channel close to the Fond du Lac Dam.

The final model grid consisted of 11,326 grid cells, ranging in depth from less than 0.1 to 29.6 m (fig. 3). The model started at the Fond du Lac Dam and ran out into Lake Superior about 7.5 km. The deepest cells of the model were in the Lake Superior part of the model domain, which was included to give the model enough stability to transition from the relatively shallow depths of the estuary to the deeper depths in the open lake. The average grid size for non-Lake Superior cells was 5,200 square meters (m^2), with an average side length of about 70 m. The deepest grid cells within the St. Louis River estuary were 16.3 m, and the average depth across the estuary part of the model was 4.0 m. Four vertical layers were included with each grid cell, divided equally across the given depth of an individual cell. This approach is the standard approach that has been available for EFDC since the model was created. A newer grid type, known as Sigma Zed layering (Craig, 2017), was attempted but did not improve the model calibration for water-surface elevations or discharge and added an extra 1–2 hours to the model run time.

Model Data and Development

Several continuous discharge stations were used to calculate the initial and boundary conditions for the St. Louis River estuary model and to provide a calibration dataset. Data characterizing the hydrologic conditions and contributing areas, including water-surface elevations, flow velocities, and water temperatures, were compiled for this effort. Other compiled data included discharge from a subset of gaged inflow locations.

Discharge and Flow Velocity

The primary inflow to the estuary, provided as hourly data from the dam operator Minnesota Power and available as part of the ScienceBase model archive (Smith, 2020), was from Fond du Lac Dam. The Fond du Lac Dam is the upstream boundary condition for the EFDC model. Streamflow also was continuously measured for two major tributaries to the St. Louis River estuary (table 2): the Pokegama River at Logan Avenue at South Superior, Wisc. (USGS station 04024067), and the Nemadji River near South Superior, Wisc. (USGS station 04024430). Both sites were measured by the USGS. The finalized continuous streamflow record for the Nemadji River is available from the USGS National Water Information System database (USGS, 2020), and the Pokegama River is part of the model archive (Smith, 2020).

Additionally, the USGS collected continuous discharge for three gages established for this study: St. Louis River at Oliver, Wisc. (USGS station 0402403250; hereafter referred to as the “Oliver gage”); Superior Bay Entry Channel at Superior, Wisc. (USGS station 464226092005600; hereafter referred to as the “Superior entry”); and Superior Bay Duluth Ship Canal at Duluth, Minn. (USGS station 464646092052900; hereafter referred to as the “Duluth entry”). These locations were used for calibration and validation data. All three stations were satellite telemetered and transmitted data at subhourly resolution throughout 2016–17. For these three locations, the USGS deployed SonTek SideLookers (SonTek-SL) to measure water velocity and water-surface elevation (SonTek, 2019). The Oliver gage was bridge mounted, whereas the entry locations were mounted to the seawalls going into Lake Superior. The velocity was recorded in discrete bins that spanned the subsection, and then a data logger averaged those measurements from those discrete bins to calculate an average velocity every 5 minutes (Levesque and Oberg, 2012).

As part of the continuous streamflow record development, instantaneous discharge and stage measurements were periodically completed at all USGS gage locations to verify and modify the stage-discharge relation (Rantz and others, 1982a, b; Mueller and others, 2008). In addition to USGS

Table 1. Continuous measurements used in the St. Louis River estuary model development or evaluation of the model performance (calibration/validation). Continuous data types included discharge, water-surface elevation, flow velocity, and water temperature. Water temperature was not available for all inflows used for model development, so substitution was used as shown in the water temperature assignment column. Further information about the discharge (flow series) is shown in table 2.

[USGS, U.S. Geological Survey; MN DNR, Minnesota Department of Natural Resources; --, no station number or no data; X, data measured; nr, near; mi, mile; us, upstream; Ave, Avenue; WLSSD, Western Lake Superior Sanitary District; S, South; W, West; R, River; Wisc., Wisconsin; Minn., Minnesota]

USGS station number	MN DNR (or alternative) station number	Full station name	Short name	Model development	Model performance	Discharge	Water-surface elevation	Velocity	Water temperature	Water temperature assignment
--	--	Fond du Lac Station	Fond du Lac Dam	X	--	X	--	--	--	--
--	03010003	Mission Creek nr Fond du Lac, 1 mi us of MN23	Mission Creek	X	--	X	--	--	--	--
--	03163011	Merritt Creek at Duluth, Grand Ave	Merritt Creek	X	--	X	--	--	--	--
--	--	Western Lake Superior Sanitary District	WLSSD	X	--	X	--	--	X	WLSSD.
--	03163012	Miller Creek at Duluth, S 24th Ave W	Miller Creek	X	--	X	--	--	X	Kingsbury Creek; Keene Creek; Merritt Creek; Superior City ungaged-Miller/Mission Creek; Miller Creek.
[1]04024067	--	Pokegama R at Logan Ave. at S. Superior, Wisc.	Pokegama River	X	--	X	--	--	X	Red River; Little Pokegama; Pokegama River; Superior City ungaged-Pokegama; Nemadji River.
[1]04024430	--	Nemadji River near South Superior, Wisc.	Nemadji River	X	--	X	--	--	--	--
--	--	[2]Lake Superior ADCIRC	Lake Superior ADCIRC	X	--	--	X	--	--	--
--	[3]45028	Station 45028—Western Lake Superior	Lake Superior	X	--	--	X	--	X	Lake Superior ADCIRC.
--	[4]S004–364	Tischer Creek at Wallace Ave "Mt. Royal," Duluth	Tischer Creek	X	--	--	--	--	X	Mission Creek; Sargent Creek; U.S. Steel Creek; Stewart Creek.
[1]0402403250	--	St. Louis River at Oliver, Wisc.	Oliver gage	X	X	X	X	X	X	Fond du Lac Dam.
[1]464646092052900	--	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	--	X	X	X	X	X	--
[1]464226092005600	--	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	--	X	X	X	X	--	--

[1]USGS National Water Information System database (USGS, 2020).

[2]Nearshore Lake Superior water-surface elevations were provided from the Lake Superior ADCIRC model (Hayter and others, 2015).

[3]National Data Buoy Center station identification, available at https://www.ndbc.noaa.gov/station_page.php?station=45028.

[4]Minnesota Pollution Control Agency station identification.

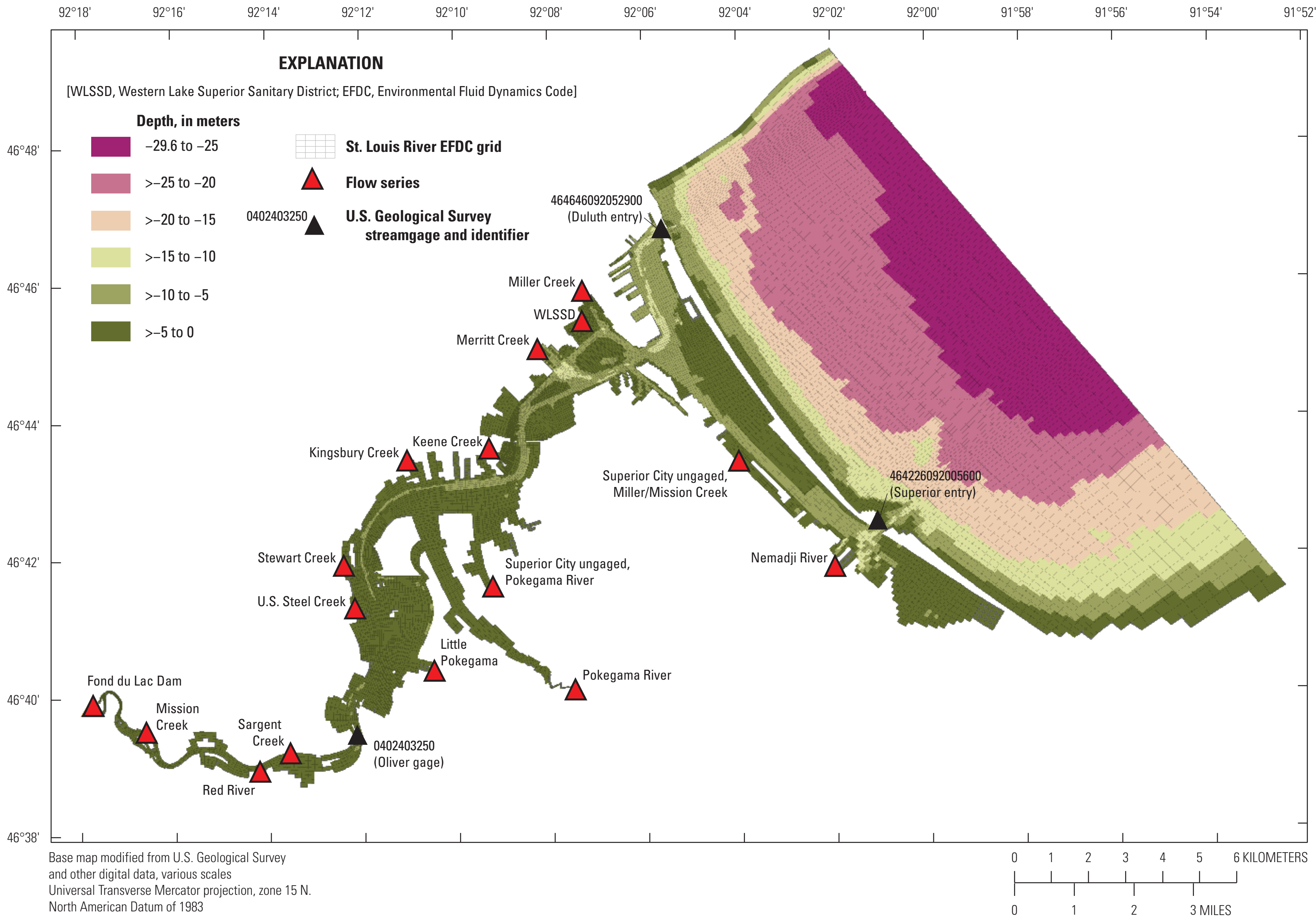

Figure 3. St. Louis River estuary Environmental Fluid Dynamics Code model domain, starting at the Fond du Lac Dam and extending into Lake Superior about 7.5 kilometers.

Table 2. Model input flow series for the St. Louis River estuary model, 2016–17, including the gaged drainage basin area, associated ungaged drainage basin area, and the applied scalar factor (*K*) between gaged and ungaged drainage basin area. For drainage basins either without a streamgage or missing streamgage record, the closest appropriate gaged record was applied, with a separate scaling factor: Mission Creek scalar (K_{miss}), Miller Creek scalar (K_{mil}), or Pokegama River scalar (K_{pok}).

[USGS, U.S. Geological Survey; MN DNR, Minnesota Department of Natural Resources; --, no station number or no data; nr, near; mi, mile; us, upstream; Ave, Avenue; S, South; W, West; WLSSD, Western Lake Superior Sanitary District; R, River; Wisc., Wisconsin]

USGS station number	MN DNR station number[1]	Full station name	Flow time series (short name)	Gaged drainage basin area	Ungaged drainage basin area	Scalar factor (*K*)	Mission Creek scalar (K_{miss})	Miller Creek scalar (K_{mil})	Pokegama River scalar (K_{pok})
				(square kilometers)					
				Minnesota					
--	--	Fond du Lac Station	Fond du Lac Dam	--	--	--	--	--	--
--	03010003	Mission Creek nr Fond du Lac, 1 mi us of MN23	Mission Creek	28.33	2.482	1.088	--	--	--
--	--	--	Sargent Creek	--	10.558	--	0.373	--	--
--	--	--	U.S. Steel Creek	--	14.420	--	0.509	--	--
--	--	--	Stewart Creek	--	4.871	--	0.172	--	--
--	--	--	Kingsbury Creek	--	40.035	--	1.413	1.550	--
--	--	--	Keene Creek	--	12.846	--	0.453	0.497	--
--	03163011	Merritt Creek at Duluth, Grand Ave	Merritt Creek	5.646	7.132	2.263	0.451	--	--
--	03163012	Miller Creek at Duluth, S 24th Ave W	Miller Creek	25.825	15.525	1.601	1.459	--	--
--	--	Western Lake Superior Sanitary District	WLSSD	--	--	--	--	--	--
				Wisconsin					
--	--	--	Red River	--	42.923	--	--	--	0.520
--	--	--	Little Pokegama	--	29.131	--	--	--	0.353
04024067	--	Pokegama R at Logan Ave. at S. Superior, Wisc.	Pokegama River	82.530	--	--	--	--	--
--	--	--	Superior City ungaged, Pokegama River	--	13.422	--	--	--	0.163
--	--	--	Superior City ungaged, Miller/Mission Creek	--	38.316	--	1.352	1.484	--
04024430	--	Nemadji River near South Superior, Wisc.	Nemadji River	1,094.128	42.192	1.039	--	--	--

[1]For MN DNR sites, the full record can be accessed by looking up the site number at https://www.dnr.state.mn.us/waters/csg/index.html.

gages, additional streamflow data were available from three MN DNR gages (table 2): Mission Creek near Fond du Lac (MN DNR station 03010003; MN DNR, 2019a); Merritt Creek at Duluth, Grand Avenue (MN DNR station 03163011; MN DNR, 2019b); and Miller Creek at Duluth, South 24th Avenue West (MN DNR station 03001012; MN DNR, 2019c). The MN DNR followed standard gaging procedures similar to the USGS for establishing the continuous discharge and water-surface elevation records (MN DNR, 2019d).

Several tributary records were not available for the modeling period, particularly the Duluth-area tributaries, so a substitution method had to be used. To calculate how to assign discharge for these tributaries, drainage basin areas were delineated in ArcGIS 10.5 (Esri, 2019) using watershed boundary datasets available from the USGS (USGS, 2013) and watershed polygon grids available online (Lake Superior Streams, 2019) for all the tributaries to the St. Louis River estuary. For tributaries (flow series) without available discharge, an area-ratio method similar to methods described by Chow and others (1988) and applied by Rendon and Lee (2015) for another EFDC model was used. The ratio between the ungaged tributary drainage basin area and the closest appropriate gaged tributary drainage basin area was calculated using equation 1:

$$R_{utw} = \frac{A_{utw}}{A_{gtw}} \tag{1}$$

where

R_{utw} is the ratio of the ungaged tributary drainage basin area (flow series) to the gaged tributary drainage basin area for a given drainage basin (unitless),

A_{utw} is the ungaged tributary drainage basin area in square kilometers,

A_{gtw} is the closest appropriate gaged tributary drainage basin area in square kilometers.

All records with the Miller Creek scalar for 2016 used the Mission Creek scalar for 2017 because the Miller Creek record was unavailable. Also, three of the Wisconsin tributaries applied the Pokegama River relation because these drainage basins were closer in slope and land-use characteristics.

There were several other Duluth-area tributaries not included in the model domain. Instead, these ungaged areas were allocated to one of the inflow series in table 2, accounting for the remainder of the ungaged area around the St. Louis River estuary. The same equation also was applied to the ungaged area for gaged drainage basins, except the ratio was the ungaged tributary area (in square kilometers) to the gaged tributary drainage basin area (in square kilometers) for the same drainage basin.

The ratio calculated using equation 1 was used to create a scalar factor to apply to the available streamflow data. The scalar factor (K) is computed using equation 2:

$$K=(1+R_{utw}) \tag{2}$$

The scalar factors and the substituted gage records for all the tributaries (flow series) with substitutions are included in table 2, in addition to calculated gaged and ungaged drainage basin areas. The scalar factors used for this substitution included Mission Creek (K_{miss}), Miller Creek (K_{mil}), and the Pokegama River (K_{pok}).

For the EFDC model, the major flow series included the following (table 2) datasets, all available as part of the model archive (Smith, 2020): Fond du Lac Dam into the main St. Louis River channel, Pokegama River, and Nemadji River. The following minor Minnesota tributaries were included as additional flow series: Mission Creek, Sargent Creek, U.S. Steel Creek, Stewart Creek, Kingsbury Creek, Keene Creek, Merritt Creek, and Miller Creek (table 1; not shown). For the Wisconsin side, the following minor tributaries were included: Red River and the Little Pokegama. In addition to these tributaries, areas of Superior, Wisc., were included as an approximation of runoff areas into the estuary (table 2): Superior City ungaged, Pokegama River, and Superior City ungaged, Miller/Mission Creek. A final discharge dataset for the effluent flow from the Western Lake Superior Sanitary District (fig. 3; table 1) was included.

Water Balance

As mentioned in the previous section, dozens of minor tributaries flow directly into the estuary in addition to the larger tributaries, the Pokegama and Nemadji Rivers (figs. 1–3; tables 1–2). The estuary water balance is controlled by a spring snowmelt in late March or early April, followed by periodic, large rainstorms in the summer. Primary inflow is from upstream at the Fond du Lac Dam. A water balance for the 2016 water year (from October 1, 2015, to September 30, 2016) for the estuary indicated 83 percent of water originated upstream from the Oliver gage, 12 percent upstream from the Nemadji River gage, and 5 percent from all other tributary sources (fig. 4). To close the water balance, all other tributary sources (fig. 4) were set to 41 percent of the Nemadji River gage daily discharge. As mentioned in the previous section, outflow for the water balance occurred through two exit points into Lake Superior: the Superior entry and the Duluth entry. Between the two entries, about 70 percent of the water leaves the estuary through the Superior entry and about 30 percent leaves through the Duluth entry, based on the 2015–16 analysis (fig. 4).

Water-Surface Elevations

Water-surface elevations were collected for three locations as calibration datasets for the St. Louis River estuary model. The three locations included the Oliver gage, the Superior entry, and the Duluth entry (table 1), all included as part of the model archive (Smith, 2020). The datum for all three stations, for the purposes of this report, was the 1985 International Great Lakes Datum. In addition to the three stations, continuous, water-surface elevations were simulated in

2016 and 2017 for the Lake Superior nearshore to define the north open boundary of the EFDC model. The Lake Superior water-surface elevations were provided from an available Advanced Circulation (ADCIRC) model (Hayter and others, 2015). The EFDC model simulated the flow in and out of the St. Louis River estuary, through the two entry channels, by equilibrating to the simulated water-surface elevations as defined by the ADCIRC model along the north open boundary. With a north open boundary, water can flow both in and out of the model domain.

Thermal Boundary Conditions

Water temperature for the St. Louis River estuary had a predictable seasonal pattern, with frozen conditions from mid-November through March. Weather patterns were superimposed on the annual climate cycle, affecting water temperature on shorter timescales of several days to weeks. The diurnal cycle imposed daily variations in water temperature, producing variations of a few degrees Celsius, with the largest variations occurring in the summer when solar energy fluxes were strongest.

Each tributary or inflow (table 2) required a temperature assignment in the EFDC model. Because each tributary or inflow did not have a continuous temperature record available, a substitution from another location was required based on the closest or most appropriate available record (table 1). The following continuous water temperature records were available and included in the model archive (Smith, 2020), either for the open-water period (April–November) or the year: the Oliver gage, Pokegama River at Logan Avenue at South Superior, Wisc. (USGS station 04024067; hereafter referred to as the “Pokegama River” gage); Tischer Creek at Wallace Avenue, Duluth, Minn. (MPCA station S004–364); Miller Creek at Duluth, S. 24th Ave W (MN DNR station 03001012), Western Lake Superior (National Data Buoy Center [NDBC] Station 45028) (NDBC, 2019), and the Western Lake Superior Sanitary District effluent outflow. The assignment of each temperature record is shown in table 1; all temperature records are available as part of the model archive (Smith, 2020).

At the two USGS gages used for temperature input (the Oliver gage and the Pokegama River site), and a third location used for model calibration (Duluth entry), water temperature

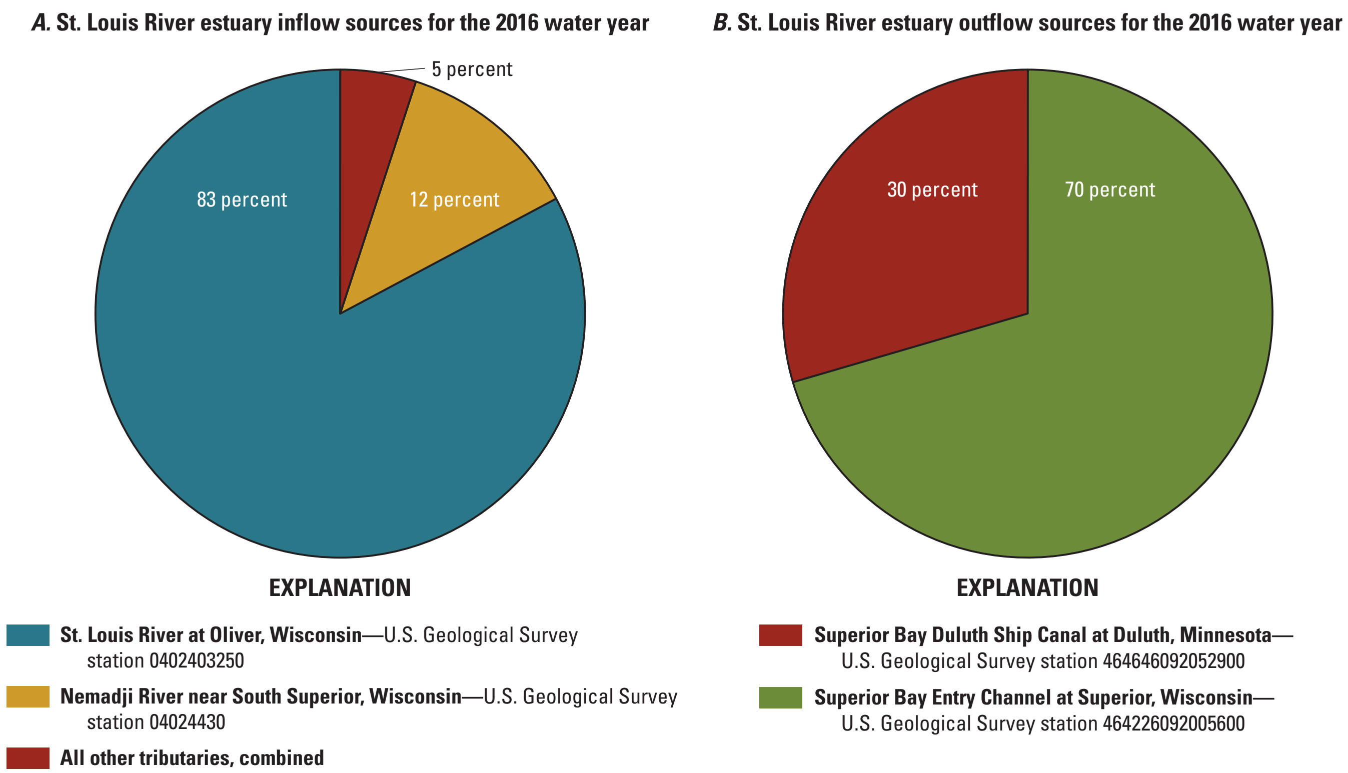

Figure 4. St. Louis River estuary water balance for the 2016 water year (October 1, 2015, to September 30, 2016). *A*, inflow sources; *B*, outflow sources. Water balance based on daily mean discharge, in cubic feet per second. For the outflow sources, the category “all other tributaries, combined” was a percentage of the daily mean Nemadji River at South Superior, Wisconsin (U.S. Geological Survey station 04024430), discharge.

was sampled from the SonTek-SL. For the SonTek-SL, the temperature resolution was plus or minus 0.01 degree Celsius (°C) and the temperature accuracy was plus or minus 0.2 °C. All USGS temperature data were processed as outlined in Wagner and others (2006). For the data provided by either MPCA or MN DNR, a water temperature was collected using a multiparameter sonde with regular maintenance, including cleaning and calibrating; however, no information about the sonde model or the depth of the measurements was available. Water temperature at the Western Lake Superior location, a buoy owned and operated by the University of Minnesota-Duluth, was measured 1 m below the water line. Finally, the Western Lake Superior Sanitary District temperature was measured at the same location as the treatment plant effluent flow measurement.

Meteorological Data

Meteorological data are required as input to the EFDC model because of the importance of surface boundary conditions to the overall behavior of the model, specifically surface heat exchange, solar radiation absorption, wind stress, and gas exchange. Required meteorological data include air temperature, atmospheric pressure, relative humidity, total precipitation, wind speed, wind direction, and cloud cover. All unit conversions from the meteorological data to the required units for the model were straightforward with the exception of cloud cover. The qualitative sky cover parameter (that is, clear, scattered, broken, and overcast) was converted to a value ranging from 0 to 1: clear was 0, scattered (1/8 to 1/2 cloud coverage) was 0.3125, broken (5/8 to 7/8 cloud coverage) was 0.75, and overcast was 1, with mixed sky cover conditions (for example, scattered and broken) averaged together.

All required data were available at least at hourly intervals for two locations: Richard I. Bong Airport (U.S. Air Force [USAF] station identification number [ID] 726427; not shown), in Superior, Wisc., within the model domain, and the Cloquet Carlton County Airport (USAF ID 726558; not shown), located closer to the Fond du Lac Dam (fig. 2). A third location, Sky Harbor International Airport (USAF ID 727456; not shown) in Duluth, Minn., was included only for wind speed and wind direction. All datasets were downloaded from the Climate Data Online portal (National Climatic Data Center, 2018). Based on the latitude and longitude of the estuary and the required meteorological inputs, evapotranspiration was included in the water balance as an internal EFDC calculation. Because multiple locations were used for the wind and meteorological series in the model, EFDC Explorer automatically calculated a weighting map for each series based on distance away from the station to every part of the model domain.

Model Parameterization

Most parameters that control the EFDC model were left as the default, as provided within the EFDC Explorer framework (Craig, 2017); however, certain parameters were varied to get an improved calibration fit (table 3), with emphasis on parameters that control the grid type, model run timing settings, hydrodynamics, and heat exchange. Many of these parameters were the same or similar to another published EFDC model, the Lake Houston EFDC model (Rendon and Lee, 2015). During the calibration process, all parameters were varied by trial and error through a series of calibration model runs to improve the overall fit of the model. Each calibration run had controlled variations in parameter settings across the ranges in table 3, with typically only one parameter changed for each calibration run to characterize the effect on the calibration metrics for water-surface elevations, discharge, and temperature. Major parameters important for calibration, including the parameter description, final parameter value, and the variation range, are shown in table 3. A truncated description of what each of these parameters control also is provided in table 3; for full parameter descriptions, consult the EFDC Explorer manual (Craig, 2017) or the original EFDC documentation (Hamrick, 1992, 2007).

A full sensitivity analysis was not completed for this study, although variation of these parameters did confirm the parameter sensitivity. Each parameter in table 3 was rated as either sensitive, neutral, insensitive, or important for model run stabilization. For a particular parameter to be considered sensitive, at least one of the calibration metrics needed to have a substantial change. Although this method was qualitative, the general practice for a parameter to be deemed sensitive was a change of at least 2 percent for the NSEC, discussed in the next section. For the model run stabilization criteria, these parameters did not necessarily change the evaluation criteria, but either made the run time more efficient or prevented the model from crashing. Although all the evaporation options available within EFDC Explorer were attempted, the EFDC original (default option) had the best calibration fit. Also, the minimum fraction of solar radiation in the top layer (FSWRATF) and the background light extinction (WQKEB) were highly sensitive, although the final values were close to the EFDC Explorer default. Alternatively, the parameters in table 3 that control hydrodynamics, including AVO, ABO, AVMX, and ABMX, were all neutral to insensitive in their effects on any of the primary calibration targets: water-surface elevation, discharge, water temperature, and flow velocity.

The selected grid type was the standard sigma vertical grid. Although the new grid type available with EFDC Explorer, sigma-zed layering, was attempted, it caused the water-surface elevation and discharge to drift far away from

Table 3. Major parameters important for calibration in the St. Louis River estuary model, including the parameter description, final parameter value, and the variation range. Each parameter was either sensitive, neutral, insensitive, or instead was important for model run stabilization.

[--, no data or not applicable; m^2/s, square meter per second; EFDC, Environmental Fluid Dynamics Code; m^{-1}, per meter]

Parameter	Description	Final parameter value	Variation range	Variation comment
IGRIDV	Selection of grid type: standard sigma versus sigma-zed layering	Standard sigma vertical grid	Attempted both grid types	Sensitive.
DTSSFAC	Dynamic time stepping (in seconds)	0.2	0.2 to 0.4	Model run stabilization.
DTSSDHDT	Dynamic time stepping rate of depth change (change in height to change in time)	0.3	0.1 to 0.5	Model run stabilization.
NUPSTEP	Minimum number of iterations for each time step	2	2 to 4	Model run stabilization.
DTMAX	Maximum time step for dynamic stepping (in seconds)	100	25 to 125	Model run stabilization.
HDRY	Depth at which cell or flow face become dry	0.1	--	Insensitive.
HWET	Depth at which withdrawals from cell are turned off	0.15	0.1 to 0.2	Insensitive.
AVO	Background, constant or eddy (kinematic) viscosity (m^2/s)	1.0×10^{-6}	1.0×10^{-5} to 1.0×10^{-7}	Neutral to insensitive.
ABO	Background, constant or molecular diffusivity (m^2/s)	1.0×10^{-6}	1.0×10^{-5} to 1.0×10^{-9}	Insensitive.
AVMX	Maximum kinematic eddy viscosity (m^2/s)	1.1×10^{-5}	1.0×10^{-5} to 1.0×10^{-6}	Neutral to insensitive.
ABMX	Maximum eddy diffusivity (m^2/s)	1.0×10^{-6}	1.0×10^{-5} to 1.0×10^{-7}	Neutral to insensitive.
Z0	Bottom roughness	0.1 to 4.0×10^{-3}	0.1 to 5.0×10^{-5}	Sensitive.
IEVAP	Evaporation option for water flux (heat exchange)	2 (EFDC original)	Attempted all combinations of heat exchange available (11 options)	Sensitive.
FSWRATF	Minimum fraction of solar radiation adsorbed in the top layer	0.3	0.25 to 0.6	Sensitive.
WQKEB	Background light extinction (m^{-1})	1.6	1.2 to 2.5	Sensitive.

the calibration targets. The other four parameters in table 3 that were altered, DTSSFAC, DTSSDHDT, NUPSTEP, and DTMAX, dealt with model run timing and controlled the model run stability.

Finally, the final bottom roughness values for the grid were varied from 0.1 to 0.004, depending on location. Close to the Fond du Lac Dam, the bottom roughness was set to 0.1 and most of the rest of the model was set to 0.004. Bottom roughness values help control the channel friction applied to the flow. The only other variation for bottom roughness was around the Duluth entry into Lake Superior, set to 0.05. Earlier attempts brought the bottom roughness values across the grid as low as 5×10^{-5}.

Model Calibration and Results

The St. Louis River estuary EFDC model was calibrated for 2016 and validated for 2017. Specifically, the model parameters were varied to find the best fit for 2016, with the model only run once for 2017 as a validation check. Model results at three locations in the model grid were compared to measured data collected from the three gages (figs. 2 and 3). The four types of data used to verify model performance were discharge, water-surface elevations, water temperature, and flow velocities. Except for water temperature, which did not have a continuous record available for the Superior entry, subhourly comparisons were done for all four records at all three locations. For all the Oliver gage records, the continuous data collection was discontinued on October 24, 2017, so the Oliver comparisons stopped earlier for the 2017 validation. Additionally, a sum of total discharge from both entries was used to better understand the full water balance from the estuary. The general magnitude and seasonal patterns between simulated output and measured data should correspond, although an exact match was not expected. Measurements were made at a point, or at least averaged across a discrete bin in the case of velocities, whereas the model output represents simulated conditions across cells that were often greater than 20 m per side, or 400 m^2.

Four statistics were used to evaluate model performance: ME, MAE, RMSE, and the NSEC (Nash and Sutcliffe, 1970). The ME is the mean difference between the simulated (model) value and the measured values, whereas the MAE, computed by equation 3 (for example, see usage in Smith and others, 2018), is the absolute mean difference between the simulated (model) value and the measured values:

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |simulated\ value - measured\ value| \quad (3)$$

where

n is the number of observations.

The ME is a goodness-of-fit statistic to help identify possible bias in the simulated values (Wilks, 1995). A positive ME indicates that the model is simulating values that are on average higher than the measured values, whereas a negative ME indicates the simulation values are biased low. The MAE averages the absolute differences between simulated and measured values where all individual differences have equal weight, with lower values being superior.

The RMSE, as computed by equation 4, is a relative term that gives a measure of the variability between the simulated and measured value:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (simulated\ value - measured\ value)^2} \quad (4)$$

The RMSE has the same units of measure as the quantity being simulated, so it represents the error associated with individual simulated values (Hyndman and Koehler, 2006) and the RMSE can range from 0 to infinity.

The last goodness-of-fit statistic, the NSEC, has been classically used to evaluate hydrological model performance (Legates and McCabe, 1999). The NSEC ranges from minus infinity to positive 1.0: any value greater than 0 indicates that the model is a better predictor of the measured data than the mean of the measured data, with 1.0 indicating a perfect match. NSEC values less than 0.0 indicate the model is worse than the mean of the measured data. For the exact NSEC formula, also termed the coefficient of efficiency, consult Nash and Sutcliffe (1970) or Legates and McCabe (1999).

Water-Surface Elevations

The St. Louis River estuary water-surface elevations varied within a narrow range in 2016–17 (figs. 5 and 6), less than about 1 m (3.3 ft), for all three locations used as calibration datasets: the Oliver gage, Superior entry, and Duluth entry. Furthermore, the relative difference among the locations was relatively flat, given the low gradient of the estuary and the lack of any extreme events. In contrast, the extreme flow during the June 2012 Duluth flood event (Czuba and others, 2012) caused water levels to rise several meters in sections of the river close to the Fond du Lac Dam.

The water-surface elevations of the St. Louis River estuary were calibrated for April 1–November 16, 2016, and validated April 1–November 16, 2017, by comparing measured water-surface elevations at three locations: the Oliver gage, the Duluth entry, and the Superior entry. The model was able to simulate the water-surface elevations with generally good agreement between the simulated and measured values for both years (figs. 5 and 6), although the degree of fit varied with the time resolution. At the daily time step in 2016, the model was able to demonstrate excellent agreement with the measured data with NSEC values at the Oliver gage, Superior entry, and Duluth entry of 0.81, 0.91, and 0.89, respectively

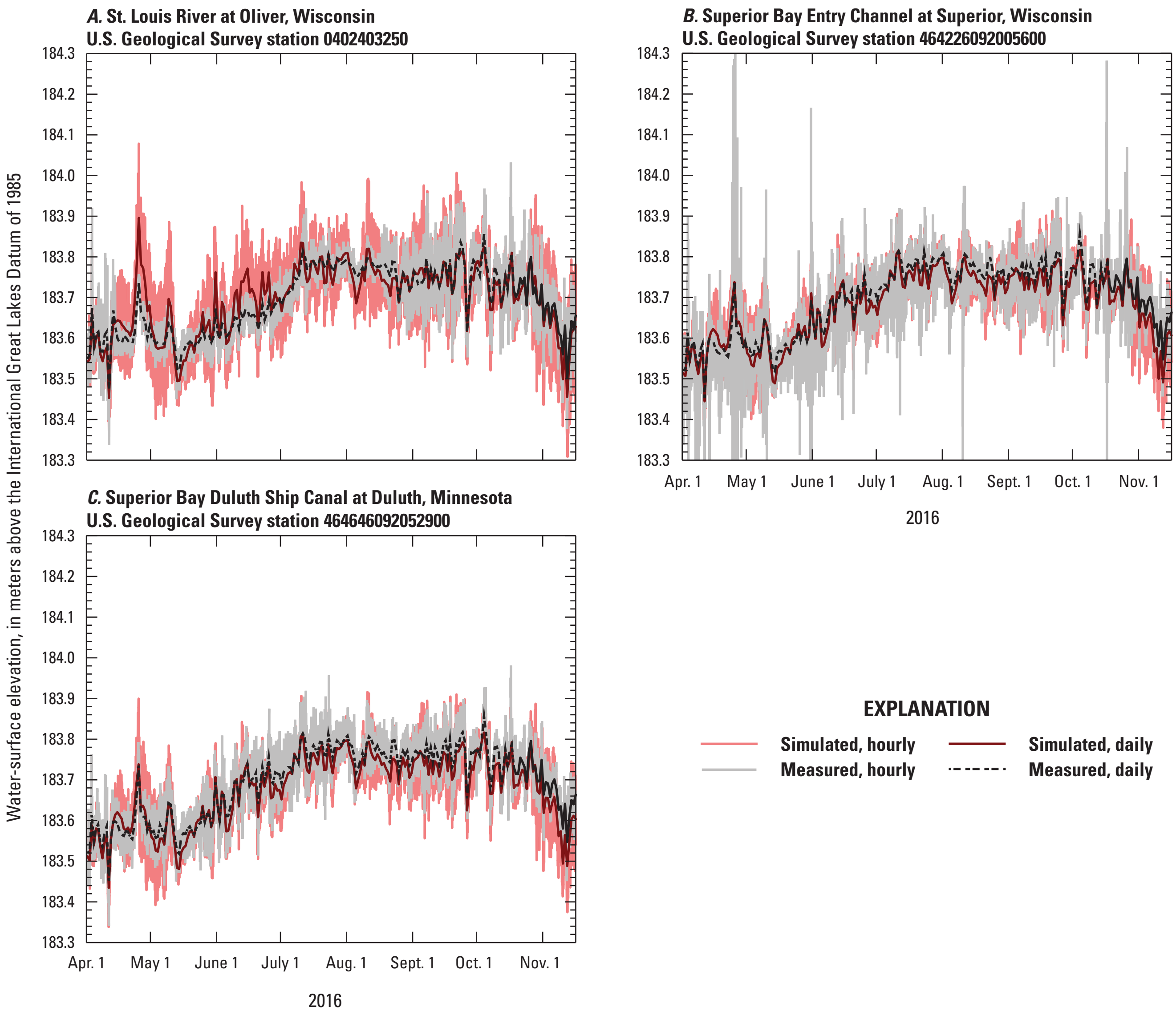

Figure 5. Hourly and daily mean water-surface elevation for St. Louis River estuary locations, Minnesota-Wisconsin, 2016. Measured and modeled data are plotted at the same locations. *A*, St. Louis River at Oliver, Wisconsin (U.S. Geological Survey [USGS] station 0402403250); *B*, Superior Bay Entry Channel at Superior, Wisconsin (USGS station 464226092005600); *C*, Superior Bay Duluth Ship Canal at Duluth, Minnesota (USGS station 464646092052900).

(table 4). At the hourly time scale in 2016, the model did an adequate job for both entries but performed poorly for the Oliver gage. The hourly NSEC values at the Oliver gage, Superior entry, and Duluth entry were 0.21, 0.40, and 0.52, respectively. For all three locations, the hourly MAE and RMSE varied less than 0.1 m, with the daily values at or below 0.04 m. The ME for all three locations was at or below 0.02 m, with only a small negative bias for the Duluth gage.

For 2017, the NSEC values were even better, with daily values for the Oliver gage, Superior entry, and Duluth entry of 0.92, 0.91, and 0.93, respectively. The hourly NSEC values also were improved over the 2016 values. NSEC values that are comparable or improved for a validation period versus a calibration period are generally considered a positive indication for a model calibration, given that no changes to the model framework were made for the validation period. For the MAE and RMSE, the calibration and validations periods were at or less than 0.08 m for the hourly evaluation criteria. For the same two statistics, the daily values were from 0.02 to 0.04 m for both years.

The general amplitude of water-surface elevations during an individual day was captured with the model, although the simulated results were generally out of sync from the measured data by at least a couple of hours (fig. 7). As shown in

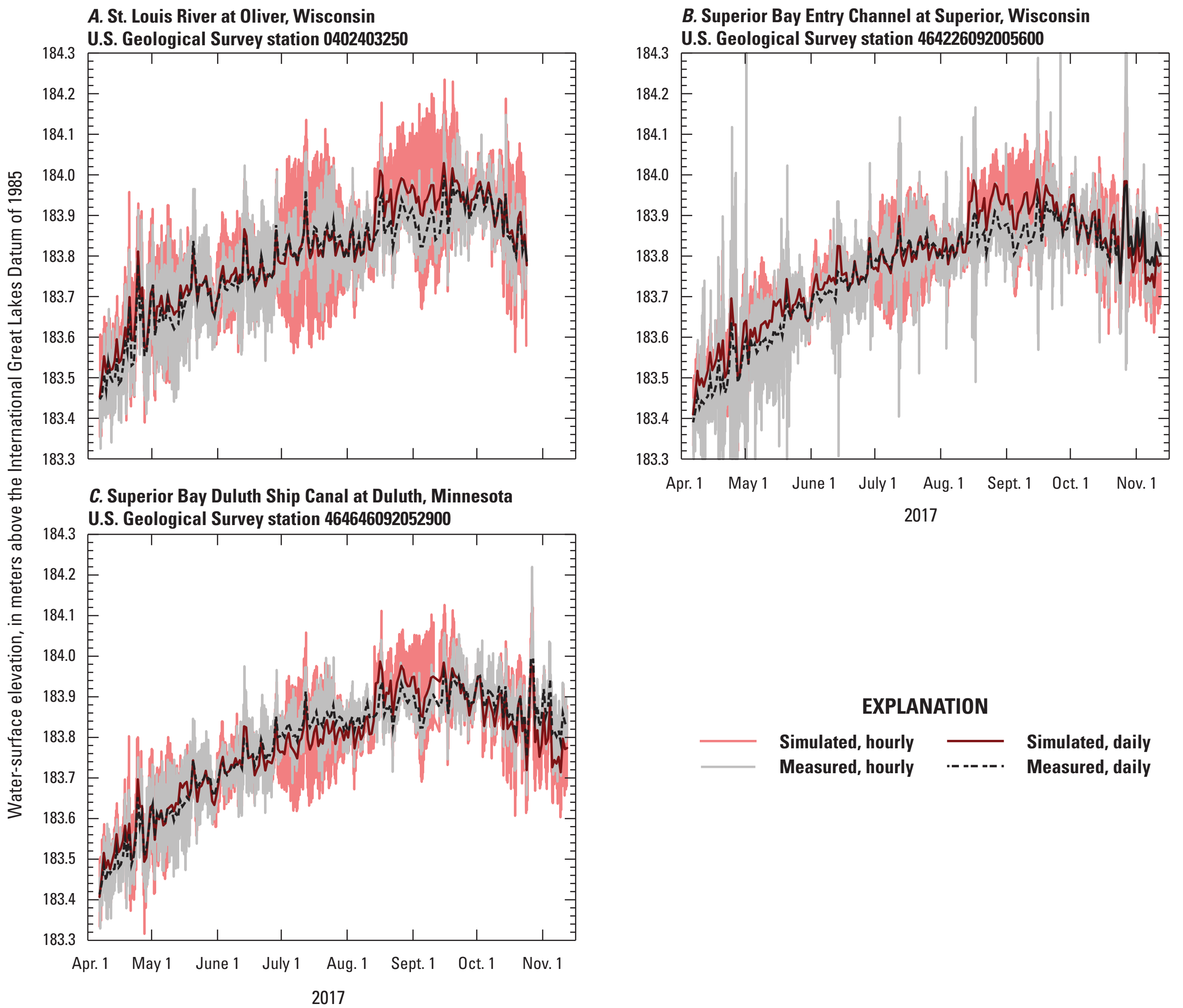

Figure 6. Hourly and daily mean water-surface elevation for St. Louis River estuary locations, Minnesota-Wisconsin, 2017. Measured and modeled data are plotted at the same locations. *A*, St. Louis River at Oliver, Wisconsin (U.S. Geological Survey [USGS] station 0402403250); *B*, Superior Bay Entry Channel at Superior, Wisconsin (USGS station 464226092005600); *C*, Superior Bay Duluth Ship Canal at Duluth, Minnesota (USGS station 464646092052900).

the Duluth entry example from July 2016, the daily amplitude during this period fluctuated from 0.1 to 0.2 m per day. This could be due, in part, to several factors including the varying resolution of inflow discharges, the usage of simulated Lake Superior water-surface elevations to calibrate the model, or the discrepancy between simulated flow and actual discharges. However, the most likely cause was the Lake Superior seiche cycle, a well-documented event triggered by the tidal cycle in the Great Lakes (Sorensen and others, 2004; Trebitz, 2006).

Discharge

Like the water-surface elevations, the discharge across the model domain was calibrated for April 1–November 16, 2016, and validated April 6–November 12, 2017, by comparing measured discharge at three locations (table 5): the Oliver gage, Superior entry, and Duluth entry. A fourth comparison was the combined flow from the Duluth entry and the Superior entry (table 5). The measurement and simulation ranges for discharge, in cubic meters per second, are

Table 4. Performance evaluation statistics for water-surface elevations of the St. Louis River estuary model, 2016–17, including mean error, mean absolute error, root mean square error, and Nash-Sutcliffe efficiency coefficient.

[USGS, U.S. Geological Survey; ME, mean error; MAE, mean absolute error; RMSE, root mean square error; NSEC, Nash-Sutcliffe efficiency coefficient; Wisc., Wisconsin; Minn., Minnesota]

USGS station number	USGS station name	Short name	Hourly evaluation criteria				Daily evaluation criteria			
			ME	MAE	RMSE	NSEC	ME	MAE	RMSE	NSEC
			(meters)			(dimensionless)	(meters)			(dimensionless)
2016										
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	0.00	0.06	0.08	0.21	0.00	0.03	0.04	0.81
464226092005600	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	0.01	0.06	0.09	0.40	−0.02	0.02	0.03	0.91
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	−0.02	0.05	0.07	0.52	−0.02	0.02	0.03	0.89
2017										
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	0.02	0.08	0.10	0.42	0.02	0.03	0.03	0.92
464226092005600	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	0.02	0.07	0.10	0.56	0.02	0.03	0.04	0.91
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	−0.01	0.06	0.08	0.70	−0.01	0.03	0.03	0.93

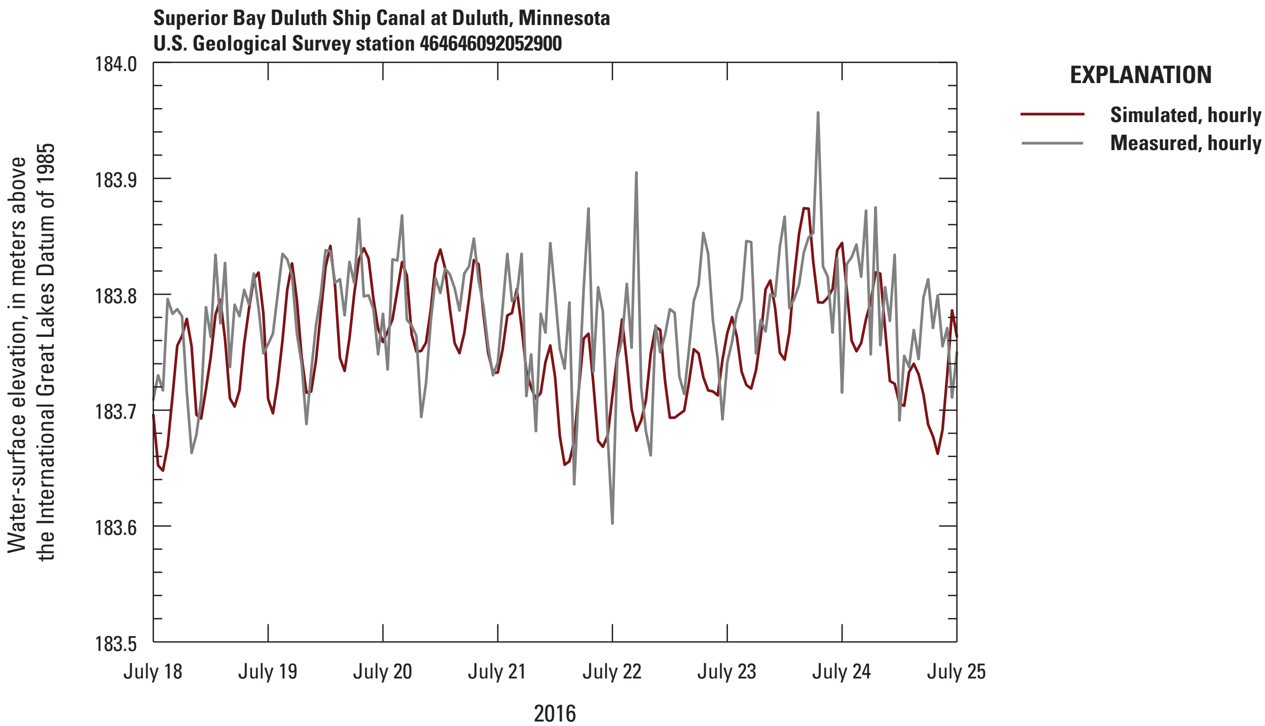

Figure 7. Hourly water-surface elevation for the Superior Bay Duluth Ship Canal at Duluth, Minnesota (U.S. Geological Survey station 464646092052900), for July 18–25, 2016, demonstrating the subdaily water-level fluctuation cycle.

summarized in table 5 for the three locations plus the combined entries, including the minimum, the maximum, and the average.

St. Louis River estuary discharge was largely controlled by dam outflow from the Fond du Lac Dam. Based on the water balance (fig. 4), about 83 percent of water flow was upstream from the Oliver gage for water year 2016 (October 1, 2015, to September 30, 2016), of which most of the water was from the Fond du Lac Dam. Based on the overall measurement average for 2016–17, about 74 and 84 percent of the flow originated at or upstream from the Oliver gage for 2016 and 2017, respectively (table 6). The simulations were closer to the assumed water balance ranges, falling in a narrower average range of 82 and 86 percent for 2016 and 2017, respectively, for the Oliver gage. For outflow, about 78 and 71 percent of the discharge flowed out through the Superior entry for 2016 and 2017, respectively, with the assumed discharge to be close to about 70 percent in a given year (fig. 4). The simulated discharge through the Superior entry was close to the measured average for both years.

Discharge was more dynamic than the water-surface elevations, both for the measured data and simulated values, although the measurement range was wider for all three locations (table 5). For example, the 2016 measurement range for the Superior entry was −1,644 to 2,276 cubic meters per second (m^3/s), almost double the range for the simulation values, although most of the range fell into a slightly narrower range from −600 to 1,200 m^3/s. Generally, the constantly changing flux exiting the estuary into Lake Superior (positive flows) and entering the estuary from Lake Superior (negative flows) occurred throughout the year (fig. 8). The wider range also was apparent for the 2017 Superior entry discharge, with similar ranges, although the simulated range was slightly wider (fig. 9). The Duluth entry also had a dynamic range (figs. 8 and 9), given the effect from Lake Superior; however, upstream at the Oliver gage (figs. 8 and 9), the Lake Superior effect was subdued but negative flows did occur. This effect illustrated the strong effect of the Lake Superior seiche on flows for the estuary. This dynamic flow, even as far upstream as the Oliver gage, strengthened the importance of a hydrodynamic model for contaminant transport and confirmed the seiche effect (Trebitz, 2006).

A period of 3 days from July 2016 (July 19–22) is shown in figure 10 for the Duluth entry. Within 3 days, the measured discharge fluctuated from less than −650 to 1,200 m^3/s. These changes from negative to positive flows also occurred within hours, once again illustrating the competing effects of constant discharge from upstream, particularly flow from Fond du Lac Dam, and the potential inflows coming into the estuary from Lake Superior seiche activity.

From a performance standpoint, the model was able to simulate discharge with generally good agreement in both years, although similar to the water-surface elevations, the 2017 validation was better than the 2016 calibration period. For the daily NSEC values in 2016, the NSEC values were 0.98, 0.62, 0.49, and 0.71 for the Oliver gage, Superior entry, Duluth entry, and total entries, respectively. The high NSEC value for the Oliver gage was expected, given its proximity

Table 5. Measurement and simulation ranges for discharge (in cubic meters per second), including the minimum, maximum, and average, of the following locations for 2016–17: St. Louis River at Oliver, Wisconsin; Superior Bay Entry Channel at Superior, Wisc.; Superior Bay Duluth Ship Canal at Duluth, Minnesota; and Superior Bay Entry Channel at Superior, Wisc., plus Superior Bay Duluth Ship Canal at Duluth, Minn.

[USGS, U.S. Geological Survey; Wisc., Wisconsin; Minn., Minnesota; --, no station number]

USGS station number	USGS station name	Short name	Measurement range (hourly)			Simulation range (hourly)		
			Minimum	Maximum	Average	Minimum	Maximum	Average
			(cubic meters per second)					
		2016						
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	−277.5	473.0	88.39	−113.3	433.5	88.66
464226092005600	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	−1,644	2,276	93.54	−949.5	1,121	83.18
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	−1,510	1,737	26.27	−721.8	692.5	25.33
--	Superior Bay Entry Channel at Superior, Wisc., and Superior Bay Duluth Ship Canal at Duluth, Minn.	Total entries	−3,154	4,013	120.1	−1,621	1,772	108.4
		2017						
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	−350.4	524.0	139.6	−133.3	466.0	143.5
464226092005600	Superior Bay Entry Channel at Superior, Wisc.t	Superior entry	−1,586	1,770	118.7	−1,147	1,254	120.1
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	−1,482	1,445	47.93	−784.0	767.8	45.06
--	Superior Bay Entry Channel at Superior, Wisc., and Superior Bay Duluth Ship Canal at Duluth, Minn.	Total entries	−2,801	3,043	167.1	−1,905	1,925	166.0

to Fond du Lac Dam. The discharge for the total entries was better than the discharge for the two individual entries because the model was unable to completely distribute the flow according to the measured data but, collectively, was a reasonable simulation; however, based on the average discharge and NSEC at or greater than 0.49 for the daily values, the model was a fair approximation (table 7).

On the other hand, for the hourly evaluation criteria, the model performed poorly, with values less than 0 for the outflow locations. As a predictor, the model performed worse than using the measured data average, by the definition of the NSEC; however, when the data were aggregated to daily values, the seiche effect on discharge in and out of the estuary was suppressed. For the MAE and RMSE, the hourly MAE and RMSE were generally an order of magnitude higher for all four discharge evaluation targets than the daily MAE and RMSE, including the Oliver gage. Finally, the ME did not show a significant trend either positive or negative, except the Duluth gage in 2016 did show a negative bias but then the Duluth gage had a positive bias in 2017.

Table 6. Water balance ratios, in percentages, for the measurement and simulation average discharges for 2016 and 2017. The inflow ratio was based on all discharge measured at the Oliver gage, whereas the outflow ratio split the overall discharge between the Superior and Duluth entries, as shown in table 5.

[Oliver gage, St. Louis River at Oliver, Wisconsin (U.S. Geological Survey [USGS] station 0402403250); Superior entry, Superior Bay Entry Channel at Superior, Wisc. (USGS station 464226092005600); Duluth entry, Superior Bay Duluth Ship Canal at Duluth, Minnesota (USGS station 464226092005600)]

Short name	Measurement	Simulation
	2016 inflow	
Oliver gage	74	82
	2016 outflow	
Superior entry	78	77
Duluth entry	22	23
	2017 inflow	
Oliver gage	84	86
	2017 outflow	
Superior entry	71	72
Duluth entry	29	27

Temperature

Temperature calibration was important because temperature affects water density and the vertical exchange of constituents; furthermore, annual freezing cycles also are important to capture for general hydrodynamics. Finally, temperature affects all biogeochemical processes within the water column, so if the EFDC model is eventually expanded for water-quality modeling, the temperature calibration is considered a critical step in the model development.

Several boundary conditions affect the water temperature, including the initial water temperature and the sediment temperature exchange; however, the two most important boundary conditions are the availability of the inflow temperature records for at least a subset of the flow series (table 1) and high-resolution meteorological records from close to the model domain. A total of 6 records were available for at least part of the 2 simulation years for the inflow series, with all the inflow temperatures assigned a water temperature series (table 1). For meteorological records, 2 complete atmospheric records and 3 wind series were available. Because solar radiation was not directly available for any of the nearby meteorological records, an internal calculation within the model was made based on the amount of cloud cover and the latitude/longitude.

Like the water-surface elevations and discharge, water temperature was calibrated for April 1–November 16, 2016, and validated April 6–November 12, 2017, by comparing measured water temperature at two locations (table 8): the Oliver gage (truncated in 2017) and the Duluth entry. For calibration purposes, the Oliver gage was more of an internal check on the model. The Duluth entry was the only other independent temperature record available for model calibration, so this record was important as a model calibration check on the model's heat budget. In both cases, the measured temperatures were compared to the simulated temperature 1 m below the water surface. The applied temperature for the Fond du Lac flow series, one of the most important flow series in the model domain, was the Oliver gage record, so the high NSEC and low MAE/RMSE were expected; however, the NSEC values for the Duluth entry also were favorable. The hourly NSEC values for the Duluth entry were at or greater than 0.70 for both years, with daily NSEC values of 0.84 and 0.82 for 2016 and 2017, respectively (table 8).

The water temperature amplitude during an individual day was generally small. For the Oliver gage temperature record, amplitude varied within a narrow range of less than 1 °C (figs. 11*A* and 12*A*). Even for the Duluth entry record (figs. 11*B* and 12*B*), the measured and simulated fluctuations for hourly measurements had amplitudes of less than 2 °C. For the calibration (2016) and validation (2017) periods, the simulated temperatures were slightly higher by about 1 °C for the Oliver gage (table 8; fig. 11*A*; fig. 12*A*) with MAE/RMSE values less than 1 °C (table 8). On the other hand, the Duluth entry had a higher drift for the simulated values, with MAE and RMSE values as high as 3 °C. The drift between measured and simulated values was most apparent during the summer months (figs. 11*B* and 12*B*). This drift is also highlighted with the ME values, as the simulated

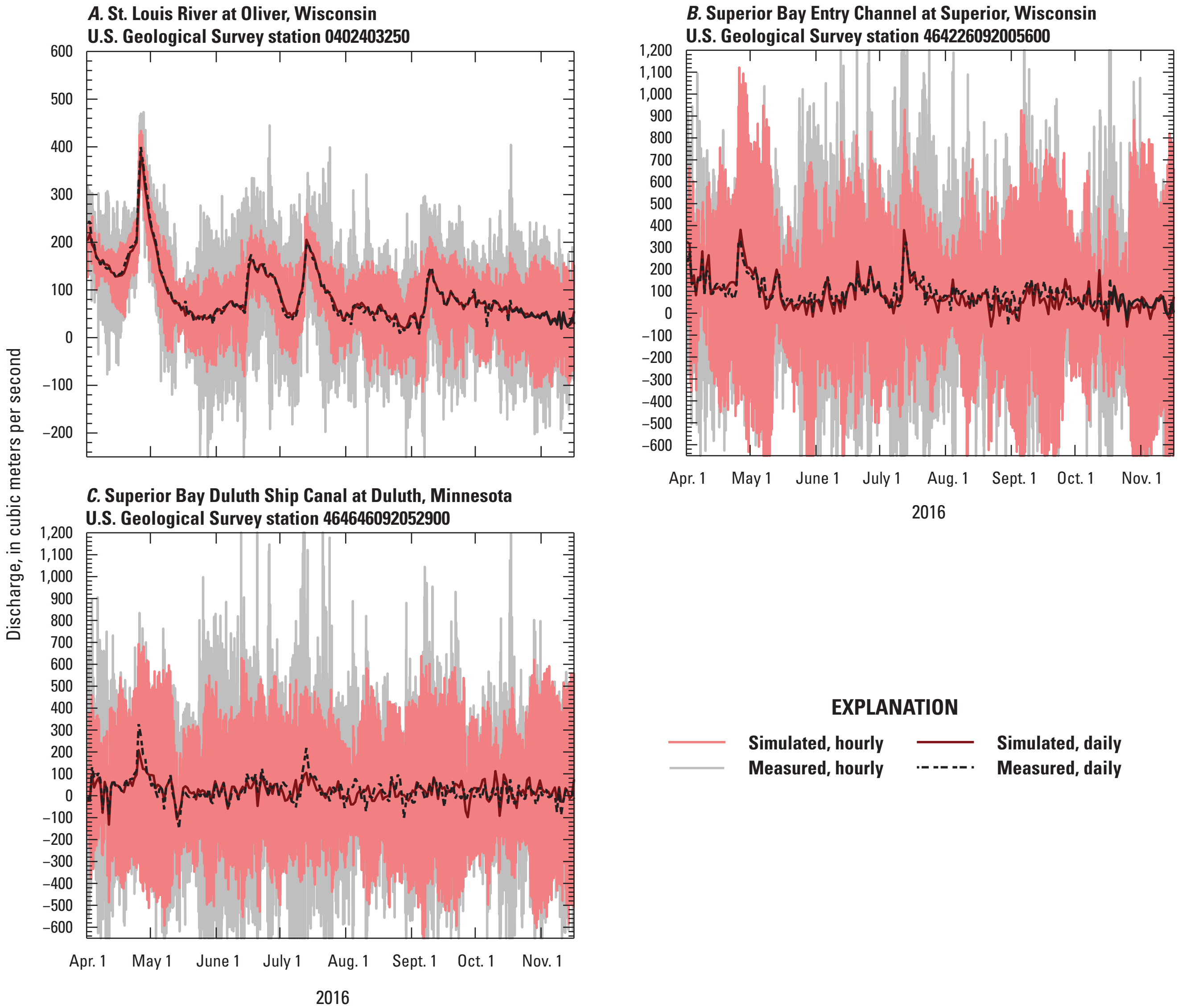

Figure 8. Hourly and daily mean discharge for St. Louis River estuary locations, Minnesota-Wisconsin, 2016. Measured and simulated data are plotted at the same locations. *A*, St. Louis River at Oliver, Wisconsin (U.S. Geological Survey [USGS] station 0402403250); *B*, Superior Bay Entry Channel at Superior, Wisc. (USGS station 464226092005600); *C*, Superior Bay Duluth Ship Canal at Duluth, Minnesota (USGS station 464646092052900).

values were biased high for both locations, up to 1.8 °C for the Duluth gage. Although different evaporation options were attempted, as discussed in the "Model Parameterization" section, the best calibration fit was the EFDC original model despite the offset in the summer months.

The temperature offset for the calibration and validation periods could be explained by a couple of factors. Measurement location for the temperature calibration and validation data is important. With only single measurement locations available for each location, rather than several depths, the offset in temperature could be related to a data limitation. The measured temperature records might not be capturing the full temperature spectrum, so a proper match between the simulated and measured data can be challenging. Also, the continuous temperature records available for model construction were limited to a small set of locations, which had to be applied across multiple locations. In particular, the boundary condition for Lake Superior was based on a single observed temperature record from a buoy record, Western Lake Superior (NDBC Station 45028), about 12 mi offshore in Lake Superior from Duluth, Minn. However, it is known that Lake Superior is stratified, so a single water temperature measurement from 1 m below the water surface would not represent the profile. Finally, the lack of a spin-up period for the model to reach

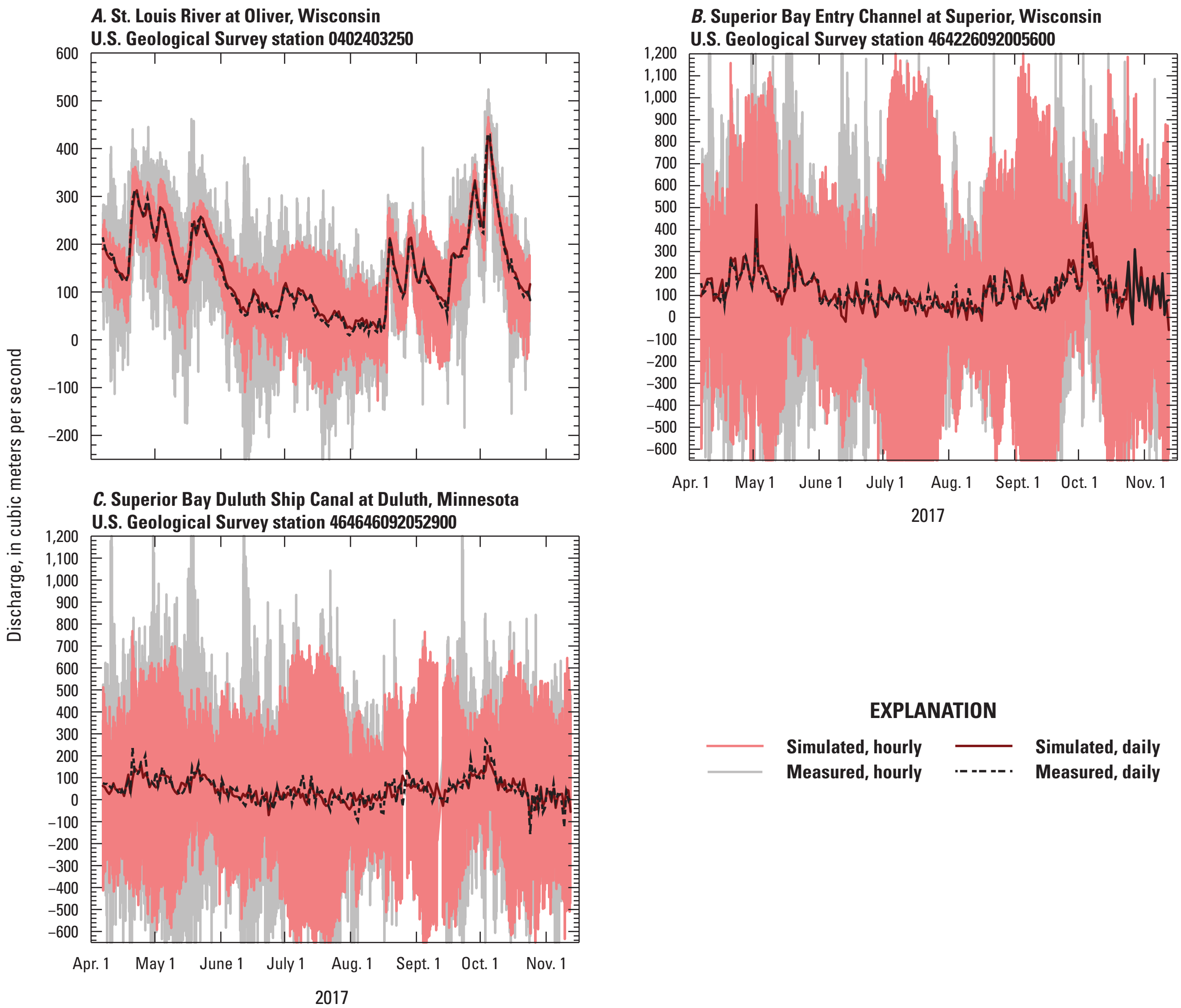

Figure 9. Hourly and daily mean discharge for St. Louis River estuary locations, Minnesota-Wisconsin, 2017. Measured and simulated data are plotted at the same locations. *A*, St. Louis River at Oliver, Wisconsin (U.S. Geological Survey [USGS] station 0402403250); *B*, Superior Bay Entry Channel at Superior, Wisc. (USGS station 464226092005600); *C*, Superior Bay Duluth Ship Canal at Duluth, Minnesota (USGS station 464646092052900).

equilibrium could have been an issue with calibration, leading to an offset in the summer heat budget between the model simulation and the measured data.

Flow Velocity

Because the discharge measurements and simulations are partially a product of the flow velocity, the similarity in the predictive success of the model was expected. The model was able to capture the complex dynamics of flow velocity in and out of the estuary into Lake Superior, although the amplitude for the simulated flow velocity was smaller than the measured flow velocity. For comparison purposes, all three gaging locations (the Oliver gage, Superior entry, and Duluth entry) were used as calibration datasets. To extract the results from the EFDC model, two outputs were used—the XYZ magnitude and the direction component—to calculate positive versus negative flow velocity. For the daily NSEC values in 2016, the NSEC values were 0.97, 0.69, and 0.43, for the Oliver gage, Superior entry, and Duluth entry, respectively. At the hourly time step, only the Oliver gage had a positive NSEC value. For all three locations in 2017, the daily NSEC values were higher (table 9).

Flow velocity for model calibration is generally considered a difficult calibration target; however, when the data are available, it is still considered an important check for the simulated flow velocities to see if the magnitudes are generally similar to the measured flow velocities. As an example,

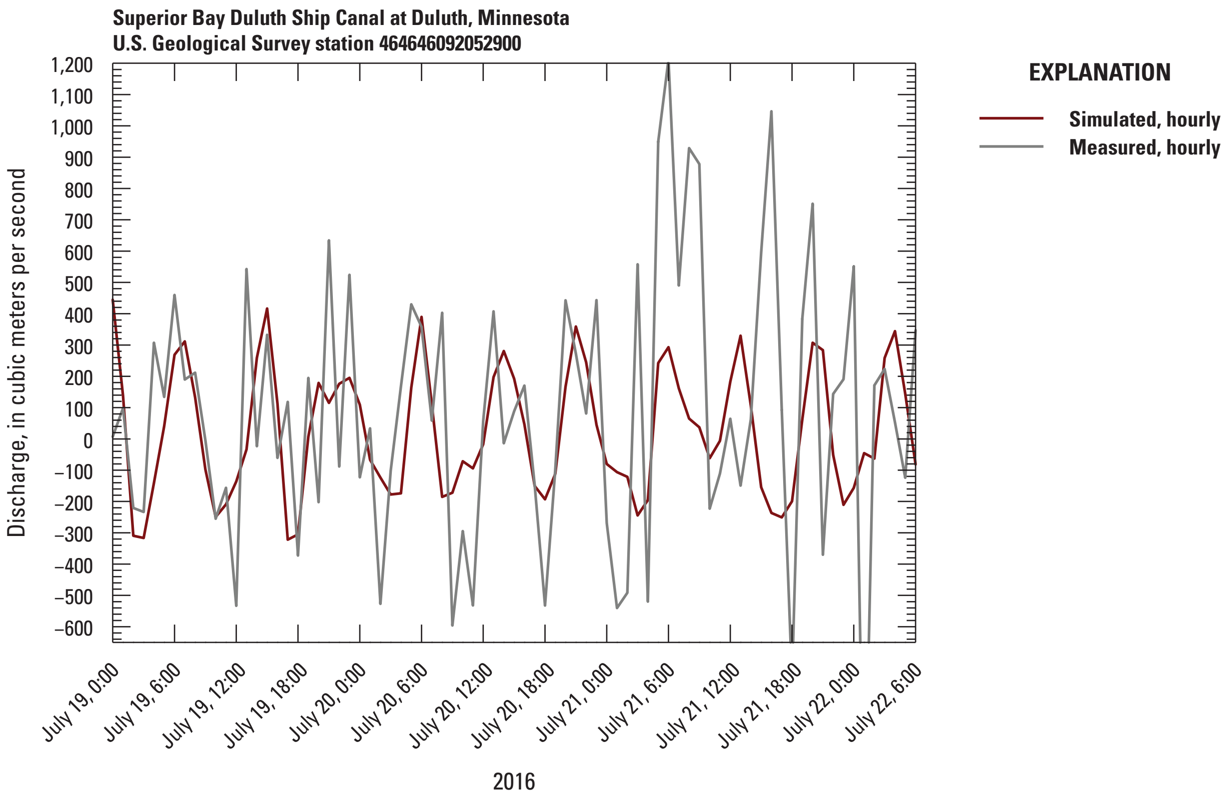

Figure 10. Hourly water-surface discharge for the Superior Bay Duluth Ship Canal at Duluth, Minnesota (U.S. Geological Survey station 464646092052900), for July 19–22, 2016, demonstrating the subdaily discharge fluctuation cycle.

the 2016 daily flow velocities (in meters per second) for the Duluth and Superior entries are shown in figure 13. Overall, the model was able to capture the general trajectory and timing of the water velocity at the daily scale, in addition to the seasonal trends in flow velocity. Attempts were made to further improve the simulated water velocities to the measured data by adjusting the bottom roughness values to increase the water velocities, but these adjustments did not appreciably alter flow velocity for either of the entry locations.

It is important to note that the velocity data are highly dependent on the SonTek SideLooker location and the part of the channel for which the velocity measurements were averaged. The model output was depth averaged, whereas the data measurement was set to specific locations and depths within the channel. With these considerations, the comparison between the simulated and measured velocities can be difficult and often is not presented.

Model Limitations

A full understanding of model limitations and data assumptions is necessary to better evaluate the performance of any hydrodynamic model. Because it is not possible to collect continuous data for every tributary, the extrapolation to ungaged tributaries was necessary to meet the boundary conditions for the model; for example, temperature records from other sites were applied, and discharge for many of the smaller tributaries was estimated through an area-ratio method rather than direct measurements. For the model simulation, the overall water balance was a good approximation of the measured data, but the estimated data could have been a factor in the poor approximation of the evaluation targets (discharge, water-surface elevations, water temperature) at the hourly time scale.

The time frame for the model calibration and validation was limited; however, funding for the USGS gages that provided the model calibration and validation data was limited to the 2 years used for this study. Other examples of EFDC models with a 1-year calibration period exist (Dynamic Solutions, LLC, 2013; Rendon and Lee, 2015), although in these cases, the calibration was a full year and these models also were in warmer climates without an ice season. Ideally, the calibration period would have run for a full year with a minimum of a short spin-up period of 2–3 months. The shorter period for this study could partially explain the temperature calibration offset in particular, making it more difficult for the model to properly simulate the proper heat budget. Also, the most important component of the calibration period for any hydrologic model such as EFDC is selecting a period with a range of hydrologic events (Yapo and others, 1996; Juston and others, 2009).

Table 7. Performance evaluation statistics for discharge of the St. Louis River estuary model, 2016–17, including mean error, mean absolute error, root mean square error, and Nash-Sutcliffe efficiency coefficient.

[USGS, U.S. Geological Survey; ME, mean error; MAE, mean absolute error; RMSE, root mean square error; NSEC, Nash-Sutcliffe efficiency coefficient; Wisc., Wisconsin; Minn., Minnesota; --, no station number]

USGS station number	USGS station name	Short name	Hourly evaluation criteria				Daily evaluation criteria			
			ME	MAE	RMSE	NSEC	ME	MAE	RMSE	NSEC
			(cubic meters per second)			(dimensionless)	(cubic meters per second)			(dimensionless)
			2016							
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	0.28	70.94	90.29	0.27	0.43	6.052	8.458	0.98
464226092005600	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	−0.93	335.7	428.8	−0.62	−1.78	29.65	37.86	0.62
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	−10.41	306.3	385.8	−0.43	−8.57	29.44	39.60	0.49
--	Superior Bay Entry Channel at Superior, Wisc., and Superior Bay Duluth Ship Canal at Duluth, Minn.	Total entries	−11.64	615.0	781.2	−0.54	−11.70	42.44	56.58	0.71
			2017							
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	3.92	75.16	95.96	0.38	3.80	7.741	10.00	0.99
464226092005600	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	−2.80	404.5	513.0	−1.44	−2.54	26.04	35.02	0.75
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	1.45	341.6	429.3	−0.71	0.62	29.32	39.03	0.59
--	Superior Bay Entry Channel at Superior, Wisc., and Superior Bay Duluth Ship Canal at Duluth, Minn.	Total entries	−0.92	721.0	910.3	−1.06	−0.68	45.04	60.25	0.75

Table 8. Performance evaluation statistics for water temperature of the St. Louis River estuary model, 2016–17, including mean error, mean absolute error, root mean square error, and Nash-Sutcliffe efficiency coefficient.

[USGS, U.S. Geological Survey; ME, mean error; MAE, mean absolute error; RMSE, root mean square error; NSEC, Nash-Sutcliffe efficiency coefficient; Wisc., Wisconsin; Minn., Minnesota]

USGS station number	USGS station name	Short name	Hourly evaluation criteria				Daily evaluation criteria			
			ME	MAE	RMSE	NSEC	ME	MAE	RMSE	NSEC
			(degrees Celsius)			(dimensionless)	(degrees Celsius)			(dimensionless)
			2016							
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	0.4	0.6	0.9	0.98	0.4	0.6	0.1	0.99
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	1.5	2.3	3.0	0.73	1.5	1.9	2.3	0.84
			2017							
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	1.8	0.7	0.9	0.97	1.8	0.6	0.0	0.98
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	1.5	2.2	2.9	0.70	0.6	1.8	2.2	0.82

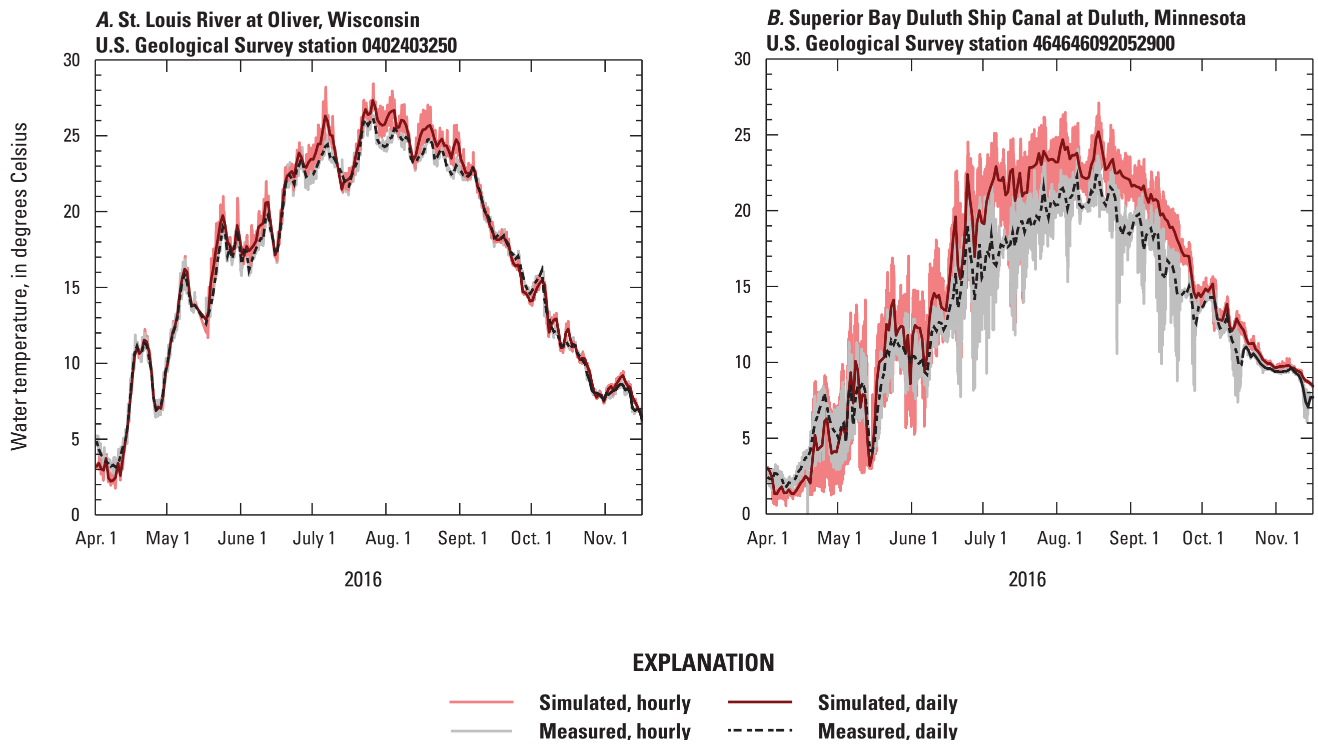

Figure 11. Hourly and daily mean temperature for St. Louis River estuary locations, Minnesota-Wisconsin, 2016. Measured and modeled data are plotted at the same locations. *A*, St. Louis River at Oliver, Wisconsin (U.S. Geological Survey [USGS] station 0402403250); *B*, Superior Bay Duluth Ship Canal at Duluth, Minnesota (USGS station 464646092052900).

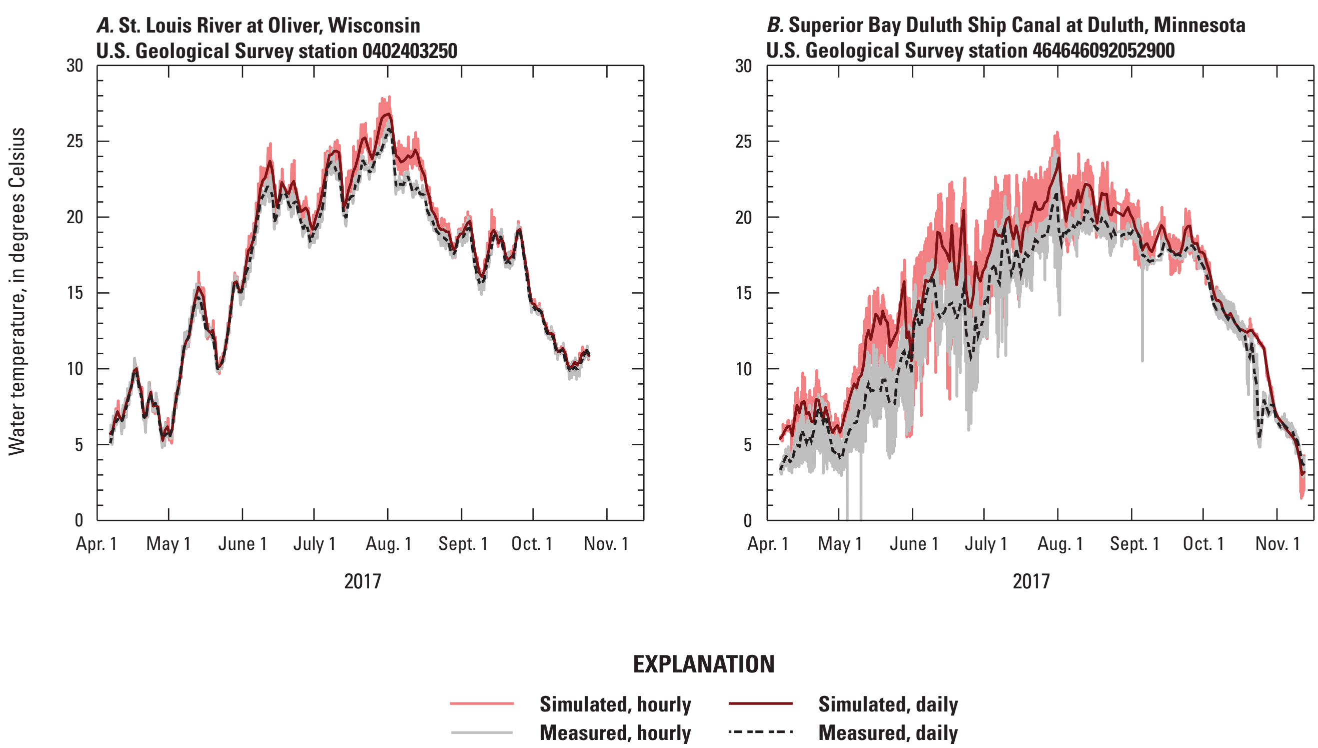

Figure 12. Hourly and daily mean temperature for St. Louis River estuary locations, Minnesota-Wisconsin, 2017. Measured and modeled data are plotted at the same locations. *A*, St. Louis River at Oliver, Wisconsin (U.S. Geological Survey [USGS] station 0402403250); *B*, Superior Bay Duluth Ship Canal at Duluth, Minnesota (USGS station 464646092052900).

Table 9. Performance evaluation statistics for flow velocity of the St. Louis River estuary model, 2016–17, including mean error, mean absolute error, root mean square error, and Nash-Sutcliffe efficiency coefficient.

[USGS, U.S. Geological Survey; ME, mean error; MAE, mean absolute error; RMSE, root mean square error; NSEC, Nash-Sutcliffe efficiency coefficient; Wisc., Wisconsin; Minn., Minnesota]

USGS station number	USGS station name	Short name	Hourly evaluation criteria				Daily evaluation criteria			
			ME	MAE	RMSE	NSEC	ME	MAE	RMSE	NSEC
			(meters per second)			(dimensionless)	(meters per second)			(dimensionless)
2016										
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	0.00	0.09	0.12	0.28	0.00	0.01	0.01	0.97
464226092005600	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	−0.01	0.16	0.21	−0.29	−0.01	0.02	0.02	0.69
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	−0.01	0.31	0.39	−0.50	−0.01	0.03	0.04	0.43
2017										
0402403250	St. Louis River at Oliver, Wisc.	Oliver gage	0.00	0.09	0.12	0.39	0.00	0.01	0.01	0.99
464226092005600	Superior Bay Entry Channel at Superior, Wisc.	Superior entry	0.00	0.18	0.23	−0.72	0.00	0.01	0.02	0.78
464646092052900	Superior Bay Duluth Ship Canal at Duluth, Minn.	Duluth entry	−0.01	0.35	0.44	−0.80	−0.01	0.03	0.04	0.56

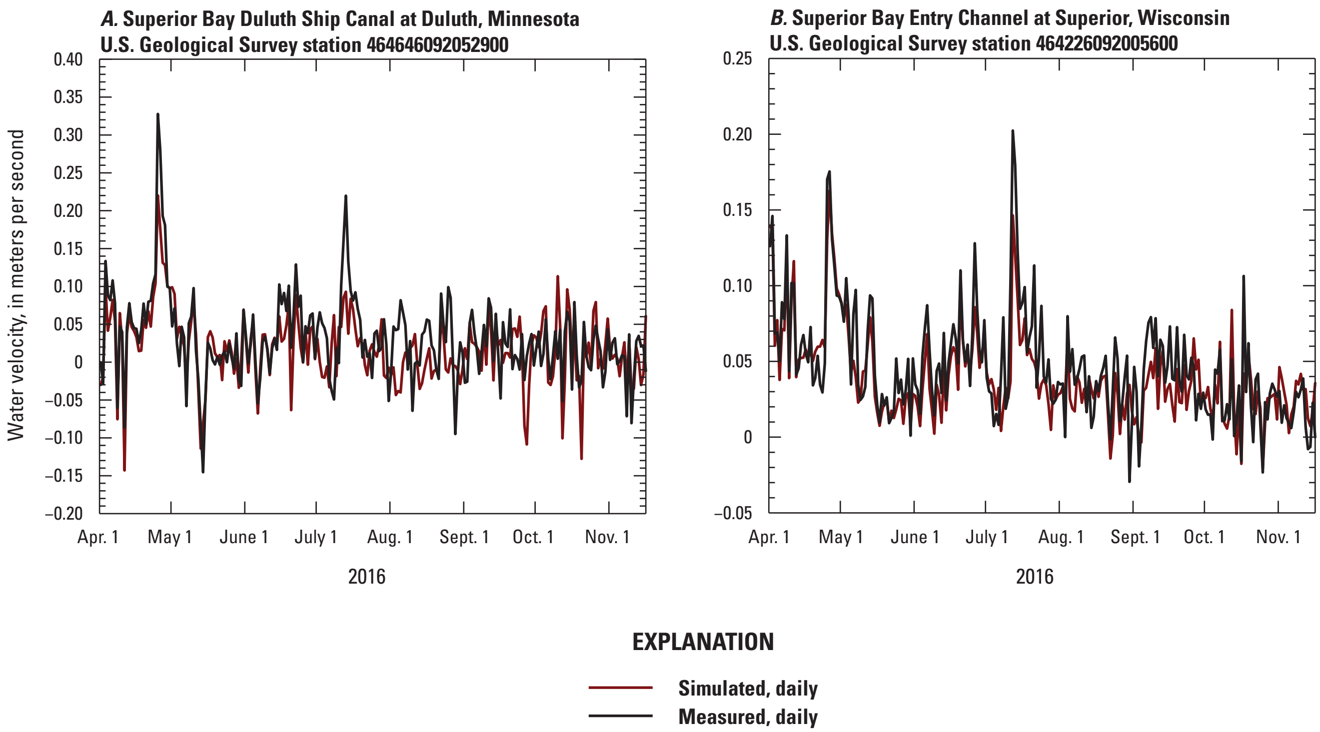

Figure 13. Daily mean flow velocity for St. Louis River estuary locations, Minnesota-Wisconsin, 2016. Measured and modeled data are plotted at the same locations. *A*, Superior Bay Duluth Ship Canal at Duluth, Minnesota (U.S. Geological Survey [USGS] station 464646092052900); *B*, Superior Bay Entry Channel at Superior, Wisconsin (USGS station 464226092005600).

Not only do data limitations exist, but structural selections such as segment geometry, the number of vertical layers, and the numerical transport scheme can potentially impose a bias in the outcome of the model. The grid is an approximation based on the available bathymetry, and the grid cell size can impose a bias in the final simulation. In the model construction, the final grid geometry was a balance between simulating the real conditions while preserving reasonable model run times.

Summary

The St. Louis River estuary is a large freshwater estuary, next to Duluth, Minnesota, that encompasses the Lake Superior headwaters. The St. Louis River estuary also is one of the most complex and compromised near-shore systems in the upper Great Lakes with a long history of environmental contamination caused by logging, mining, paper mills, and other heavy industrial activities. Despite its designation as a Great Lakes Area of Concern and multiple remediation and restoration projects throughout the past several decades, a widely available assessment tool capable of evaluating ecosystem-level responses to these projects has not existed for the estuary.

To address the needs of multiple partners working to improve water quality for the estuary, the U.S. Geological Survey (USGS) in collaboration with the U.S. Army Corps of Engineers, Engineer Research and Development Center, and in cooperation with the U.S. Environmental Protection Agency, built a predictive, mechanistic, three-dimensional hydrodynamic model for the estuary using the Environmental Fluid Dynamics Code (EFDC) framework. The EFDC model solves the vertically hydrostatic, free-surface, turbulent-averaged equations of motions for a variable-density fluid. EFDC is a widely used modeling framework that has been applied in a variety of surface-water studies. In the current version, the model is capable of simulating continuous discharge, water-surface elevations, water temperature, and flow velocity, although the flow velocities were only used as a check rather than a model performance target. Also, the modular EFDC framework allows for future adaptations to simulate other water-quality modeling, such as sediment and nutrients, once the appropriate datasets have been collected and processed.

The St. Louis River estuary model was calibrated and validated for 2016 and 2017, respectively. Model results were compared to measured data collected from three gaging stations. The four types of data used to verify model performance were continuous discharge, water-surface elevations, water temperature, and flow velocities. Flow and temperature boundary condition data included a mixture of USGS streamgage data, Minnesota Department of Natural Resources gage data, and estimates derived from the gage data.

The model was able to simulate the water-surface elevations with generally good agreement between the simulated and measured values for both years at the daily time step but only performed an adequate simulation at the hourly time step. At the daily time step, the model was able to demonstrate excellent agreement with the measured data based on Nash-Sutcliffe efficiency coefficients greater than 0.8 for all three gaging station locations. For the mean absolute error and root mean square error, the calibration and validation periods were at or less than 0.1 meter for the hourly evaluation criteria. For the same two statistics, the daily values were from less than 0.04 meter for both years.

Discharge was more dynamic than the water-surface elevations, both for the measured and simulated data, although the measurement range was wider for all three locations. Generally, most of the discharge fell into a range from −650 to 1,200 cubic meters per second, but the constantly changing flux exiting the estuary into Lake Superior (positive flows) and entering the estuary from Lake Superior (negative flows) occurred throughout the year. Even upstream at the St. Louis River at Oliver, Wisconsin, gage (USGS station 0402403250), the effect of flows into the estuary from Lake Superior did occur, although the effect was subdued. Despite the smaller reverse flows at the Oliver gage, these reversals did demonstrate the strong effect of the Lake Superior seiche on flows for the estuary.

From a performance standpoint, the model was able to simulate discharge with generally good agreement in both years, although the 2017 validation was better than the 2016 calibration period. For the daily Nash-Sutcliffe efficiency coefficients, the simulated values were 0.98, 0.62, 0.49, and 0.71 for the Oliver gage; the Superior Bay entry channel at Superior, Wisc. (USGS station 464226092005600); the Superior Bay Duluth Ship Canal at Duluth, Minn. (USGS station 464646092052900); and total entries (combination of the Superior entry and Duluth entry), respectively. The discharge for the total entries was better than the discharge for the two individual entries because the model was unable to completely distribute the flow according to the measured data. For the hourly evaluation criteria, the model performed poorly, with Nash-Sutcliffe efficiency coefficients less than 0 for the entries into Lake Superior, so as a predictor of discharge at the hourly scale, the model performed worse than using the measured data average. Similar to discharge, the model was a good predictor of flow velocity at the daily time scale but had difficulty matching the measured data at the hourly scale. For discharge and flow velocity, matching at subdaily time steps for a system as complicated as the St. Louis River estuary is considered difficult because the match is highly sensitive to coordinating the exact measurement location to the simulated value.

The final calibration target was water temperature, calibrated for the Oliver gage and the Duluth entry. For calibration purposes, the Duluth entry was the more important target because the Oliver gage was more of an internal check on the model. The Nash-Sutcliffe efficiency coefficient values for the Duluth entry were high; hourly Nash-Sutcliffe efficiency coefficients for the Duluth entry were at or greater than 0.7 for both years, and daily values were 0.84 and 0.82 for 2016 and 2017, respectively.

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