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Impact of Lake Michigan water level rise on complex bidirectional flow in the Chicago Area Waterway System (CAWS)

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ABSTRACT

In the past decade, continuously rising water levels in Lake Michigan have been threatening lakefront areas, especially in metropolitan regions like the Greater Chicago area. This provides the motivation to analyze the impact that high lake levels have on the Chicago Area Waterway System (CAWS). As the only primary free connection between the CAWS and Lake Michigan, the Calumet Area waterway subsystem plays a key and unique role. In this work, a numerical model covering the Calumet subsystem and having Lake Michigan as a boundary condition, is set up, calibrated, and validated using limited field observations. It is found that the Calumet subsystem has become bidirectional, where both discharge and flow directions are controlled by lake levels. When lake levels are below −0.15 m (-0.5 ft, Chicago City Datum, CCD), the discharge in the Grand Calumet River is around zero, with water flowing along its east branch towards Indiana. When lake levels are above +0.46 m (+1.5 ft, CCD), the flow reverses direction and drains west into Illinois. In 2020, the mean lake-level was at +1.07 m (+3.5 ft, CCD), and the base discharge in the Grand Calumet River was approximately 8.5 m^3/s (300 ft^3/s). The higher Lake Michigan's level is, the larger the discharge would be into Illinois. Potential impact of this extra discharge on Lake Michigan Diversion Accounting (LMDA) of the State of Illinois and flood management in the Chicago Sanitary and Ship Canal (CSSC), is analyzed; while the nature of the bidirectional flows is characterized with the intent of shedding light on this complex phenomenon.

1. Introduction

In 2020, Lake Michigan water levels recorded at the National Oceanic and Atmospheric Administration (NOAA) Tides & Currents station 9087044 at the Calumet Harbor have exceeded the highest recorded levels in the past 100 years (Fig. 1(a)). As shown in Fig. 1 (b), the water levels recorded at this station show a continually rising trend since January 2013 (Gronewold et al., 2015), which have risen from −0.91 m (−3 ft, in Chicago City Datum, CCD) to +1.22 m (+4 ft, CCD), at a rate of 0.3 m/yr (1 ft/yr), where 0 ft, CCD = 579.48 ft above National Geodetic Vertical Datum (NGVD29) = 578.58 ft above International Great Lakes Datum (IGLD85) at the NOAA Calumet Harbor gaging station. This threatens the inhabitants of the Greater Chicago metropolitan area since the city might not be able to easily drain high streamflows towards Lake Michigan during extreme precipitation events, leading to backwater effects on the combined sewer system, and, thus, causing urban flooding (Rojas-Aguirre et al., 2019).

The risk of high Great Lakes water level effects on lakefront urban hydraulic systems has not been well explored. Similar research has mostly focused on coastal erosion and flooding problems in coastal cities due to sea-level rise.

Kana et al. (1984) studied the shoreline change pattern at Charleston, South Carolina, under the threat of sea-level rise. Similarly, Lebbe et al. (2008) and Cooper and Lemckert (2012) focused on shoreline erosion problems in Belgium and Australia. Other studies by Atkinson et al. (2013) have focused on the storm surge flooding risk in Texas in response to the rising sea level. Kwadijk et al. (2010) and Orton et al. (2020) studied the increased flooding risk on waterways in The Netherlands and New York, USA. All the aforementioned cases and many others are for *unidirectional systems*, that is, water flows towards the sea through waterways connected to it. The Chicago Area Waterway System (CAWS), located at the basin divide between the Great Lakes and Mississippi River, is cataloged as a *bidirectional system*, because of the Chicago River reversal project completed in 1900 (Lanyon, 2012; Hill, 2019). The

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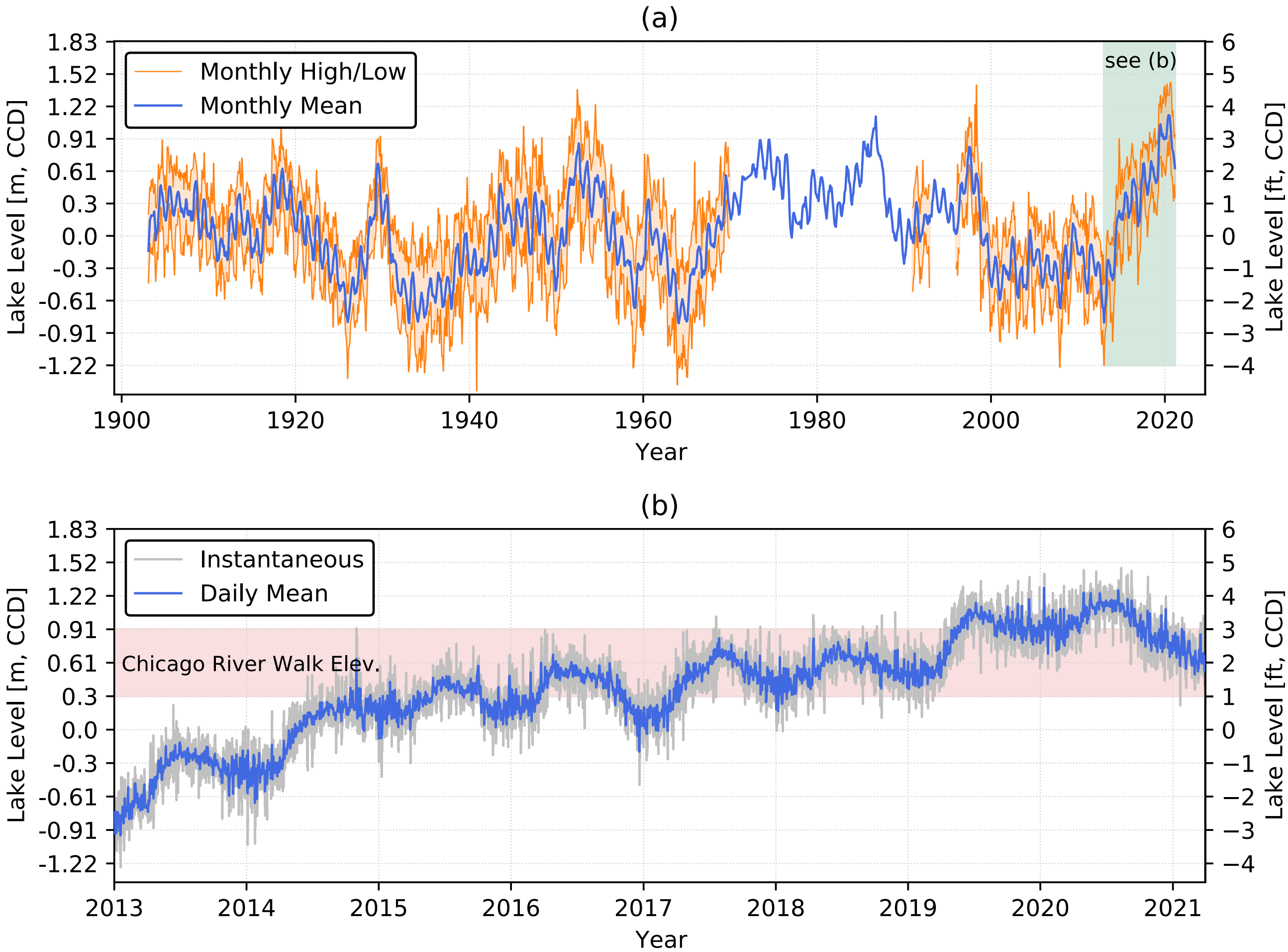

Fig. 1. Water level change in Lake Michigan. (a) Data range: 1903–2021. (b) Data range: 2013–2021. Data source: NOAA.

water in the CAWS can flow towards both the Great Lakes Basin and the Mississippi River Basin. This unique feature brings up the following questions: How will the system respond to the rapidly rising lake levels in recent years? Will the flooding risk be the same as in other unidirectional systems? How should the hydraulic control structures be operated to mitigate flooding?.

There are other concerns. In a large urban waterway system like the CAWS, in addition to flooding risk, there are other risks such as water quality issues, invasive species, and negative impacts on navigation, that must be carefully examined (Rasmussen et al., 2011). Located at the border of Illinois and Indiana, the Grand Calumet River area is a critical part of the CAWS. It consists of a set of channels and rivers connected to each other that can be divided into three parts: the approximately 16 km (10 miles) long East Branch, the approximately 6.4 km (4 miles) long Indiana Harbor Canal, and the approximately 9.6 km (6 miles) long West Branch (Fig. 2). This area is listed as one of the 19 remaining Areas of Concern (AoC) of the Great lakes (GLRI, 2019), and it is the primary open connection between the CAWS and Lake Michigan without hydraulic control structures. The water in this historically industrial area contains chemical pollutants that are considered harmful to human beings, fish, and wildlife (Chantrill, 2015), and can flow either to Lake Michigan or towards the Mississippi River basin through the CAWS, depending on the difference in water levels between Lake Michigan and the CAWS (Duwelius, 1996; Shrestha and Melching, 2003; Manache et al., 2007; Melching et al., 2015; Schoon, 2016).

Because of the low flow discharge in the Grand Calumet River, in previous numerical studies of the CAWS, e.g., Quijano et al. (2017); Sinha et al., (2012, 2013); and Zhu et al. (2017a, b), it was common to set this tributary as a boundary condition and exclude it from the modeling domain. After 2017, however, a historical high daily averaged flow discharge was recorded. A flow discharge between 5.67 m^3/s (200 ft^3/s) and 14.16 m^3/s (500 ft^3/s) was found in the Grand Calumet River subsystem, which used to be negligible between 2000 and 2009 when the lake level was relatively low (-0.3 m, or −1 ft, CCD). Between 2009 and 2016, due to a dredging project led by the U.S. Environmental Protection Agency (USEPA) (Espey et al., 2019), the flow discharge in the West Branch of the Grand Calumet River was close to zero as well. The impact of the post-dredging hydraulic condition of the Grand Calumet River subsystem in the CAWS remained unknown. Moreover, previous risk assessments of water quality, sediment toxicity, and wetland restoration in this area were based on the low flow condition (Romano et al., 1977; Simon et al., 1988; Ingersoll et al., 2002; Martinez et al., 2010; Schoon, 2016). Hence, investigation of potential risks and impact of the new hydraulic condition due to both lake level rise and dredging is necessary due to the high Lake Michigan water levels.

In this work, a high-resolution numerical model for the Calumet Area waterway subsystem, which is the southern part of the CAWS, is established. The model is calibrated based on the scientific investigation performed in May 2010 by Jackson and Lageman (2013) for a condition of complete isolation from Lake Michigan. Long-

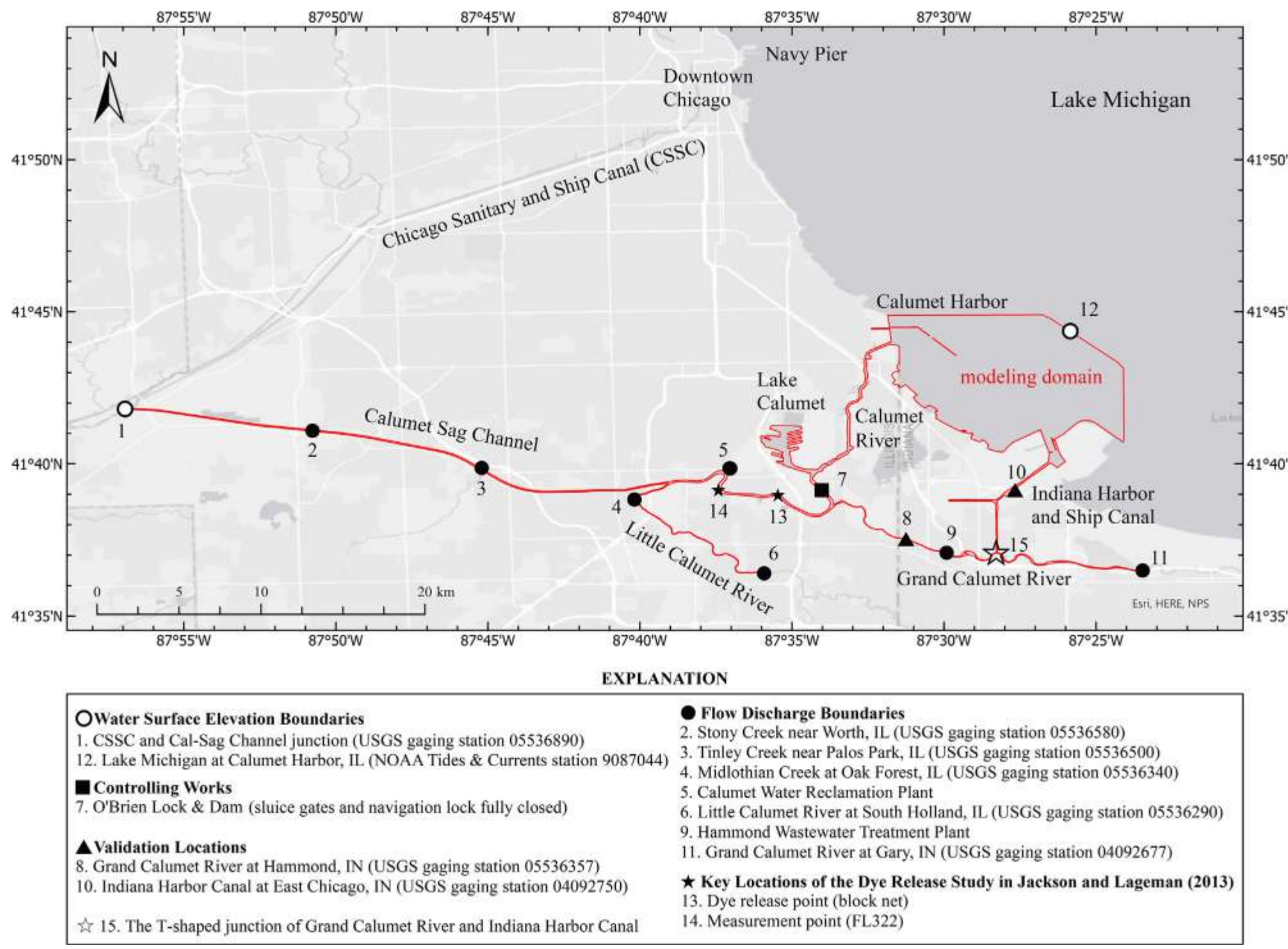

Fig. 2. Calumet Area Waterway subsystems – the modeling domain of this study. Locations of the model boundaries and model validation points are marked.

term hydraulic behavior of the system is studied with steady boundary conditions, which provides a picture of the mean behavior of the Calumet Area waterway subsystem's hydrodynamic conditions and the impact of lake level changes on the CAWS. Considering the mean behavior of flow discharge removes short-term fluctuations and helps reveal the average trend due to the impact of climate variance. The objective of the present study is to assess the hydrologic risk of the Calumet Area waterway subsystem and the CAWS in response to rising water levels in Lake Michigan. Of particular interest are the implications of lake levels for drainage, navigation, and water quality management in the bi-state Calumet Area, which is experiencing community revitalization, ecological restoration, and plans for a national heritage area recognition (Lanyon, 2020).

2. Methods

The study domain covered by the numerical model is shown in Fig. 2. It extends from the junction of the Chicago Sanitary and Ship Canal (CSSC) and Calumet-Sag (Cal-Sag) channel to the Grand Calumet River, Indiana Harbor Canal, and Lake Michigan. The model boundary of Lake Michigan is set approximately 9.6 km (6 miles) away from the Indiana Harbor canal mouth. O'Brien Lock and Dam is the only controlling works in this area, which includes four sluice gates (3.05 m × 3.05 m) and a lock chamber (305 m × 34 m) that allows discretionary flows from Lake Michigan for navigation and for improving the water quality into the system. Measured data from eight U.S. Geological Survey (USGS) gaging stations, a U.S. Army Corps of Engineers (USACE) gaging station, and a NOAA Tides & Currents station in this area were used in the model calibration.

The modeling domain is discretized into an unstructured triangular finite element mesh with the element size varying from 1 m in the relatively narrow reach of the Grand Calumet River to 200 m in Lake Michigan. The two-dimensional hydrodynamic model TELEMAC-2D is used to solve the time-dependent shallow water equations, as shown in Eqs. 1,2, using the finite element method. The model has 157,033 nodes with 286,244 triangular elements. For each simulated scenario, the typical runtime is approximately 10 h using Skylake compute nodes on the supercomputer Stampede2.

$$\frac{\partial h}{\partial t} + \nabla(h\mathbf{U}) = S_h \tag{1}$$

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U}\cdot\nabla\mathbf{U} = -\mathbf{g}\nabla H + \frac{1}{h}\nabla\cdot(h\nu_t\nabla\mathbf{U}) + \mathbf{S} \tag{2}$$

where h is the water depth; t is the time; $\mathbf{U} = (U_1, U_2)$ is the depth-averaged velocity vector in Cartesian coordinates (x- and y-direction, respectively); $\boldsymbol{g}$ is the vector of gravitational acceleration; H is the water surface elevation; and ν_t is the turbulent eddy viscosity; S_h and $\mathbf{S} = (S_1, S_2)$ are the source/sink terms in mass and momentum conservation, respectively. The source/sink term $\mathbf{S}$ in the momentum conservation equation constitutes different forces, such as bottom friction, $\mathbf{F}^f$, drag, and head loss term, $\mathbf{F}^t$, the Coriolis force, $\mathbf{F}^c$, and wind shear, $\mathbf{F}^w$. In this work, the bottom friction term

$\mathbf{F}^f$ is represented by the friction law with $F_i^f = -U_i\sqrt{U_1^2+U_2^2}C_f[\cos(\alpha)h]^{-1}$, where the friction coefficient is $C_f = [(1/\kappa)\ln(12h/k_s)]^{-2}$; ,$k_s$ is Nikuradse roughness height with length unit, cos(α) is the cosine reciprocal of the steepest slope at a point, and κ is von Krman's constant (= 0.41).

The vertical averaged standard k-ε method is applied for the turbulence closure as in Eqs. 3,4, in which the turbulent kinetic energy (TKE) and the dissipation of the TKE are determined by two transport equations, respectively:

$$\frac{\partial k}{\partial t} + \mathbf{U}\cdot\nabla k = \frac{1}{h}\nabla\cdot\left(h\frac{v_t}{\sigma_k}\nabla k\right) + P - \varepsilon + P_{kv} \tag{3}$$

$$\frac{\partial \varepsilon}{\partial t} + \mathbf{U}\cdot\nabla \varepsilon = \frac{1}{h}\nabla\cdot\left(h\frac{v_t}{\sigma_\varepsilon}\nabla \varepsilon\right) + \frac{\varepsilon}{k}[C_{1\varepsilon}P - C_{2\varepsilon}\varepsilon] + P_{\varepsilon k} \tag{4}$$

where k is the TKE; ε is the dissipation of the TKE; P is the TKE production term; P_{kv} and $P_{\varepsilon k}$ represent extra production terms due to the vertical shear in the depth-averaging process in k and ε equations; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are the k-ε model constants; $\sigma_k = 1$ and $\sigma_\varepsilon = 1.3$ are constants.

The numerical model contains seven flow discharge boundaries: Stony Creek; Tinley Creek; Midlothian Creek; Little Calumet River; Grand Calumet River east arm at Gary, Indiana; Calumet Water Reclamation Plant and Hammond Waste Water Treatment Plant (WWTP). There are also 2 stage boundary conditions at the CSSC & Cal-Sag channel junction and in Lake Michigan, 8 to 16 km (5 to 10 miles) offshore (see Fig. 2 for their locations). The discharge from the Calumet Water Reclamation Plant (WRP) is assumed to be equal to 14.84 m^3/s (524 ft^3/s), which is the maximum discharge recorded in Jackson and Lageman (2013). The Hammond Waste Water Treatment Plant is assumed to run at a capacity of 36 million gallons per day (MGD) (1.58 m^3/s) for dry weather conditions and maximum capacity (68 MGD, 2.98 m^3/s) during wet weather conditions (Hammond Sanitary District, 2019; Grant, 2019). The other five inflow boundary conditions data are taken from USGS gaging stations. The model boundary to simulate Lake Michigan is set 8 to 16 km (5 to 10 miles) away from the Indiana Harbor to avoid numerical boundary effects. Water surface elevations recorded at the Calumet Harbor (NOAA Tides & Currents station 9087044) represent the Lake Michigan water elevations. Water surface elevation data from USGS gaging station 05536890 located on the CSSC represents the water surface elevation at the CSSC & Cal-Sag channel junction.

On May 20, 2010, Jackson and Lageman (2013) started a 5-day-long scientific investigation on the flow in the Calumet-Sag Channel, which provides a valuable dataset to understand the local hydrodynamics along with the Calumet Area and the Cal-Sag Channel. Flow discharge was measured at multiple locations in the area. The Calumet WRP discharge was recorded. A dye release experiment was performed, and the dye plume concentration was mapped 19 times over four days. Herein, the May 2010 measurement data reported by Jackson and Lageman (2013), together with data from USGS gaging station 04092750 on the Indiana Harbor Canal, USGS gaging station 05536357 on the Grand Calumet River at Hohman Ave at Hammond, Indiana, and USACE gauge at O'Brien Lock & Dam located at River Mile 326.5 above the mouth of the Illinois River, are used to perform the calibration of the numerical model.

The calibration simulation period starts on May 17, 2010, and ends on May 27, 2010, which is three days ahead and three days after the period of Jackson and Lageman's May 2010 study. The calibration of the numerical model was conducted by matching the flow discharge and water surface elevation with the measured time series. The dye release experiment was numerically reproduced in the model to further calibrate the flow conditions. In the numerical model, the dye was released at 12:39 pm on May 20, 2010, near the Block Net location in Jackson and Lageman's report, which is the same time and location as in their report (see Location 13 in Fig. 2). The dye plume can also be analyzed using an analytical solution of the one-dimensional (1D) Advection–Diffusion equation (ADE). The relation that describes the conservation of mass for a passive solute takes into consideration advection, diffusion, and turbulent mixing as is shown in the following equation (Zhu et al., 2017b):

$$\frac{\partial C}{\partial t} + \mathbf{U}\frac{\partial C}{\partial x} = v\frac{\partial^2 C}{\partial x^2} + S_c \tag{5}$$

where C is the concentration; $v = v_t/P_r$ is the diffusion coefficient; Pr is Prandtl number; and S_c is a source/sink term, which equals zero in this case.

The 1D concentration profile downstream of an finite-duration source of a fixed concentration of a conservative scalar is:

$$C(x,t) = \frac{C_0}{2}\left[\left[\operatorname{erfc}\left(\frac{x-ut}{\sqrt{4v_t t}}\right) - \operatorname{erfc}\left(\frac{x-u(t-t_{\text{stop}})}{\sqrt{4v_t(t-t_{\text{stop}})}}\right)\right] + \exp\left(\frac{ux}{v}\right)\left[\operatorname{erfc}\left(\frac{x+ut}{\sqrt{4v_t t}}\right) - \operatorname{erfc}\left(\frac{x+u(t-t_{\text{stop}})}{\sqrt{4v_t(t-t_{\text{stop}})}}\right)\right]\right] \tag{6}$$

where s_{stop} is the time that dye release stopped; and C_0 is the initial dye concentration.

The time series of dye concentration was measured at location FL322, which is around 3 km westward of the Block Net location (i.e., initial release location, Location 14 in Fig. 2). Numerical time series results and 1D ADE analytical results are compared with the measurement at location FL322 to further calibrate the model.

After the numerical model calibration, steady-state runs of the waterway system in response to the lake level rise were performed against a thirty-year (1991–2020) flow measurement dataset as both model validation and prediction runs. Steady-state simulations with different lake levels ranging from −0.46 m (-1.5 ft, CCD) to +1.68 m (+5.5 ft, CCD) were performed. Different lake levels were considered with intervals of every 0.15 m (0.5 ft). The purpose of simulating high lake-level conditions is that instantaneous lake levels have been recorded at more than +1.68 m (+5.5 ft, CCD) at the Chicago Lock (USGS gaging station 04087440) at around 23:00 on April 29, 2020. The impacts of lake level rise on the CAWS, Indiana Harbor, the Grand Calumet River, and the Hammond WWTP are quantified and presented in the next section.

3. Numerical modeling results

In this section, calibration of the numerical model is provided, and risk assessment of Lake Michigan water level rise to CAWS is performed. Two trends are observed in the data and comfirmed by the modeling results: (1) flow discharge in the Grand Calumet River has reversed its direction and keeps increasing; (2) net flow discharge in Indiana Harbor, which is currently towards Lake Michigan, is decreasing, and it will reverse its direction when the lake elevation is higher than +1.52 m (+5 ft, CCD). With the current lake level at around +1.07 m (+3.5 ft, CCD), the discharge has been decreased by approximately 5.66 m^3/s (200 ft^3/s, 40% decrease compared to averaged discharge).

According to this analysis, by considering the impact of lake level rise on the Calumet Area subsystem, the required water surface gradient in the CSSC will increase 0.12 m (0.4 ft) in dry weather, when the lake level reaches extreme levels at +1.68 m (+5.5 ft, CCD). In a flooding event, when the CSSC discharges is around 311.49 m^3/s (11,000 ft^3/s), if the lake level is at +1.68 m (+5.5 ft, CCD), it will require an extra 0.15 m (0.5 ft) in water surface elevation to convey the flow, and downtown Chicago could experience an extra water level increase of 0.06 m (0.2 ft). The focus of this study is mainly on modeling the hydrodynamics under non-extreme weather conditions. The waterway system response to extreme weather conditions will be presented in future analyses.

3.1. Model calibration: May 2010 case

The 5-day-long scientific investigation by Jackson and Lageman (2013) between May 20 and May 24, 2010, in the Cal-Sag Channel is numerically reproduced with the southern CAWS TELEMAC model. In this study, a well-calibrated CAWS HEC-RAS model developed by Santacruz and Garcia (2014) is used to help with the calibration process. The calibrated Nikuradse roughness height in the TELEMAC model is $k_s = 0.17$ m, which corresponds to a Manning coefficient $n \simeq 0.029 s/[m^{1/3}]$. Through time series comparison of flow discharge and free surface elevation at different locations of the study domain, the model was proven to provide as reliable results as the HEC-RAS model over the study domain. Since the HEC-RAS model's study domain was not extended to Lake Michigan, Lake Calumet, and the Grand Calumet Area, the USGS and USACE gauge data at these locations were used for calibration. The time-series comparisons are shown in Fig. 3.

In this study, the Calumet WRP is assumed to be running at a constant capacity of 14.84 m^3/s (524 ft^3/s). The simulated flow velocity at the Acme Bend in the Cal-Sag Channel agrees with the measured data of Jackson and Lageman (2013) (see Fig. 4). The magnitude of velocities in the numerical model agreed with the measured data. Both the stagnation line and general circulation are well captured by the model.

In dry weather conditions, the Grand Calumet River discharge is around 0 m^3/s, and the O'Brien Lock & Dam is fully closed. Between the Little Calumet River junction and the O'Brien Lock & Dam, the Cal-Sag Channel acts as a closed water body with fluctuating stages. These fluctuations generate instantaneous flow discharges ranging from +17 m^3/s (+600 ft^3/s) to −17 m^3/s (-600 ft^3/s). According to (Jackson and Lageman, 2013), a similar magnitude of fluctuations was observed in the discharge measurement, at the Block Net location in the Cal-Sag Channel (see Figure 2 Location #13). The root mean square error (RMSE) between the numerical model and measured data is 7.49 m^3/s (264.62 ft^3/s), while the correlation coefficient is 0.31. The cause of fluctuations in the measured data is presumably due to wind action, downstream fluctuating inflows, or other random factors during the survey, which were not measured during the field campaign, and, therefore, were not considered in the model. The fluctuating discharges generate bidirectional flows in the system; hence, the discharge from Calumet WRP can flow both eastward and westward (see Fig. 5). A total of 35 discharge measurements were taken by Jackson and Lageman (2013) near the block net (Location #13 in Fig. 2), which indicated that the mean discharge and the median discharge are, 1.1 m^3/s (39 ft^3/s) and 1.3 m^3/s (45 ft^3/s), respectively. By extracting the 35 discharge results at the identical time and location, the numerical model gives a mean discharge of 1.15 m^3/s (40.5 ft^3/s) and median discharge of 1.29 m^3/s (45.7 ft^3/s). However, it is suspected that 35 measurements are not sufficient to represent the actual net discharge in the channel. By taking the average of the complete simulation results, both mean and median discharge is around 0 m^3/s. This result is consistent since the channel is a closed system during that period with zero inflow. The dye

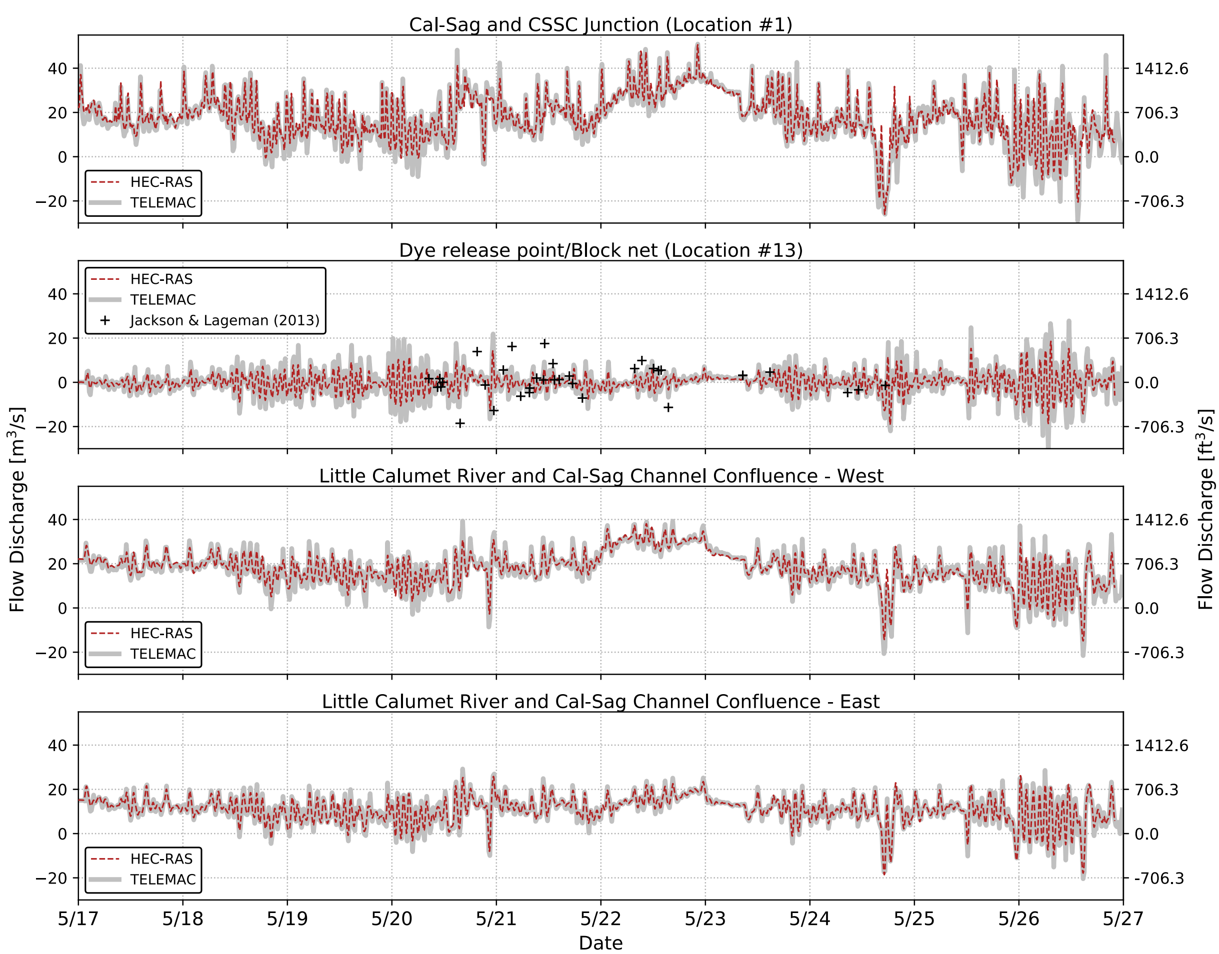

Fig. 3. Calibration results of the southern CAWS TELEMAC model at different locations. The simulated time series of discharge and surface elevation are plotted against measured data and results from the HEC-RAS model by Santacruz and Garcia (2014) and Rojas-Aguirre et al. (2019).

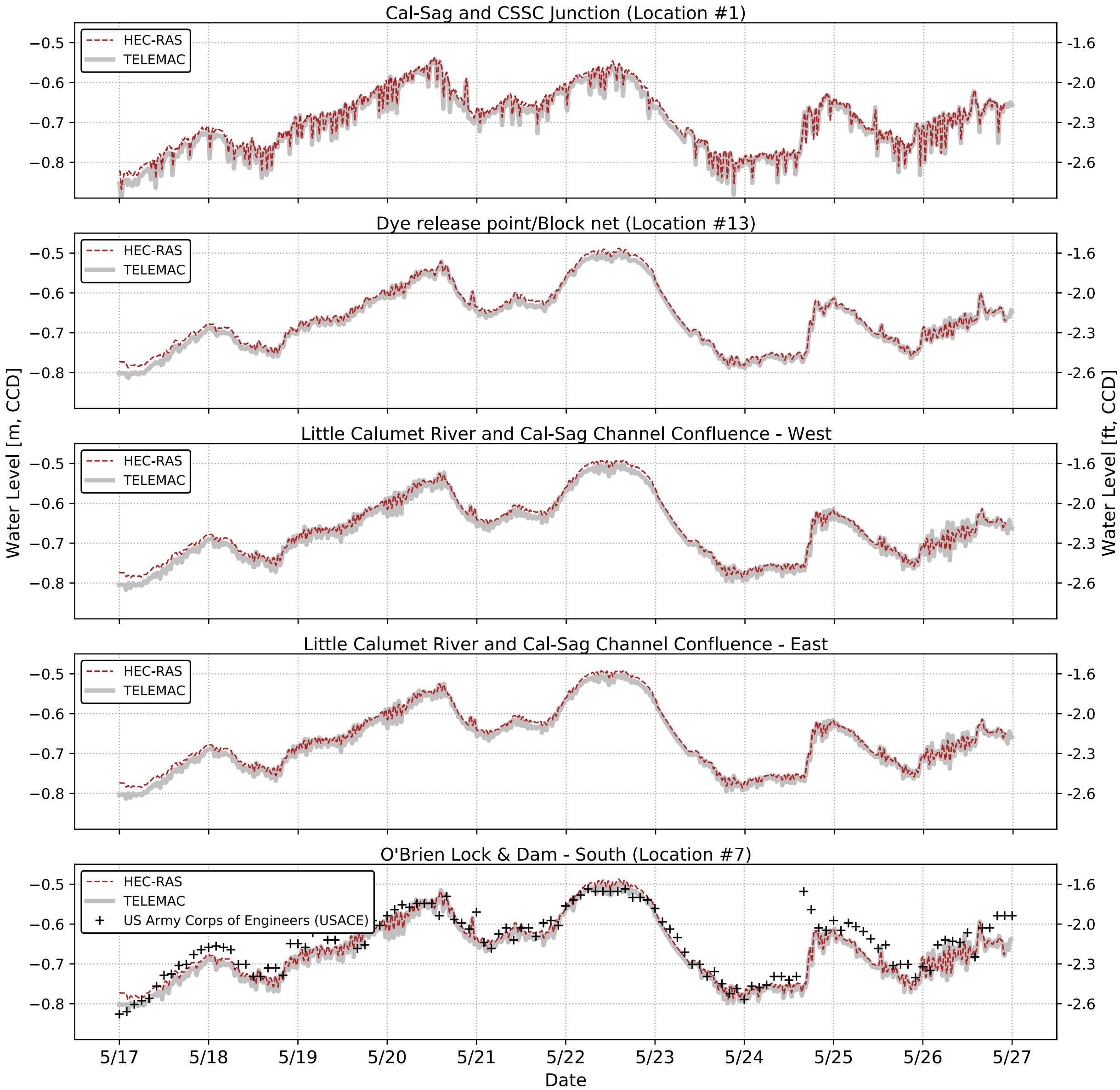

Fig. 3 (*continued*)

release experimental study in the next paragraph provides more insight into the hydraulic conditions of the channel. Fig. 6.

The dye release performed by Jackson and Lageman (2013) is numerically reproduced in this study. The dye is treated as a passive solute in the numerical model. The dye is injected at the same time and location as described in the report at 12:39 pm on May 20, 2010. In the first attempt of modeling, the simulated dye plume did not agree with the measurements. As described in the previous paragraph, the mean discharge in the channel is around zero. The plume stays near the initial injection location and does not move westward. However, the report indicates that the plume was moving westward and was detected at location FL322 (Location 13 in Fig. 2) 17 hours after the release. The traveling speed of the plume front is approximately 0.045 m/s (0.15 ft/s). A pure diffusion process cannot explain this speed nor the 1.1 m^3/s (39 ft^3/s) net flow discharge registered in the report. In order to match the measured plume traveling speed, a hypothetical extra discharge of 9.91 m^3/s (350 ft^3/s) is assigned at Grand Calumet River junction. It is suspected that this extra discharge comes from unknown local outfalls in the Little Calumet River and the Grand Calumet River, while a small portion might come from leakage through the lakefront structure at the O'Brien Lock & Dam; more details are discussed in Section 4.2. Such discharges are not recorded by any USGS gaging stations in this area, but, to the extent that they exist, they will be included in the flow measured at the USGS gaging station at Lemont, Illinois; amounting to 11% of the allowable annual Lake Michigan Diversion of 90.61 m^3/s (3,200 ft^3/s) limit (Wisconsin *v.* Illinois, 1980). After adding the total 9.91 m^3/s (350 ft^3/s) extra discharge, the simulation result shows a good match with the measured data in the Cal-Sag Channel (see Fig. 7). The source of this extra discharge, needed to match the field observations, should be assessed in future studies.

The simulated dye concentration distribution near Acme Bend in Cal-Sag Channel agrees with the Google Earth images (see Fig. 8). The dye concentration is diluted by the flow out of the Calumet WRP and follows the circulation of the flow, which agrees with the measurements of Jackson and Lageman (2013). Overall, the numerical model is proven to be able to capture the hydrodynamics in the simulation domain – the southern CAWS.

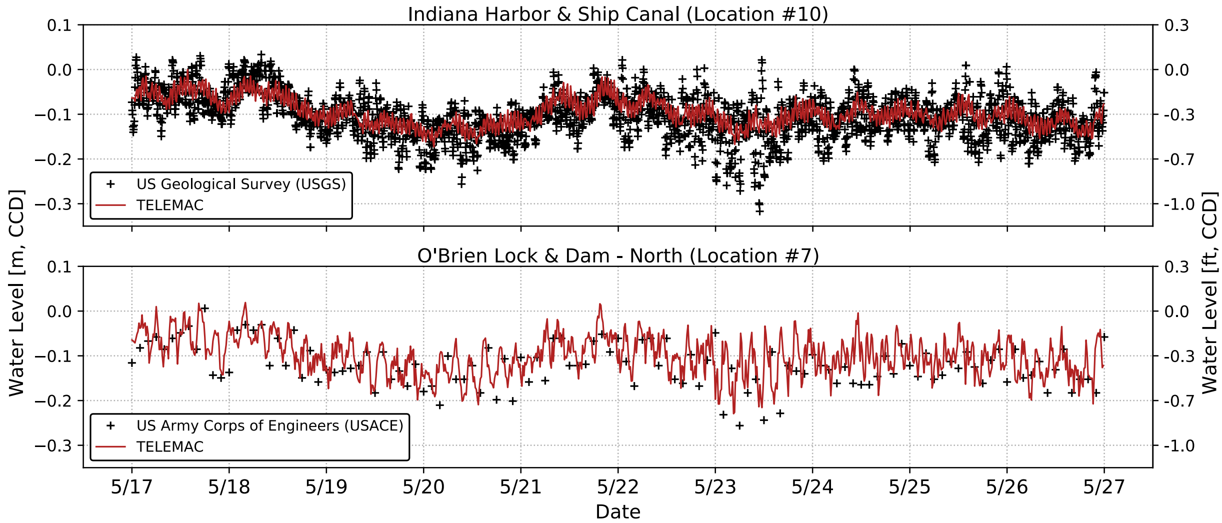

Fig. 3 (*continued*)

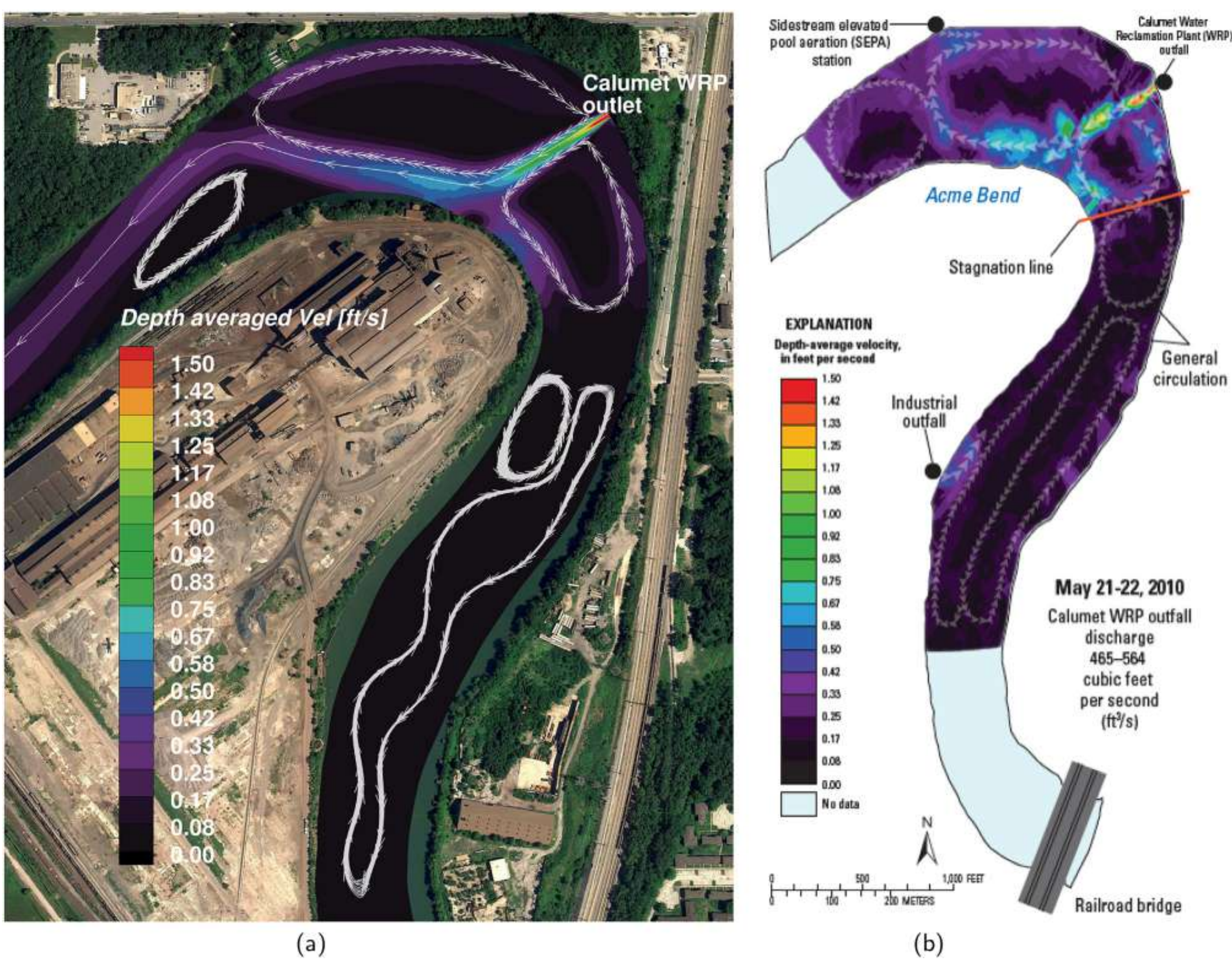

Fig. 4. Flow characteristics in Acme Bend, outflow of Calumet Water Reclamation Plant; (a) numerical modeling results; (b) figure adapted from Jackson and Lageman (2013).

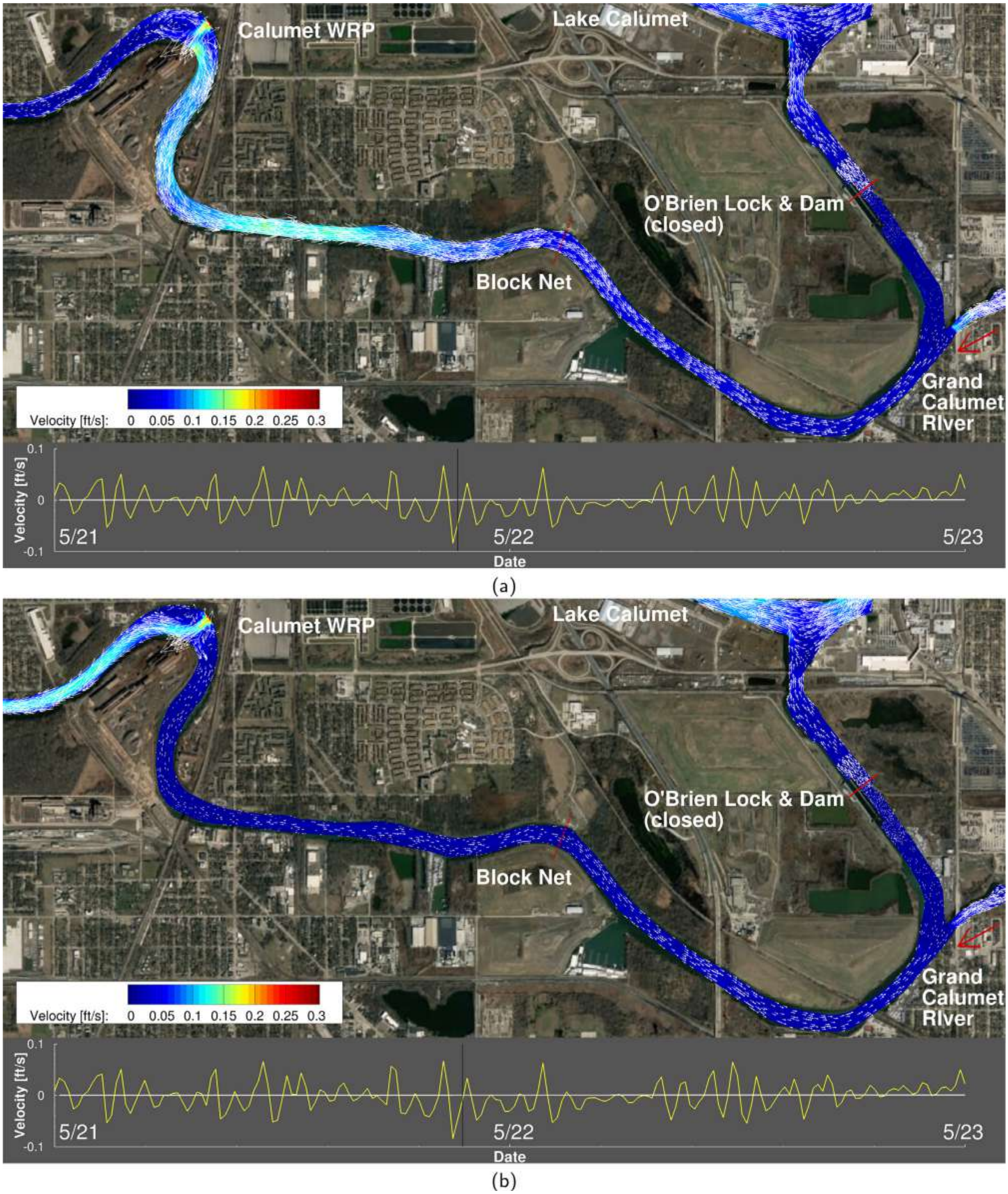

Fig. 5. Bidirectional flow in the Cal-Sag channel. (a) Negative discharge – discharge from Calumet WRP flows towards upstream. (b) Positive discharge – discharge from Calumet WRP flows towards downstream.

3.2. Prediction runs of Calumet Area waterways subsystem in response to lake level rise

Based on the calibrated model, steady-state simulations with different lake levels were performed to compare with the thirty-year measured data series (1991-2021). Different lake levels ranging from −0.46 m (-1.5 ft, CCD) to +1.68 m (+5.5 ft, CCD) were used in the simulations, with intervals of every 0.15 m (0.5 ft). The impact of lake level rise is quantified at the Grand Calumet River, Hammond Waste Water Treatment Plant (WWTP) outfall, Indiana Harbor, and CSSC & Cal-Sag channel junction.

3.2.1. Grand Calumet River West Branch

In the CAWS, discharges in the West Branch of the Grand Calumet River seem to be most affected by changing Lake Michigan water levels. Recent streamflow records (between 2016 and 2021)

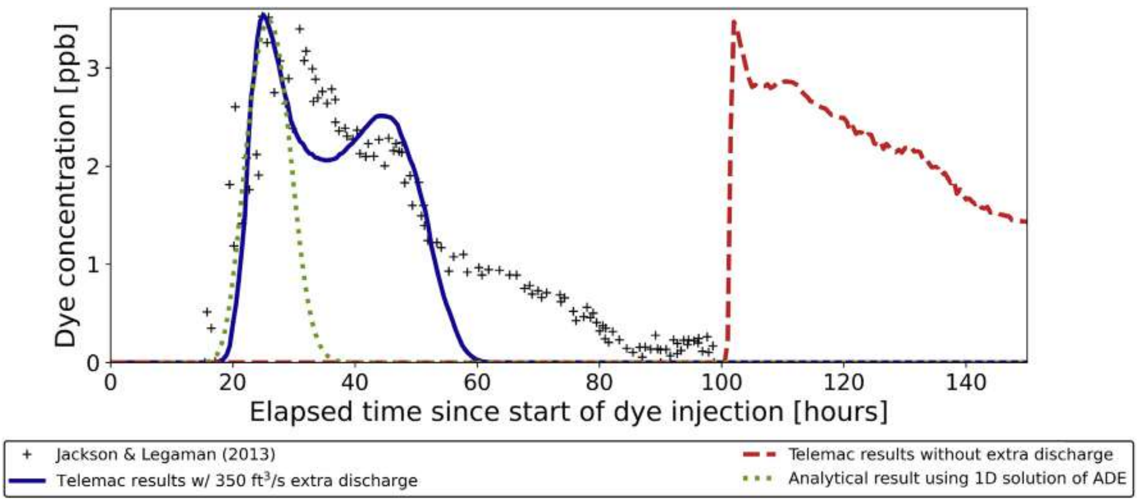

Fig. 6. Dye release concentration at measurement point FL322 with and without the extra flow discharge.

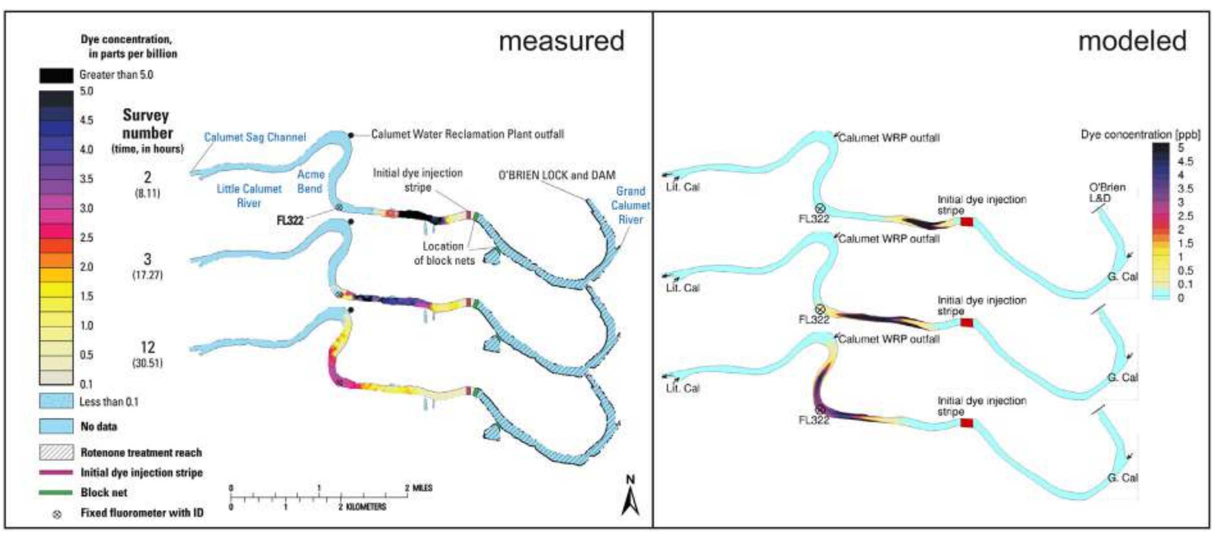

Fig. 7. Comparison between measurements and numerical dye release simulation assuming 9.91 m^3/s (350 ft^3/s) of extra discharge at the Grand Calumet River junction. Left figure adapted from Jackson and Lageman (2013).

for the Grand Calumet River (USGS gaging station 05536357), show that the discharge ranges from 8.5 to 14.16 m^3/s (300 to 500 ft^3/s). In contrast, between 2000 and 2009, the discharge was approximately 0 m^3/s, when the lake level was at −0.3 m (-1 ft, CCD).

The U.S. Environmental Protection Agency (USEPA) conducted multiple dredging operations in the Grand Calumet River from October 2009 through 2016. The river flow was frequently interrupted by these operations. The discharge data from such time periods has been excluded from the validation process. A good agreement is found between the historical data and the numerical model results (see Fig. 9). The coefficients of determination (R^2 score) are around 0.8 for the cases with and without 36 MGD discharge from Hammond WWTP, while the R^2 score is 0.72 for the case of 68 MGD. The slightly higher R^2 scores for the first two cases indicates the possibility that the normal effluent discharge from the Hammond WWTP ranges from 0 to 36 MGD.

The relationship between lake level and the Grand Calumet River discharge is quantified by the numerical model. For lake levels lower than −0.15 m (-0.5 ft, CCD), the Grand Calumet River has around zero flow discharge. For higher values, the discharge keeps increasing and is directly correlated to the Lake Michigan stage. In 2020, when the lake level was at +1.07 m (+3.5 ft, CCD), and there was a mean discharge of 8.5 m^3/s (300 ft^3/s) in the Grand Calumet River flowing into the CAWS. This discharge is included in the flow records for the USGS gaging station 05536890 at CSSC near Lemont, Illinois, indicating that the Grand Calumet River contributed around 9% of the target mean annual discharge of 90.61 m^3/s (3,200 ft^3/s) as specified in the U.S. Supreme Court decree, modified in Wisconsin *v.* Illinois (1980).

3.2.2. Hammond Waste Water Treatment Plant (WWTP)

The flow dynamics near the Hammond WWTP outlet are controlled by the Lake Michigan stage as well (see Fig. 10). Three flow patterns have been summarized as follows. When the lake level is below −0.15 m (-0.5 ft, CCD), the outflow from the Hammond WWTP flows towards the lake. When the lake level is between −0.15 m (-0.5 ft, CCD) and +0.46 m (+1.5 ft, CCD), the outflow splits and flows towards both the CAWS and the lake. When the lake level is higher than +0.46 m (+1.5 ft, CCD), all outflow from the Hammond WWTP flows towards the CSSC. For example, in 2020,

Fig. 8. Tracer simulation near the outflow of the Calumet WRP. The Left figure is the simulation result. The right figure is an aerial image from Google Earth.

due to the relatively high water level of Lake Michigan, the outflow from the Hammond WWTP was continually flowing towards the CAWS. Similar hydraulic behavior has been observed by Espey et al. (2019).

The quantification of the flow split and discharge in the Grand Calumet River West Branch is listed in Table 1. In dry weather conditions with the lake level lower than −0.15 m (-0.5 ft, CCD), the Hammond WWTP mean effluent discharge is around 36 MGD (1.58 m^3/s) flowing towards Lake Michigan. For the same or lower lake levels, under wet weather conditions, the Hammond WWTP runs at its maximum capacity of 68 MGD (2.98 m^3/s) generates a constant discharge of 0.8 m^3/s (28.2 ft^3/s) in the Grand Calumet River West Branch flowing towards the CAWS, Illinois. When the lake level is above +0.46 m (+1.5 ft, CCD), under both dry and wet weather conditions, the effluent from the Hammond WWTP reverses completely and flows towards the CAWS, Illinois.

3.2.3. Indiana Harbor Canal and Grand Calumet River East Branch

The Indiana Harbor Canal hydrodynamics are experiencing a change as well. From the thirty-year historical data between 1991 and 2021, there is an approximately net positive discharge of 14.16 m^3/s (500 ft^3/s) recorded at the USGS gaging station 04092750 in the harbor canal before 2017. Positive discharge indicates discharge from the East Branch of the Grand Calumet River and the harbor area flows towards Lake Michigan. Because the model did not include the effluent from the Water Treatment Plant at East Chicago, and several small ungagged watersheds in that area, it slightly under estimates the discharge in comparison to the measured data (see Fig. 11). The discharge records at this location have large fluctuations, due to the impact of Lake Michigan level variability, changing wind direction, and navigation traffic in/out of the harbor. The measured data is averaged for every 0.15 m (0.5 ft) interval. When the lake level is below +0.91 m (+3 ft, CCD), the model prediction yields a high confidence with a R^2 score of 0.7. Outside this range, the data points are too sparse to observe a clear trend. According to this model's prediction, after July 2019, this discharge was reduced to around 8.5 m^3/s (300 ft^3/s) due to the lake level rise. Similarly, the flow direction in the harbor will be reversed if the lake level is higher than +1.5 m (+5 ft, CCD). At different lake levels, flow patterns at the Grand Calumet River and Indiana Canal junction are different. A simplified graph of this T-shaped junction is shown in Fig. 11, which is the junction at location 15 in Fig. 2. The West Branch of the T-shaped junction is the West Branch of the Grand Calumet River, with Hammond WWTP. The East Branch of the T-shaped junction is the East Branch of the Grand Calumet River, which connects to Gary, Indiana, where there are Gary WWTP and U.S. Steel effluents discharge. The Gary WWTP has a design capacity of 60 MGD (2.63 m^3/s) and a peak capacity of 90 MGD (3.94 m^3/s), while U. S. Steel Plant has capacities of 60 MGD (2.63 m^3/s) for processed water and 200 MGD (8.76 m^3/s) for non-contact cooling water U. S. Army Corps of Engineers, (2000). The north branch of the T-shaped junction is the Indiana Harbor Canal. When the lake level is below −0.15 m (-0.5 ft, CCD) (Case I), discharge from the Hammond WWTP and Gary, Indiana, flows into Lake Michigan. The total discharge is around 15.86 m^3/s (560 ft^3/s). When the lake level is between −0.15 to +0.46 m (between −0.5 and +1.5 ft, CCD) (Case II), part of the effluent from Hammond WWTP will flow into Lake Michigan, and part to the CAWS, Illinois; the entire discharge from Gary, Indiana, would flow into the lake. If the lake level keeps increasing from +0.46 m (+1.5 ft, CCD) up to +1.52 m (+5 ft, CCD) (Case III), the entire effluent from the Hammond WWTP and a portion of the effluent from Gary, Indiana, would split with a part towards the CAWS, Illinois, and a part to Lake Michigan. Lake levels beyond +1.52 m (+5 ft, CCD) (Case IV) lead to negative discharges, which means lake water will start to flow into the Grand Calumet Area and towards Illinois, and all the remaining discharges would also flow towards Illinois.

The conclusion drawn from this model could be seen as an extension of U.S. Army Corps of Engineers (1997) study. For the case lake level less than +0.09 m (+0.3 ft, CCD), the U.S. Army

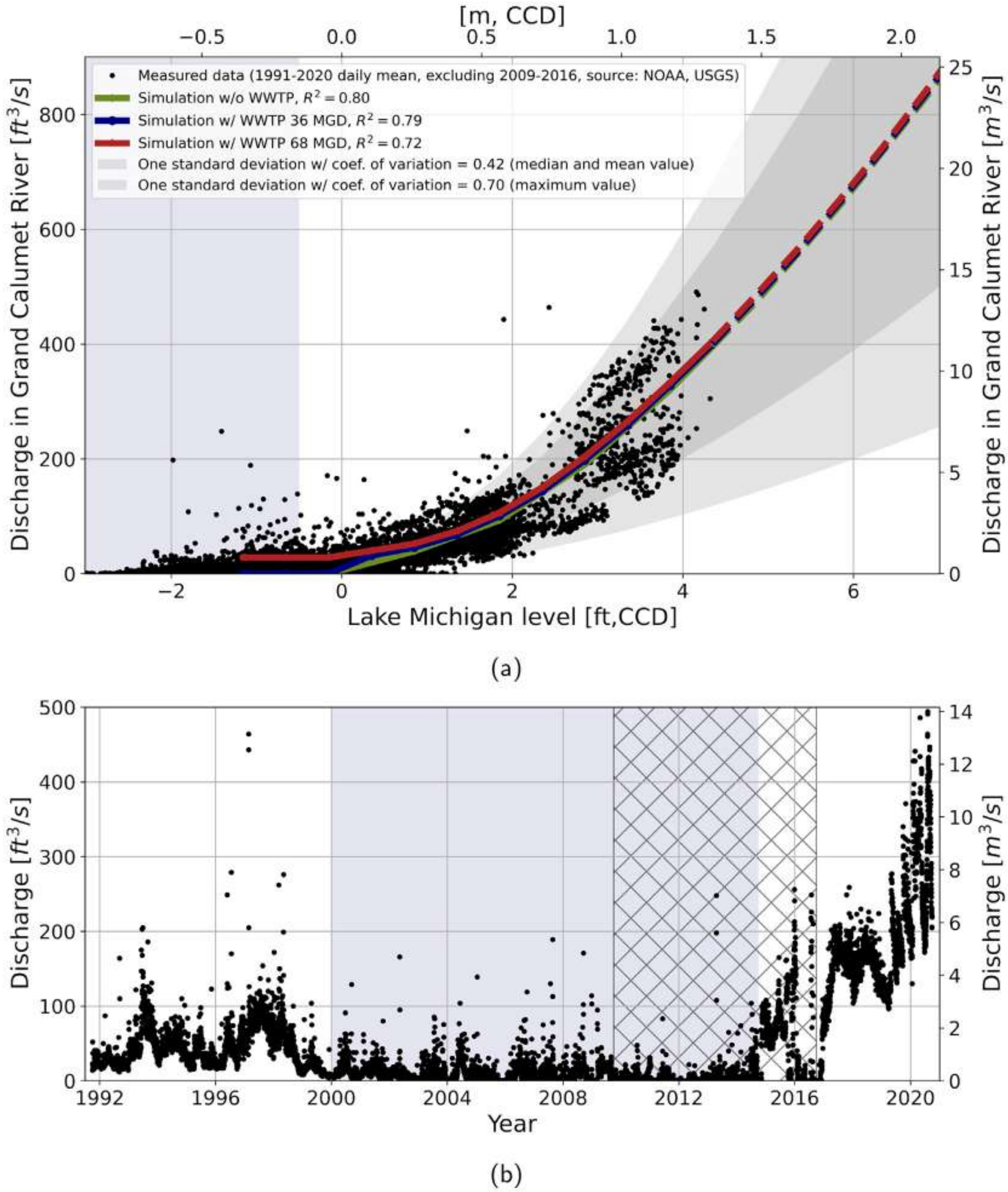

Fig. 9. (a) The Grand Calumet River discharge at different lake stages versus numerical simulation results. The low lake level data (⩽ −0.15 m or ⩽ −0.5 ft, CCD) is recorded between 2000 and 2014 (the period with light blue background). Dashed lines represent the trend predicted by this model. The modeled results reflect the long-term average trend of the system in response to Lake Michigan level changes, but not the actual time-series of lake-level fluctuations. Hence, the actual behavior of the lake would covers a wide spectrum of lake level records (Mortimer, 2004), which cannot be compared to the model results obtained with daily mean lake level data. To obtain a full picture of the actual behavior, further verification and future studies will be needed. The grey shaded area represents the range of one standard deviation with coefficients of variation 0.43 and 0.7, which correspond to the median/mean values and maximum value in the data range, where the lake level is below +1.2 m (+4 ft, CCD). (b) The 30-year time series plot of the Grand Calumet River discharge data recorded at the USGS gaging station 05536357. The period between 2009 and 2016 (cross hatched) is when frequent dredging operations were taking place, and the data is excluded from the analysis.

Corps of Engineers (USACE) equation indicates that 45% of Hammond and Whiting, Indiana, water supply (both treated at the Hammond WWTP) flows towards Illinois. By simulating Hammond WWTP alone and taking the lake level at 0 m CCD, this model predicts 53% of water reaching Illinois. The exact number will depend on the discharge from the Hammond WWTP (see Table 1). For the case of lake level at +0.3 m (+1 ft, CCD), the USACE equation indicates 58% Hammond discharge reaches Illinois, while in this paper, the percentage is between 67% to 100%. For the case of lake level greater than +0.55 m (+1.8 ft, CCD), the USACE equation indicates 100% of Hammond and East Chicago, Indiana, water reaches Illinois, while in this study, the same conclusion was drawn. The main threshold lake level in the USACE report are: at +0.09 m (+0.3 ft, CCD), Lake Michigan starts to have impacts on Hammond WWTP discharge; the Grand Calumet River will experience 100% flow reversal when lake level is between +0.46 and +0.55 m (between +1.5 and +1.8 ft, CCD). In this study, the threshold level of the starting of lake impacts is between −0.15 and 0 m (-0.5 and 0 ft, CCD), and the 100% flow reversal threshold is predicted to be +0.46 m (+1.5 ft, CCD). In general, this study shows a good agreement with the U.S. Army Corp of Engineers (1997) in the range of lake level is between

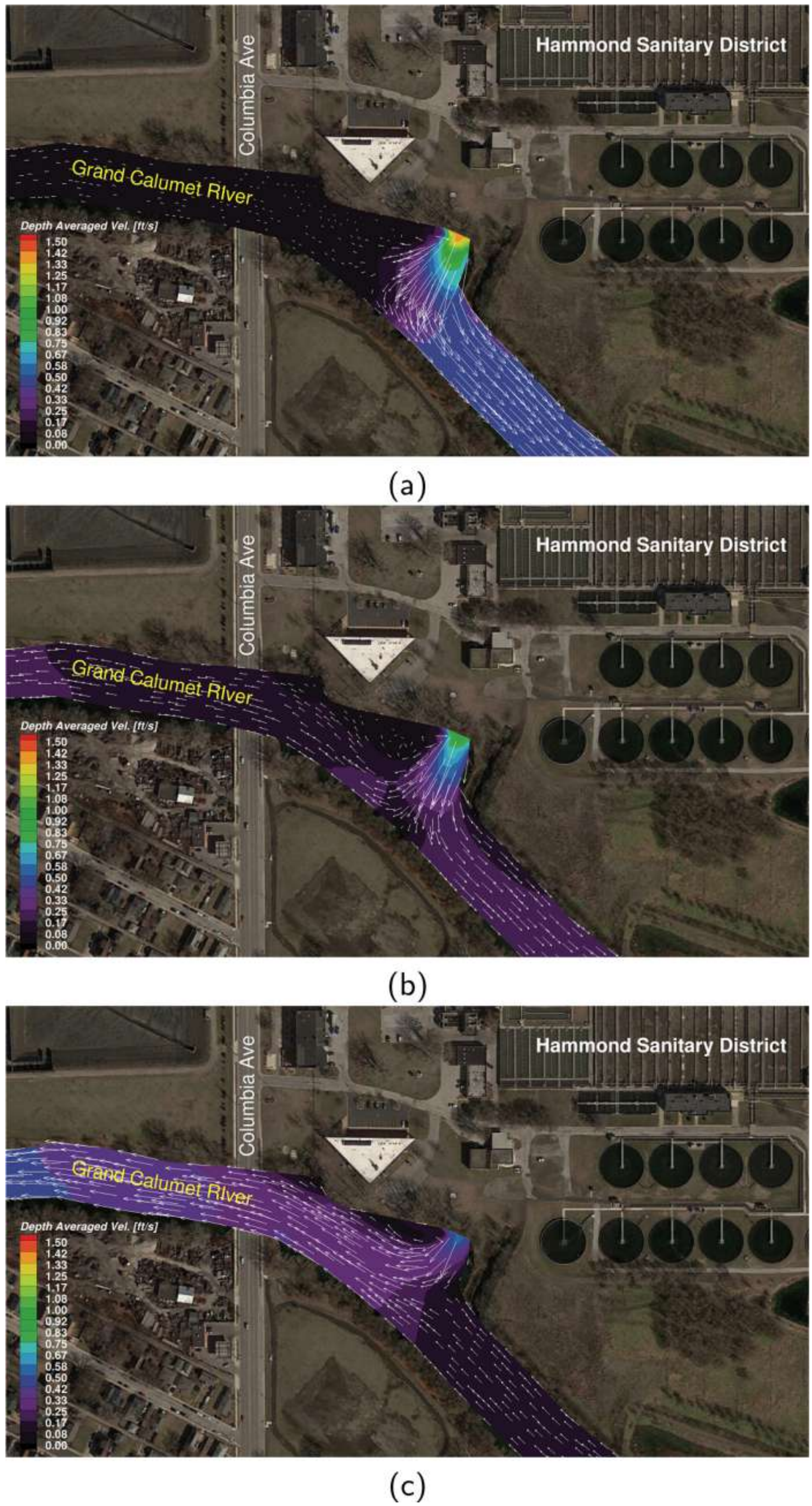

Fig. 10. Grand Calumet River flow dynamics near Hammond WWTP outfall hydraulics relates to Lake Michigan water level; (a) −0.15 m or −0.5 ft, CCD, (b) +0.3 m or +1 ft, CCD, and (c) +0.91 m or +3 ft, CCD.

Table 1
Lake Michigan level induced discharge in Grand Calumet Rivers west branch and its source component. Lake levels below the dashed lines are predicted simulation results, which might require further investigation. These levels have been reached in the instantaneous records; they have not been reached in the daily averaged data. See table in English Units in Electronic Supplementary Material (ESM), Table S1.

Case 1: Hammond WWTP running at 36 MGD (1.58 m^3/s)				
Lake level (m, CCD)	From Hammond WWTP (m^3/s)	From Gary, IN (m^3/s)	From Lake Michigan (m^3/s)	**Total discharge** (m^3/s)
-0.46	0.00	0.00	0.00	0.00
-0.30	0.00	0.00	0.00	0.00
-0.15	0.00	0.00	0.00	0.00
0.00	0.35	0.00	0.00	0.35
0.15	1.05	0.00	0.00	1.05
0.30	1.53	0.00	0.00	1.53
0.46	1.58	0.74	0.00	2.32
0.61	1.58	1.75	0.00	3.33
0.76	1.58	3.09	0.00	4.67
0.91	1.58	4.70	0.00	6.28
1.07	1.58	6.59	0.00	8.17
1.22	1.58	8.50	0.00	10.08
1.37	1.58	10.61	0.00	12.19
1.52	1.58	12.88	0.00	14.47
1.68	1.58	13.88	1.49	16.95
Case 2: Hammond WWTP running at 68 MGD (2.98 m^3/s)				
-0.46	0.80	0.00	0.00	0.80
-0.30	0.80	0.00	0.00	0.80
-0.15	0.80	0.00	0.00	0.80
0.00	0.93	0.00	0.00	0.93
0.15	1.27	0.00	0.00	1.27
0.30	1.72	0.00	0.00	1.72
0.46	2.49	0.00	0.00	2.49
0.61	2.98	0.51	0.00	3.49
0.76	2.98	1.87	0.00	4.85
0.91	2.98	3.48	0.00	6.46
1.07	2.98	5.36	0.00	8.34
1.22	2.98	7.25	0.00	10.23
1.37	2.98	9.37	0.00	12.34
1.52	2.98	11.64	0.00	14.62
1.68	2.98	13.88	0.23	17.09

0 m and +0.55 m (between 0 ft and +1.8 ft, CCD). In addition, the new model provides a broader range of predictions on Lake Michigan level (between −0.46 m and +2.13 m, or between −1.5 ft and 7 ft, CCD), which includes the 120-year historical high lake level that was not considered in U.S. Army Corp of Engineers (1997). This study also considered discharge from Gary, Indiana, which is not shown in the USACE equation.

4. Implications to flood, navigation, diversion accounting, and water quality management in the Chicago Sanitary and Ship Canal (CSSC)

4.1. Implications to flood and navigation management in CSSC

From the analysis at different locations in the Calumet Area waterway subsystem, which is also called the southern CAWS, the rise in the Lake Michigan water-surface elevation will lead to a net discharge increase in the CSSC, which is downstream of this subsystem. A net discharge increase ranging from 0 m^3/s to 17 m^3/s (600 ft^3/s) is analyzed in this section. The Hydraulic Performance Graph (HPG) analysis developed with the HEC-RAS model (Yen and González-Castro, 2000; Rojas-Aguirre et al., 2019) suggests that an increase of the water surface gradient between the CSSC & Calumet-Sag channel junction and Lockport Power House (LPH) is required to convey this extra net discharge along the CSSC, see Fig. 12. Based on the numerical modeling results, in extreme lake conditions, when the lake level reaches 1.68 m (+5.5 ft, CCD), an extra 17 m^3/s (600 ft^3/s) discharge will be delivered to the CSSC through the Cal-Sag Channel. Under the condition of high stream flows coming from the northern part of the CAWS, a higher hydraulic gradient is required to convey the same amount of additional flow discharge (coming from the Cal-Sag channel) than for low stream flow conditions. For the case of 311.49 m^3/s (11,000 ft^3/s) coming from the northern part of the CAWS, approximately 0.15 m (0.5 ft) difference in water surface elevation is required to convey this extra discharge; whereas 0.03 m (0.1 ft) difference is required when the flow coming from the northern CAWS is 90.61 m^3/s (3,200 ft^3/s).

To evaluate the impact of the water elevations in the northern part of the CAWS due to the extra flow discharge induced by high lake level, the HPGs are developed from the junction of the North Shore Channel and the North Branch Chicago River (J. North Shore Channel) to Lockport Power House (LPH), considering the normal operation of the CAWS (Fig. 13). The following are the assumptions to assess the impact in the northern part of the CAWS: (1) water elevation at LPH is fixed at −2.44 m (-8 ft, CCD); (2) a constant flow discharge of 311.49 m^3/s (11,000 ft^3/s) is assumed along the CSSC reach between Cal-Sag-CSSC junction (J. Cal-Sag) and LPH; (3) a constant flow discharge of 169.9 m^3/s (6,000 ft^3/s) originated from the northern part of CAWS and 56.63 m^3/s (2,000 ft^3/s) from Bubbly Creek; and (4) a constant flow discharge of 84.95 m^3/s (3,000 ft^3/s) coming from the Cal-Sag channel. Under the these conditions, the water surface elevation expected at the J. North Shore Channel is 1.44 m (4.74 ft, CCD), while the elevation at Wolf Point is 0.12 m

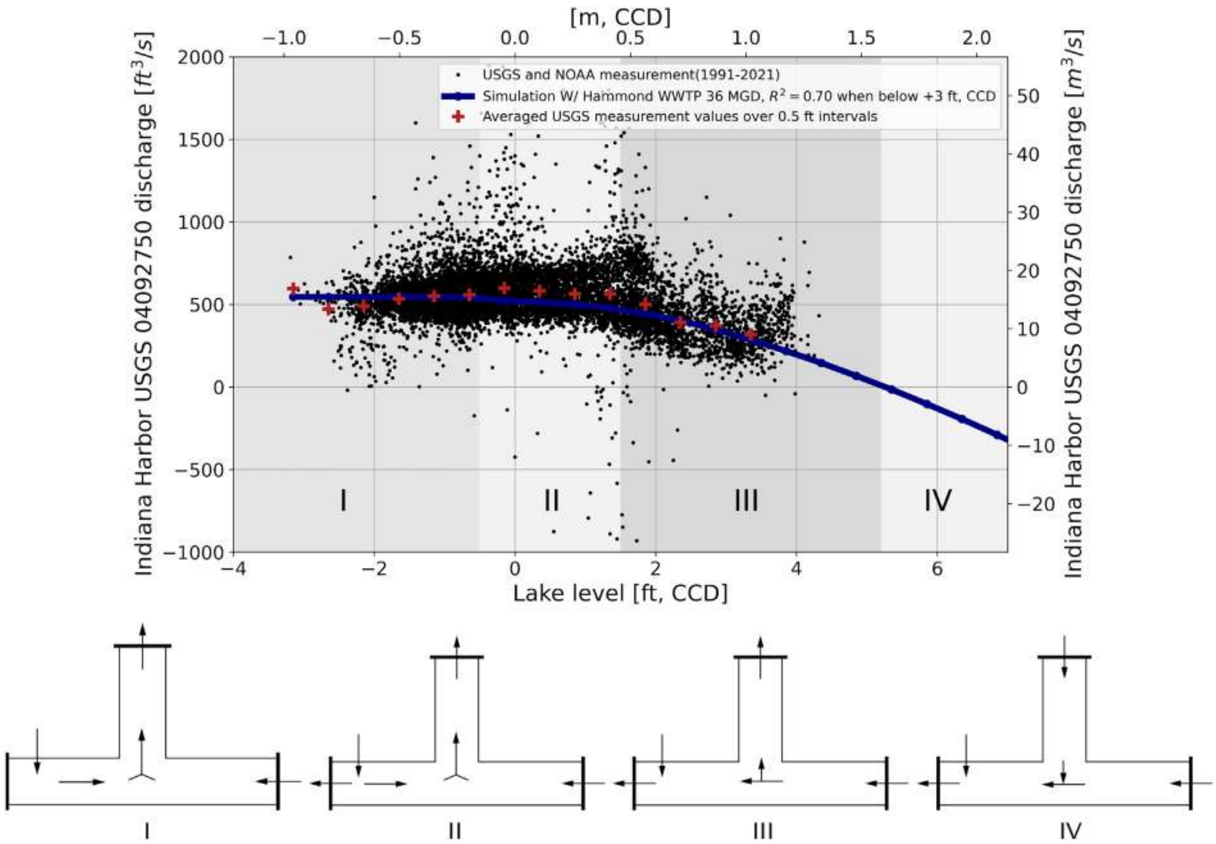

Fig. 11. Indiana Harbor discharge at different lake stages. Negative discharge means the Indiana Harbor Canal is taking water from Lake Michigan. The lower four figures represents the hydrodynamic condition at the Indiana Harbor Canal junction (at Location 15 in Fig. 2). North side is the Indiana Harbor Canal; East side is the Grand Calumet River East Branch from Gary, Indiana; West side is the Grand Calumet River West branch and the Hammond WWTP. After 2019, this junction is under condition III, when lake level is above 0.6. m (2 ft, CCD).

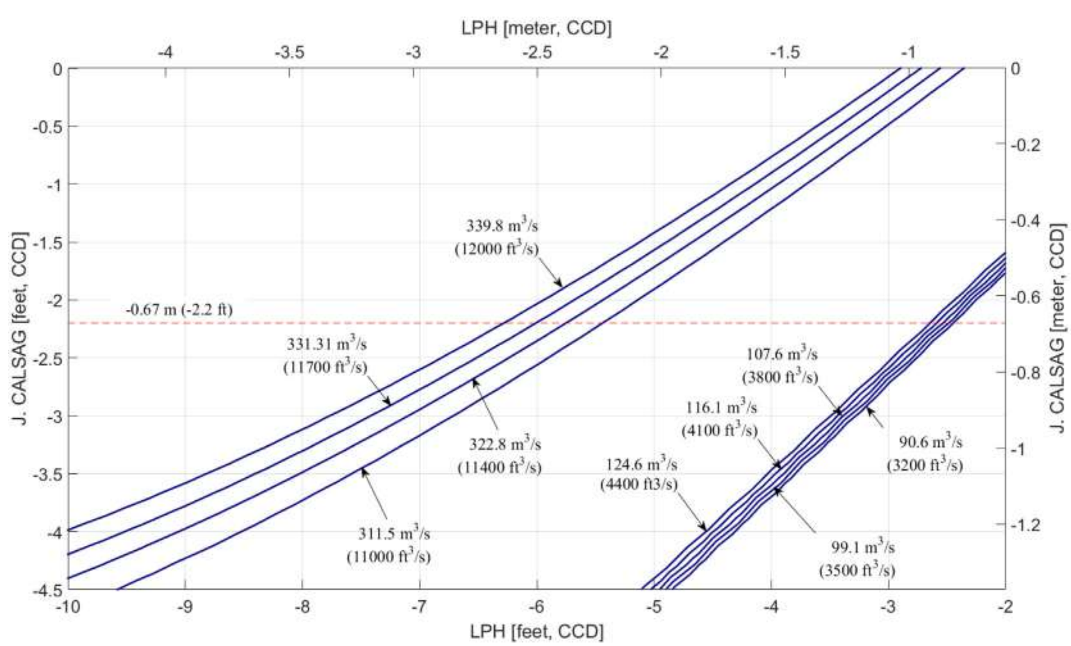

Fig. 12. Hydraulic Performance Graphs (HPG) from CSSC & Calumet-Sag channel junction (J. Cal-Sag) to Lockport Power House (LPH), Illinois. Red dashed line is the CSSC–Cal Sag junction average level.

(0.4 ft, CCD) (see blue arrows in Fig. 13). With the extra flow discharge (17 m^3/s, or 600 ft^3/s) coming from the Grand Calumet River, the water surface elevations at J. North Shore Channel and Wolf Point increased to 1.47 m (4.84 ft, CCD) and 0.18 m (0.6 ft, CCD), respectively (see red arrows in Fig. 13). Therefore, through this analysis, the extra flow discharge could lead to an increase

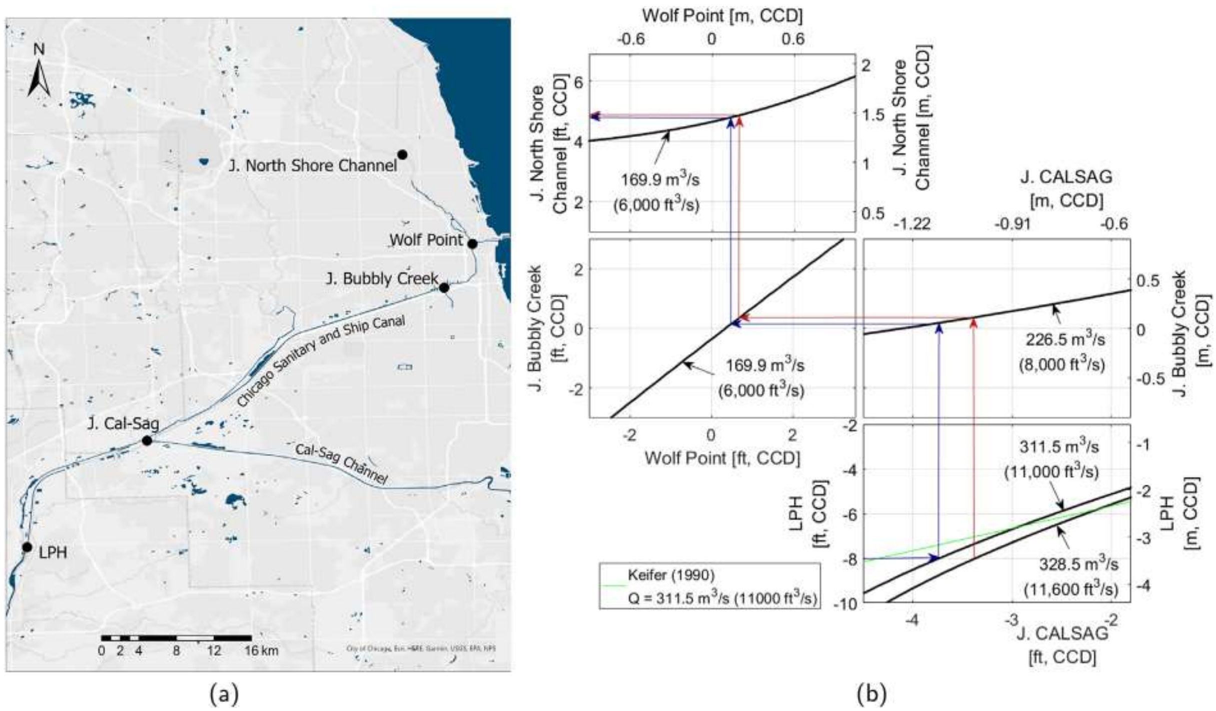

Fig. 13. (a) Key locations in the HEC-RAS model (Rojas-Aguirre et al., 2019), which is used to compute Hydraulic Performance Graphs (HPGs) developed from the junction of North Shore Channel and Chicago River North Branch (J. North Shore Channel) to Lockport Power House (LPH). (b) The HPG analysis along with the curve derived by Keifer (1990) for Q = 311.49 m^3/s (11,000 ft^3/s).

of the water level of 0.03 m (0.1 ft) at the North Shore channel and 0.06 m (0.2 ft) at Wolf Point. This would seem to indicate a very small impact on flood stages induced by the additional flow discharge contributed through the Cal-Sag Channel from the Calumet Area. This HPG analysis provides a general trend of the northern CAWS under the high lake level conditions. Detailed event based hydrodynamic analysis will be needed to accurately estimate such impacts.

4.2. Implications to State of Illinois Lake Michigan Diversion Accounting (LMDA)

According to the model, in 2020, the portion of water coming from the Grand Calumet River and its surrounding area accounted for 9% of the State of Illinois allowable Lake Michigan diversion. With a rising lake level, this percentage could reach up to 19%. The water management rules might need adjustment accordingly, since the flow coming from Indiana should not be counted towards the water diversion by Illinois.

In the modeling analysis, in order to advect the dye plume towards location FL322 17 h after the initial release, the flow in Cal-Sag Channel needs to have an average advection velocity of 0.046 m/s (0.15 ft/s). This speed corresponds to the net extra discharge of 9.91 m^3/s (350 ft^3/s) in the channel. Under the "zero-flow condition", the dye plume is not advected westward at the measured speed. The Jackson and Lageman (2013) report has also discussed this unachievable "absolute zero-flow condition". The plan view comparison of the plume between the measured results and numerical model has proved the correctness of this hypothesis (see Fig. 7). Attempts to apply other magnitudes of extra discharge were made, but the numerical results cannot match the measured data. There are potentially three possibilities for the source of this extra 9.91 m^3/s (350 ft^3/s) discharge: (1) unknown outfalls in Cal-Sag Channel, (2) the Grand Calumet River, and (3) O'Brien Lock and Dam structure leakage.

One possible source of this extra discharge is unknown outfalls along the Cal-Sag Channel. The Fig. 4(b), which is adapted from Jackson and Lageman (2013), has demonstrated one location of such outfalls. Because this particular outfall is located downstream of FL322, it has limited impact on the dye plume speed; it is suspected that there are more outfalls in this area that could contribute to such extra discharge.

During the dye release experiment, Jackson and Lageman (2013) measured one instantaneous flow discharge of 3.51 m^3/s (124 ft^3/s) at the Grand Calumet River junction. Although the USGS gaging station on the Grand Calumet River recorded a low flow discharge (ranging from 0.03 to 0.57 m^3/s or from 1 to 20 ft^3/s) during this time, due to the dredging operations in the west branch of the Grand Calumet River between Hohman Ave and Columbia Ave (Grant, 2019), the measured flow discharge data are not reliable. It is possible that during the dye release period, the Grand Calumet River contributed to the extra discharge. The high uncertainty in the Grand Calumet discharge measurement points to the importance of having a better understanding of the hydraulics in the Grand Calumet River area, and was one of the motivations to conduct this numerical modeling effort. The combined discharge from unknown outfalls in Cal-Sag Channel and the Grand Calumet River could be around 5.66 m^3/s (200 ft^3/s). Further investigations on the outfalls in Cal-Sag Channel and on discharge rating under the post-dredging condition in the Grand Calumet River will be needed.

The third possibility is that there is leakage coming from the O'Brien Lock and Dam hydraulic structures. The report by Oberg and Schmidt, 1994 confirms the existence of the leakage; this magnitude was estimated to be around 4.25 m^3/s (150 ft^3/s). According to the Fifth and Eighth Technical Committees on LMDA (Espey et al., 2019): "*AVM and ADCP measurements at the O'Brien Lock and Dam AVM gage suggest that there is considerable (100 ft^3/s or more) leakage through the structure. Such leakage will likely increase as lake levels rise.*" While the magnitude of the leakage is estimated in Espey et al. (2004) as: "*...there is potentially significant leakage (149 ft^3/s)*

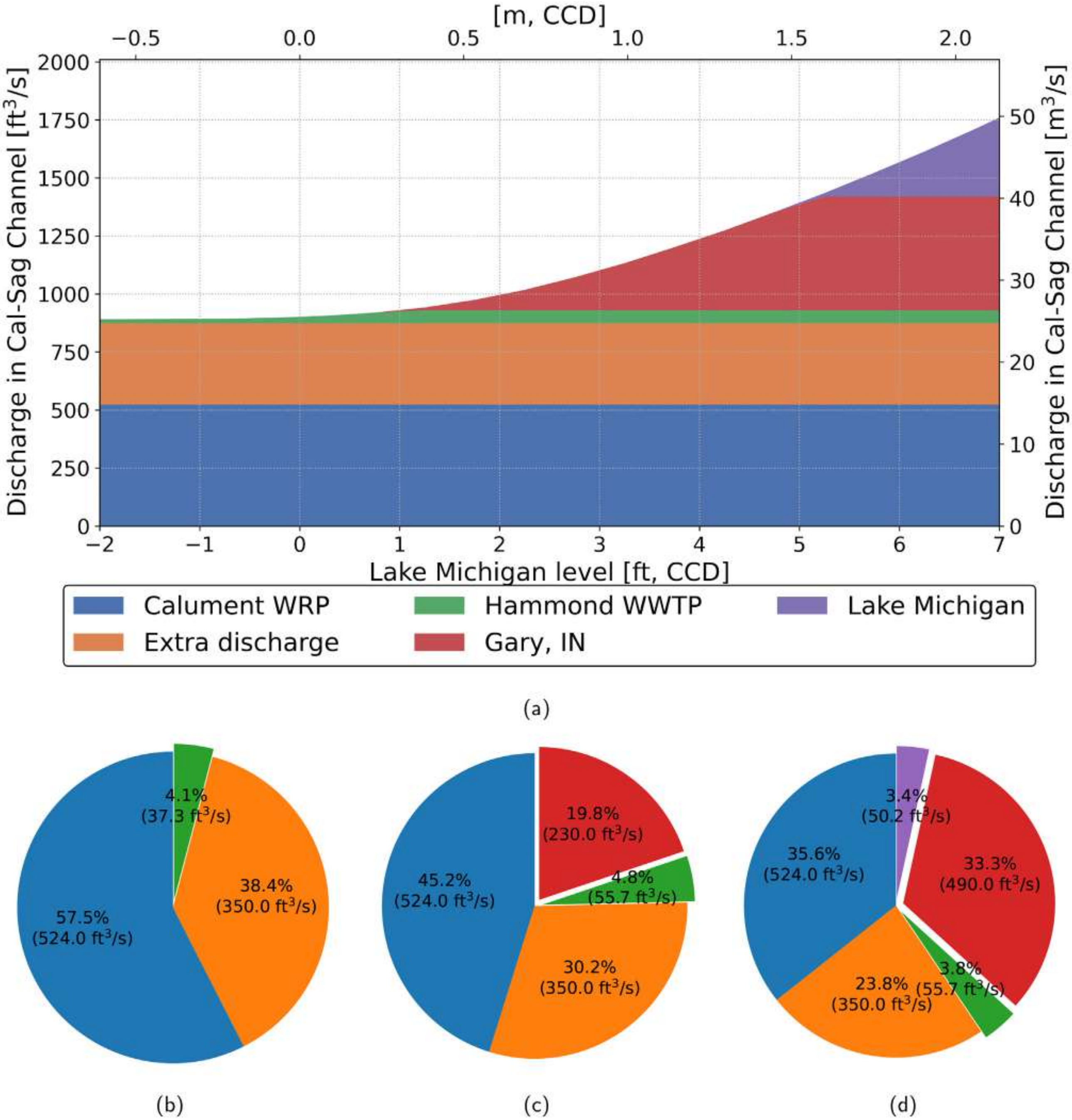

Fig. 14. Major flow components in the Calumet-Sag channel in the southern CAWS at different lake levels. (a) Discharge component at different lake level condition. (b) At +0.15 m (+0.5 ft, CCD), the total discharge from Grand Calumet River contributes 4.1%. (c) At +1.07 m (+3.5 ft, CCD), the total discharge from Grand Calumet River contributes 24.6%. (d) At +1.68 m (+5.5 ft, CCD), the total discharge from Grand Calumet River contributes 40.5%.

past the (O'Brien) lock and dam." These investigations were done 10 years prior to the report by Jackson and Lageman (2013), therefore, with the lake level rising in recent years, this leakage might need to be re-evaluated, as pointed by Espey et al. (2019).

Such an extra discharge, if exists, would be measured at the USGS near Lemont streamgage, and would account for another 11% of total allowable diversion. Further investigations might be needed.

4.3. Implications to water quality and source of water in CSSC

From this study, the water source components in the Calumet Area can be identified. When lake level is lower than −0.15 m (-0.5 ft, CCD), the Calumet Area subsystem contributes around 25.49 m^3/s (900 ft^3/s) discharge towards the CSSC, in which 14.84 m^3/s (524 ft^3/s) are from Calumet WRP, and 9.91 m^3/s (350 ft^3/s) are from other unknown sources (discussed in Section 3.1 and 4.2). When the lake level rises to the range between −0.15 m and 0.46 m (between −0.5 ft and +1.5 ft, CCD), a portion of the Hammond WWTP discharge will change direction and flow towards the CSSC. If the lake level is at the range from +0.46 m to +1.52 m (from +1.5 ft to +5 ft, CCD), discharge from the City of Gary, IN, will flow towards Illinois. If the lake level is higher than +1.52 m (+5 ft, CCD), lake water will start to flow into the Indiana Harbor through the Grand Calumet River into the CAWS (see Fig. 14). Under the high lake level condition, up to 40% of Cal-Sag

Channel flow would come from the Grand Calumet River. In 2020, for example, the lake level was between +0.91 m and +1.22 m (between +3 ft and +4 ft, CCD); there was a base flow discharge of 8.5 m^3/s (300 ft^3/s) from the Grand Calumet River towards the CSSC. It is a known fact that the Grand Calumet River area is listed as one of the 19 AoC due to its water quality and historical pollution. With larger discharge from the area each year, its impact on water quality in the CAWS and the downstream Illinois River Basin needs to be carefully examined. In particular, the amount of nutrients delivered by the Grand Calumet River when flowing towards Illinois, needs to be quantified given the ongoing efforts to reduce unnatural algae growth in the CAWS.

4.4. What would happen if Lake Michigan level is higher than +1.68 m (+5.5 ft, CCD)?

In this study, the scenarios with Lake Michigan higher than +1.68 m (+5.5 ft, CCD) are not considered. From the records of the USACE, the top level of the Chicago Lock in downtown Chicago is at the level of +1.43 m (+4.7 ft, CCD), while the ground level of Chicago River Controlling Works is at around +1.68 m (+5.5 ft, CCD). If Lake Michigan levels reach above this level, the city of Chicago will require extra risk assessment along the entire lakefront of the Metropolitan Area. Analysis in the south CAWS alone will not be sufficient to complete such a risk assessment.

It is not impossible for Lake Michigan to reach an extremely high lake level, i.e., +2.13 m to +2.44 m (+7 to +8 ft, CCD), according to the historical data. Great Lakes climate researchers have recently adjusted their projections of Lake Michigan level in mid- and late-21st century from "large drops in lake level" to "very modest drops in lake levels and the appreciable probability of small rises" (Wuebbles et al., 2019). It has been proven that predicting the Lake Michigan levels even for the near future is difficult. However, from studies using geological time scales, Lake Michigan level has been continuously reaching +2.44 m (+8 ft, CCD), with periods of every 200 to 500 years (Colman et al., 1994). Although in 2020 Lake Michigan reached its highest level in the past 120 years, because the climate is changing drastically at the beginning of this century, there might be a possibility that it will keep rising to a peak level (e.g., +2.44 m or +8 ft, CCD) in this century. We recommend a comprehensive risk assessment on the adverse impact of extreme high lake level conditions in the Chicago Metropolitan Area.

5. Conclusions and proposed future investigations

This study has provided predictions from a calibrated and validated numerical model for the hydraulics in southern CAWS. The model includes part of Lake Michigan in the simulation domain, which is the first of its kind for this area. Through a series of numerical analyses, an understanding of the long-term trends of the local hydrodynamics in response to the slowly varying Great Lakes climate has been gained. Because of the constant open connection with Lake Michigan through the Indiana Harbor Canal and the Grand Calumet River, the hydrodynamics in this area is highly correlated to Lake Michigan water levels. When the lake level is lower than −0.15 m (-0.5 ft, CCD), the lake has very little influence on the local hydraulics. After lake level passes −0.15 m (-0.5 ft, CCD), an extra base flow discharge up to 17 m^3/s (600 ft^3/s) could be generated in the Grand Calumet River towards the CAWS, Illinois. This high lake-level induced extra discharge will impact the Lake Michigan Diversion Accounting (LMDA) at Lemont, Illinois, and change the water surface elevations in the CSSC. Both flood control and navigation in the City of Chicago will be influenced. A quantified study of these impacts will be performed in future work. Although this model quantifies the long-term average trend of the system, to better understand the combined effect that short-term wind-induced fluctuations, periodic oscillations due to lake seiches, as well as storm surges have on the observed bidirectional hydrodynamics of the Grand Calumet River, further modeling and field observations are required. The impact of the Grand Calumet River discharge on the CAWS and the downstream Mississippi River basin water quality needs further investigation. Its impact on invasive species prevention facilities, such as the electrical barriers, also remains to be investigated, since new species from the Great Lakes could gain access into the CAWS and eventually reach the Des Plains, Illinois and Mississippi Rivers. Studying the impact of past and recent dredging projects on the flow conveyance capacity of the Grand Calumet River should be done to further improve the model and better understand the impact of high Lake Michigan water levels on the CAWS and the Illinois River.

CRediT authorship contribution statement

Dongchen Wang: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft. **Zhi Li:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - review & editing. **Andrés F. Rojas-Aguirre:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - review & editing. **Marcelo H. García:** Supervision, Project administration, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jglr.2021.10.008.

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