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Creating an Operational Forecasting System for the Chicago River

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Prologue

The evening of May 17, 2020, a slow-moving band of heavy thunderstorms moved through the Chicago metro area in northeast Illinois. Widespread rainfall amounts of 3-4 inches, with isolated amounts up to 5 inches, occurred from the afternoon of May 17 to the morning of May 18. The days leading up to this event were very wet, with 5-day rainfall totals ranging from 4-8 inches by May 18, a very rare amount for May[1]. Prior to the thunderstorms of May 17, soil moisture was above average, rivers were elevated, and the storage capacity of Metropolitan Water Reclamation District's (MWRD's) tunnels and reservoirs was exhausted. The result was widespread flooding across the southern half of the Chicago metro area. The lack of storage capacity for rainfall in Chicago's combined sewer area caused the majority of the rainfall to head to the Chicago River as part of a combined sewer overflow (CSO) event, which eventually caused the Chicago River to near major flood stage and reach levels not seen since October 1954. Multiple roadways and structures were flooded near the Chicago Loop.

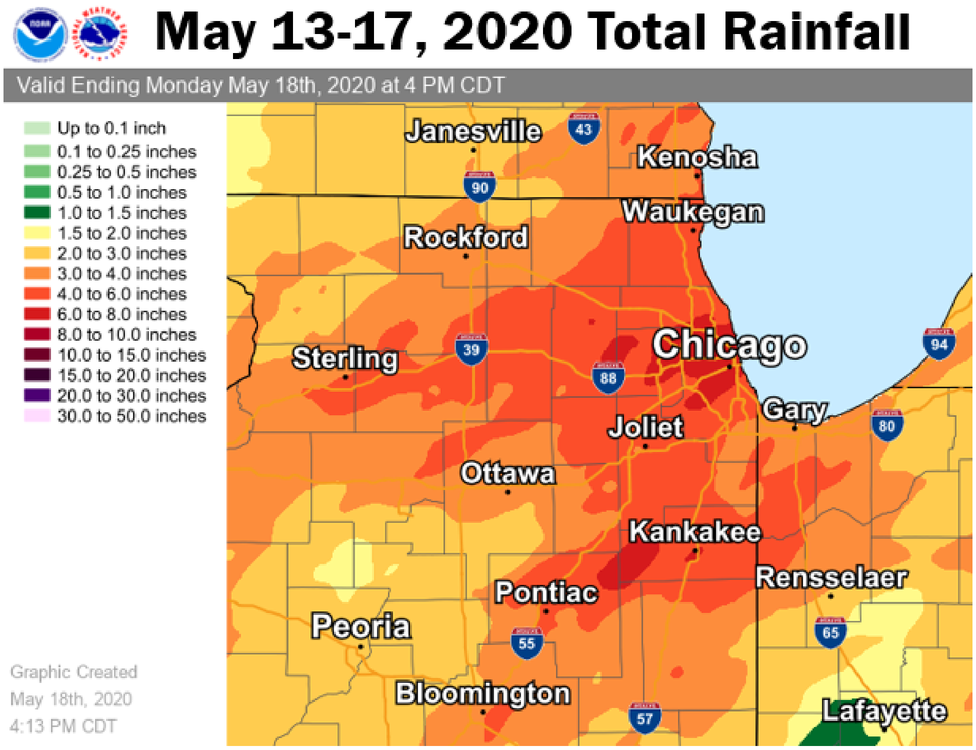

Figure: Radar-estimated rainfall bias corrected to gauge observers for the 5-day period from the morning of May 13, 2020, to the morning of May 18, 2020.

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[1] By May 19, 2020, Chicago's month-to-date rainfall had already broken the previous record for May rainfall set just one year prior (8.25 inches). By the end of May, the monthly rainfall total increased to 9.51 inches, breaking the previous record by over 1 inch. The 8.2 inches that were observed at Chicago over the 1-week period from May 13 to May 19 was the wettest May week in history, breaking the previous record by almost 3 inches.

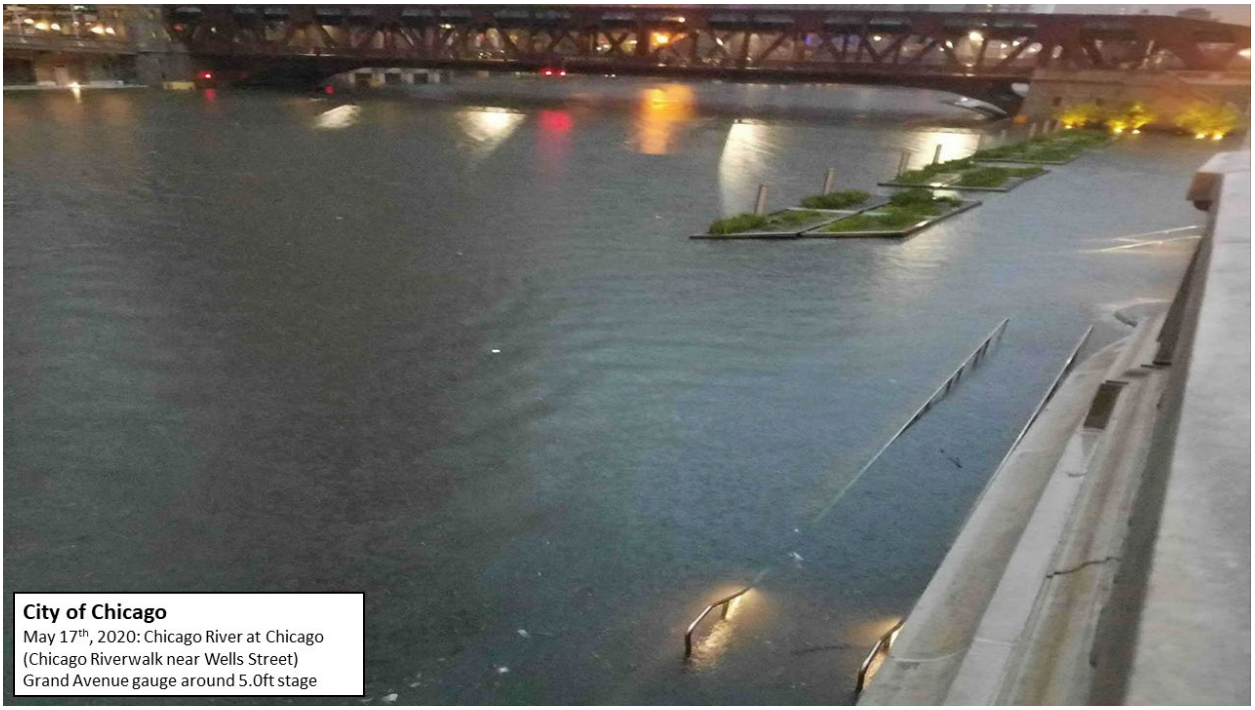

Figure: Flooding of the Chicago Riverwalk along the Chicago River near Wells Street. Photo credit: City of Chicago.

The May 2020 flood event became the impetus for a 2+ year effort to establish river forecast services for the Chicago River and the associated Chicago Sanitary and Ship Canal. On May 28, the city of Chicago held an after-action review for the flood event. Possible changes to the flood impact categories for gauges on the Chicago River were discussed, along with the potential to provide river forecasts. On June 24, a follow-up meeting was held with the city of Chicago where it was officially requested that action stage and minor flood stage be adjusted downward based upon additional observations collected from the May 17 flood event. On June 30, the city of Chicago made a formal request to the National Weather Service (NWS) Chicago office to establish river forecast services for the Chicago River, which was forwarded to the North Central River Forecast Center (NCRFC) which would ultimately have responsibility for running any forecasting models. NWS Chicago held a conference call with the US Army Corps of Engineers (USACE) Chicago District on August 5, where past modeling efforts on the Chicago River and Chicago Sanitary and Ship Canal were discussed. A very preliminary modeling framework was created and discussed.

On October 9, NWS Chicago held a conference call with the city of Chicago, MWRD, and USACE Chicago to discuss progress on the potential to provide forecast services for the Chicago River. The potential development framework was presented and revised. Subsequently, NWS Chicago used the framework for future development to create two sub-teams - a data acquisition group and a modeling group. The data acquisition group was tasked with finding a way to get real-time water level information from MWRD tunnels and reservoirs to the NWS for use in forecasting. The modeling group was tasked with reviewing hydrologic and hydraulic models already previously built for the Chicago waterway and then determining how to adapt these models for operational use. Between October, 2020, and December, 2021, NWS Chicago facilitated numerous meetings with each of these groups and led the effort to develop an operational forecasting model for use by NCRFC. While developing the more sophisticated methods for operational forecasting, a correlation was found between 1-day rainfall, tunnel and reservoir storage, and the Chicago River crest. This led to the start of river forecast services on April 15, 2021, using a simplified technique that was implemented by NWS Chicago staff.

Development on the more sophisticated modeling framework referenced in this report was completed and provided to NCRFC in December of 2021 to add to their operational modeling system. The completed method for operational modeling of the Chicago River included a hydrologic model coupled with a hydraulic model. This report documents the development process taken at NWS Chicago to create and verify this modeling framework, including the data sources, assumptions, and known issues.

1.0 Introduction/Background

Although some models of the complex hydrology of the Chicago River have previously been developed, these models are far too complex for operational forecasting. Existing models were designed for study purposes, namely, the Great Lakes and Mississippi River Interbasin Study (GLMRIS; US Army Corps of Engineers 2014). This study was conducted to examine the feasibility of separating the Lake Michigan watershed from the Illinois River watershed to limit the movement of invasive species. Because of the high resolution utilized and the complexity of these models, processing time is on the order of several hours. In contrast, optimal run times for river forecasting models for operational purposes are on the order of seconds to a minute or so. Significant simplification of the modeling approach for the Chicago River was thus required to develop an operational forecasting system for the Chicago River. For the purposes of this report, "reasonable" results generally mean model run times of approximately 1 minute or less (covering a 4-week period), forecasted peak elevation values within approximately 0.5 feet, and forecasted peak streamflow values within about 20%. The steps taken to develop, calibrate, and verify such a model are described.

1.1 Existing Models

Existing Hydrologic Engineering Center River Analysis System (HEC-RAS) models of the Chicago River and associated Chicago Waterway were provided by the US Army Corps of Engineers (USACE) Chicago District (LRC) and the Metropolitan Water Reclamation District of Greater Chicago (MWRD). Both HEC-RAS models were quite similar, due to their basis in the same study (GLMRIS). The HEC-RAS models of the Chicago Waterway were just part of the overall model system required to simulate a precipitation event in the area, however. Modeling of the Chicago Waterway involved multiple components, including:

- Hydrologic modeling of surface runoff in ungauged areas using the Hydrologic Simulation Program Fortran (HSPF)
- Hydrologic modeling of surface runoff in gauged tributary areas using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) software.
- Hydraulic modeling of the combined sewer flow headed for water reclamation plants and waterways using the Tunnel NETwork Program (TNET)
- Hydraulic modeling of the Chicago Waterway channels using HEC-RAS

Because existing models were used for study purposes, model run time was not as important as model accuracy and precision. Model run times for single rain events (spanning several days) was on the order of hours, which precluded their use in operational forecasting. Models such as TNET and HSPF are also not used in NWS operations, and it would require substantial work to connect them with the Community Hydrologic Prediction System (CHPS) at NCRFC.

1.2 Requirements for an Operational Model

Because existing models cannot be used as-is for operational forecasting, new models must either be developed from scratch, or adapted from existing models. The general requirements for a Chicago River operational forecasting model include:

- Processing time around 1 minute or less. The shorter, the better to open up additional modeling opportunities such as Ensemble Streamflow Prediction (ESP) and Hydrologic Ensemble Forecasting System (HEFS).
- Model can work with the version of the Hydrologic Engineer Center River Analysis System (HEC-RAS) software in Community Hydrologic Prediction System (CHPS).
- Hydrologic modeling can be converted to Sacramento Soil Moisture Accounting (SAC-SMA) in CHPS.
- Significantly reduced complexity for ease of future development and maintenance.
- Significantly reduced number of boundary conditions.

1.3 General Overview of Chicago River Hydrology

The hydrology of the Chicago River and associated waterways is particularly complex due to a substantial amount of human alterations which began as far back as the early 1800s. Before (European) settlement, the Chicago River was a separate basin from the Illinois and Upper Mississippi basins, except during very high water on the Des Plaines River when flooding crossed the Mud Lake wetland (Figure 1). Construction of the Illinois-Michigan Canal and the later Chicago Sanitary and Ship Canal bridged the drainage divide near Mud Lake and reversed the flow of the Chicago River, causing some of Lake Michigan to flow west through the Chicago area. Some water in the Calumet River Basin was also captured after construction of the Calumet-Saganashkee (Cal-Sag) Channel, prior to which water flowed entirely into Lake Michigan. The North Shore Channel was also constructed to provide additional flow from Lake Michigan which further diluted wastewater from Chicago. An illustration today’s waterways, primary stream gauges, and major lock structures is shown by Figure 2.

These early human alterations were followed by the construction of the Chicago Lock, O’Brien Lock, and Wilmette Controlling Works at the Lake Michigan outlets of the Chicago River, Calumet River, and North Shore Channel, respectively, which allowed for control of how much water was diverted from the lake. Because the city of Chicago and many nearby suburbs have combined sewers, precipitation runoff is mixed with sanitary wastewater and must be treated prior to flowing into surface waterways. MWRD and its predecessor, the Sanitary District of Chicago, constructed numerous sewers and storage areas over the last century to allow for storage of some of this combined sewer water prior to treatment. These combined sewers capture the overwhelming majority of precipitation runoff and also have caused changes in the subbasin boundaries (Figure 3).

In recent decades, MWRD constructed large reservoirs and large tunnels as part of the Tunnel and Reservoir Project (TARP) to greatly expand the ability to store runoff (Figure 4). During dry periods, the local combined sewers pass untreated wastewater to interceptor sewers which then move water to the water reclamation plants for treatment prior to discharging into area rivers (Figure 5). During rainfall events, the capacity of the interceptor sewers may be exceeded, causing water to enter drop shafts to the deep tunnels, eventually reaching the large storage reservoirs (Figure 6). If the rainfall event is heavy enough, the storage capacity of the deep tunnels and reservoirs may be exceeded, causing untreated wastewater and runoff to be diverted to rivers during a combined sewer overflow event (Figure 7). In the biggest rain events, enough water is diverted to rivers to trigger a flow reversal into Lake Michigan. After a rain event, water levels in the interceptor sewers, deep tunnels, and reservoirs fall as water is treated by the water reclamation plants (Figure 8).

Although numerous gauges are monitored by MWRD, USGS, and NWS staff on a regular basis, two locations are considered most important for NWS operations (Figure 2). The gauge on the North Branch Chicago River at Grand Avenue (NBGI2) is closely monitored because it is located near the confluence of the North Branch Chicago River and the Chicago River, and is generally representative of water levels across several miles of waterway. The gauge on the Chicago Sanitary and Ship Canal near Lemont (LCSI2) is closely monitored because it is located downstream of the confluence of the Cal-Sag Channel and the Chicago Sanitary and Ship Canal, and is the site of streamflow monitoring by MWRD and the USGS. NBGI2 is expected to be an official river forecast location because of the modeling efforts described in this report.

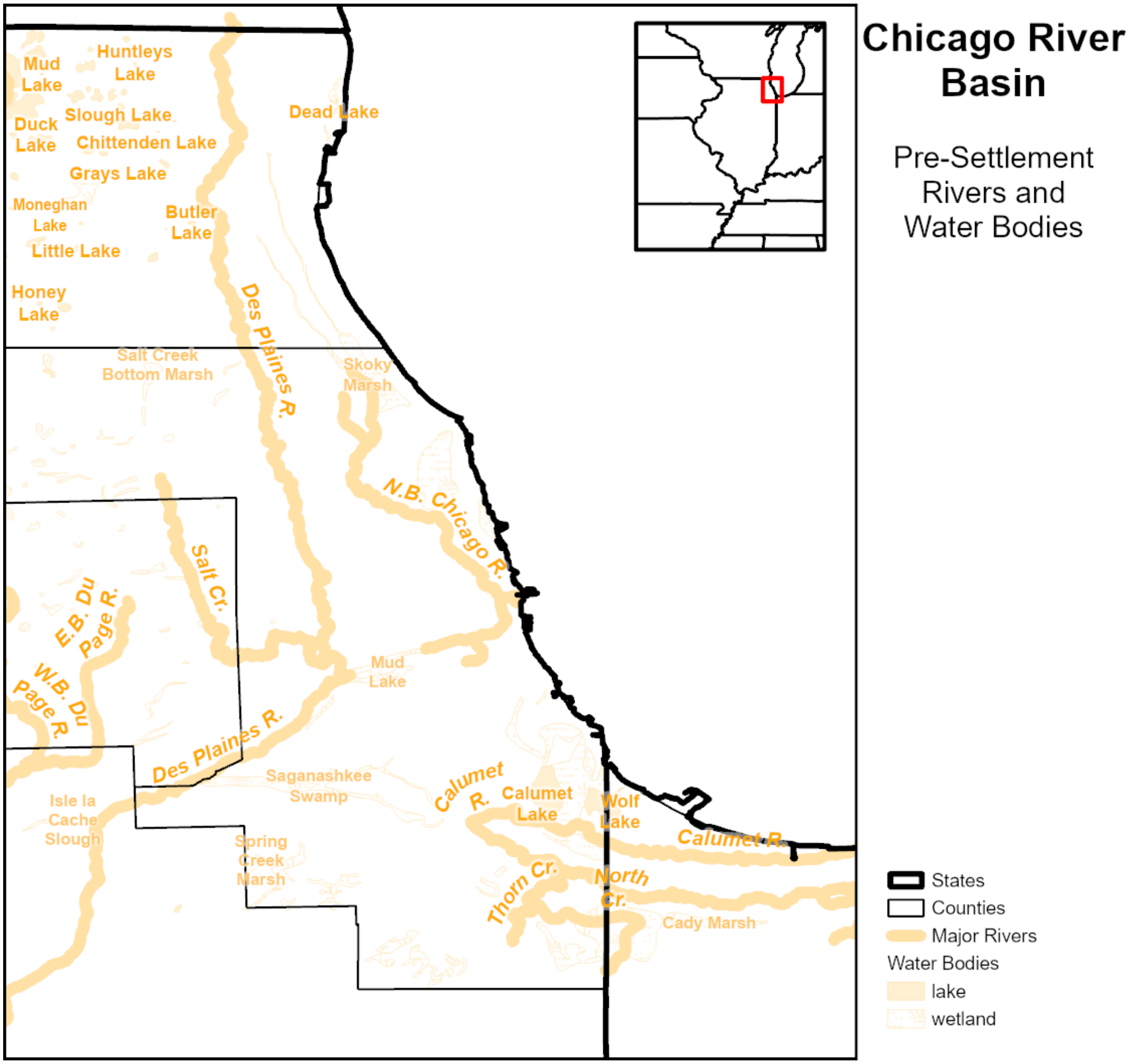

Figure 1. Pre-settlement river courses and waterbodies digitized from historic maps and other technical resources.

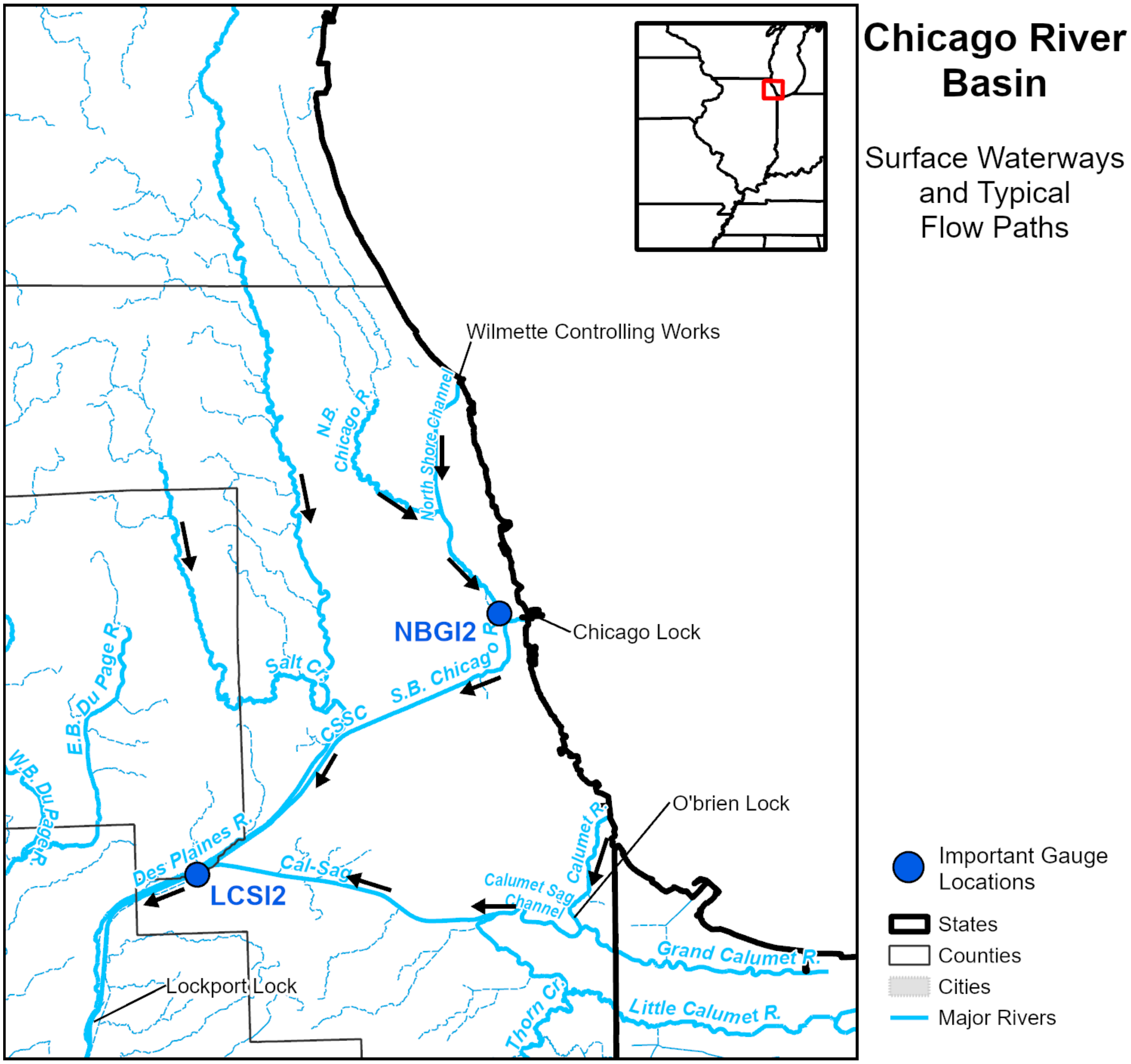

Figure 2. Present-day river courses, major stream gauges, major lock structures, and typical flow directions. NBGI2 corresponds to the North Branch Chicago River at Grand Avenue gauge, and LCSI2 corresponds to the Chicago Sanitary and Ship Canal near Lemont gauge.

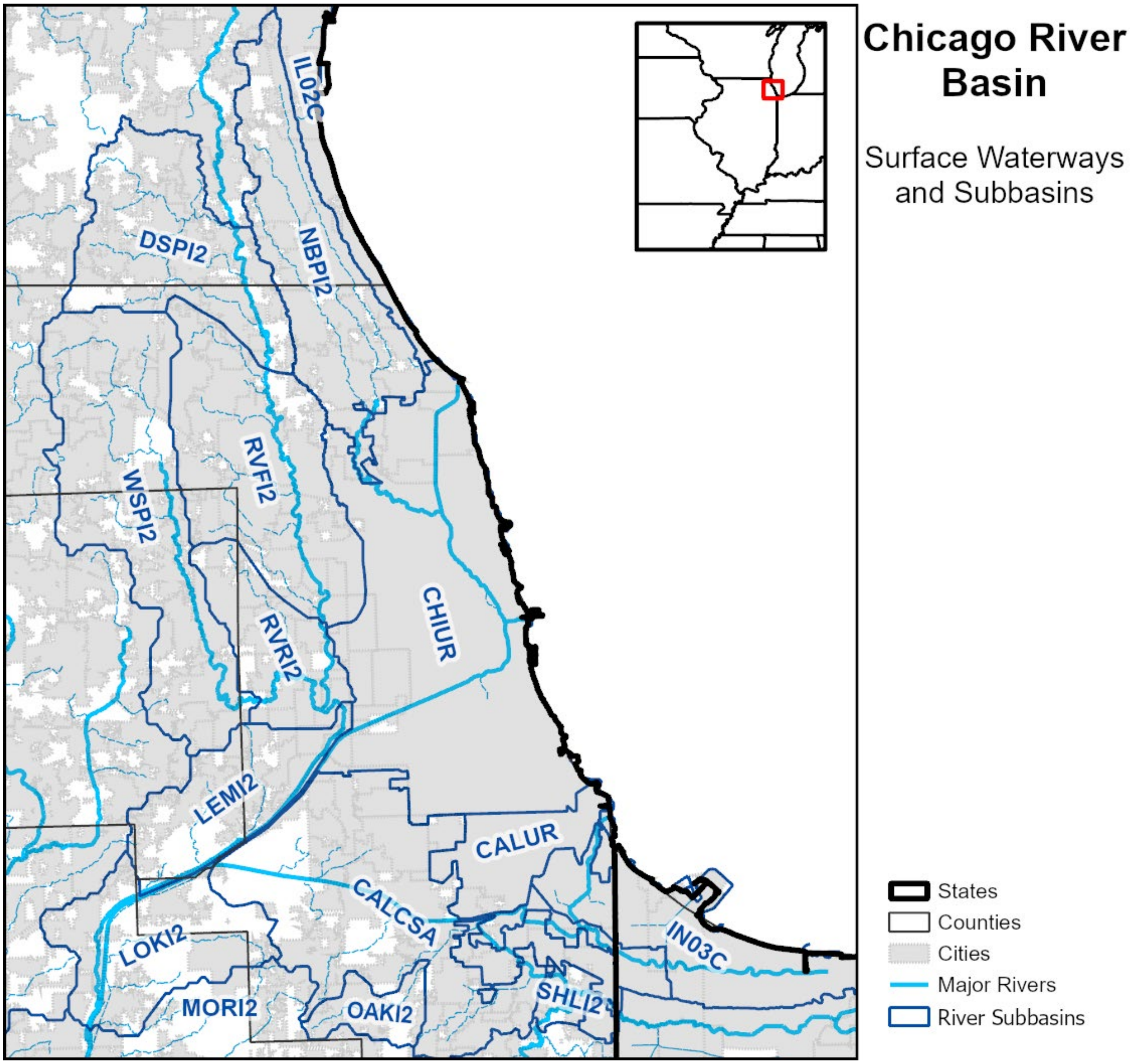

Figure 3. Present-day rivers and drainage basins in the Chicago River Basin and vicinity. Labels correspond to the drainage basin identifiers used by the National Weather Service.

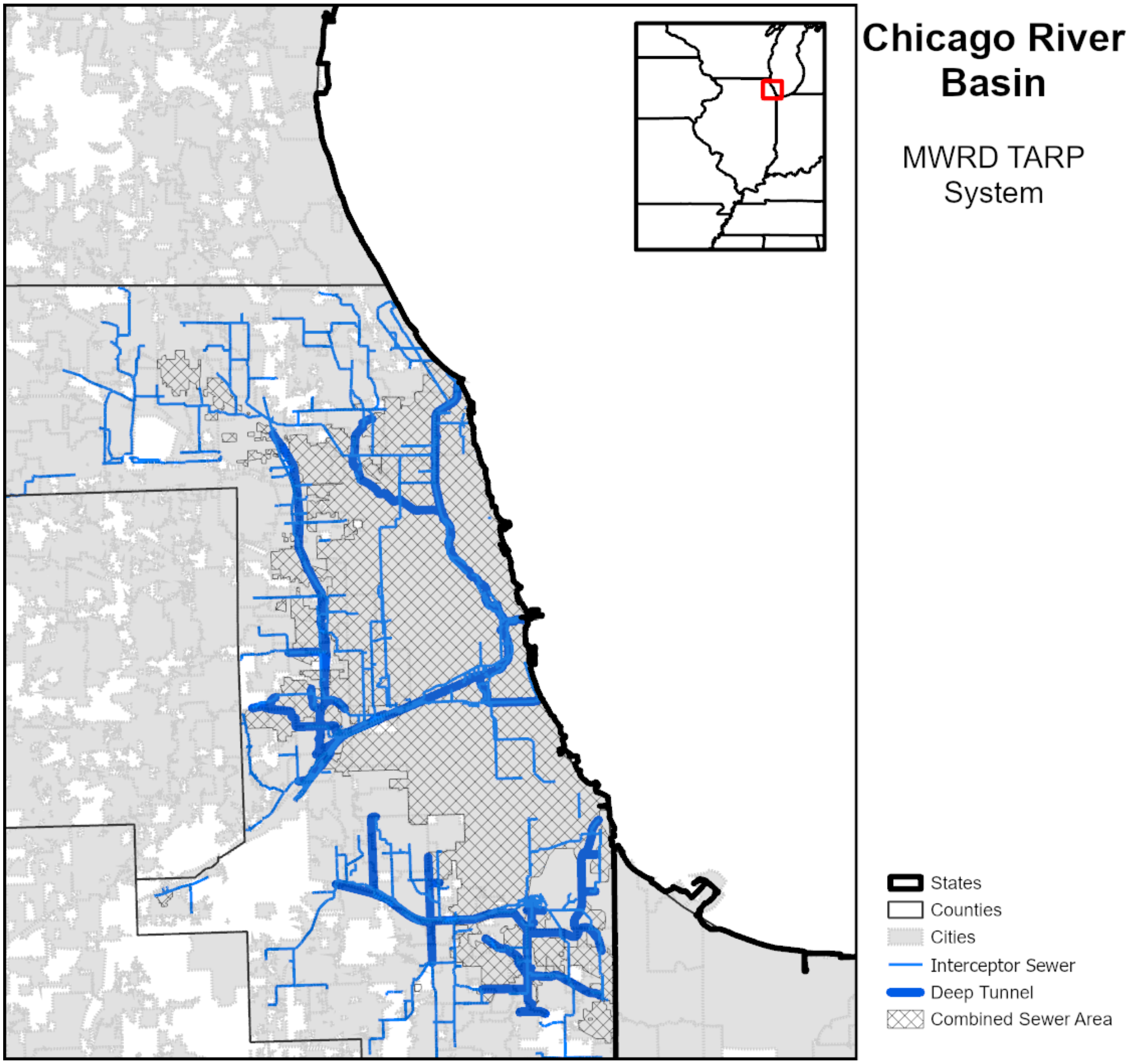

Figure 4. Major underground drainage structures constructed by MWRD as part of TARP. The Combined Sewer Area is the area where both wastewater and precipitation runoff are mixed together in a single sewer system. This combined water is treated at the treatment plants and does not reach the surface waterways unless there is a sewer overflow event.

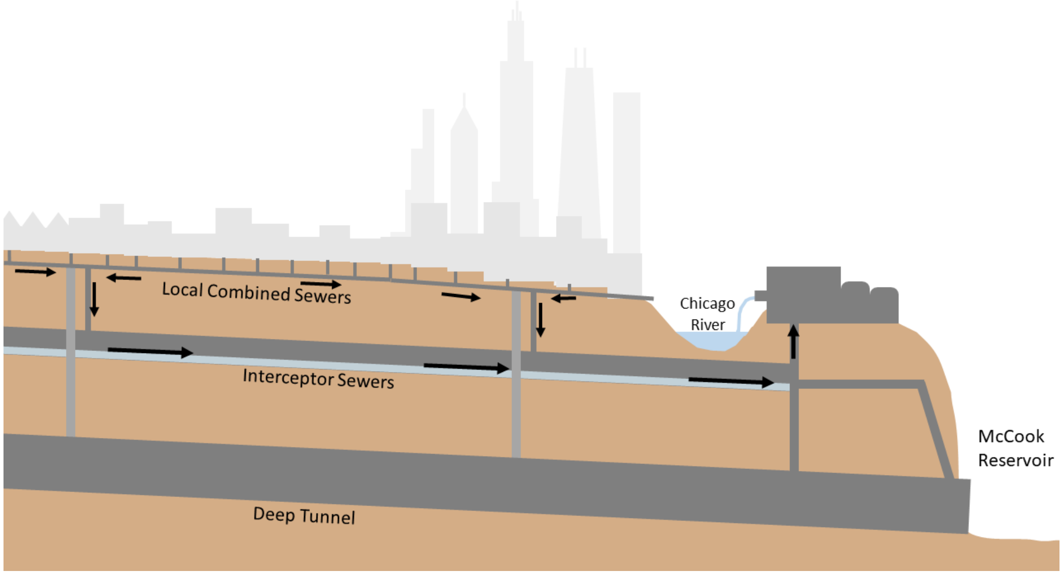

Figure 5. General overview of the combined sewer system and TARP of the Chicago area during dry weather. Local combined sewers pass untreated wastewater to interceptor sewers which then move water to the water reclamation plants for treatment prior to discharging into area rivers.

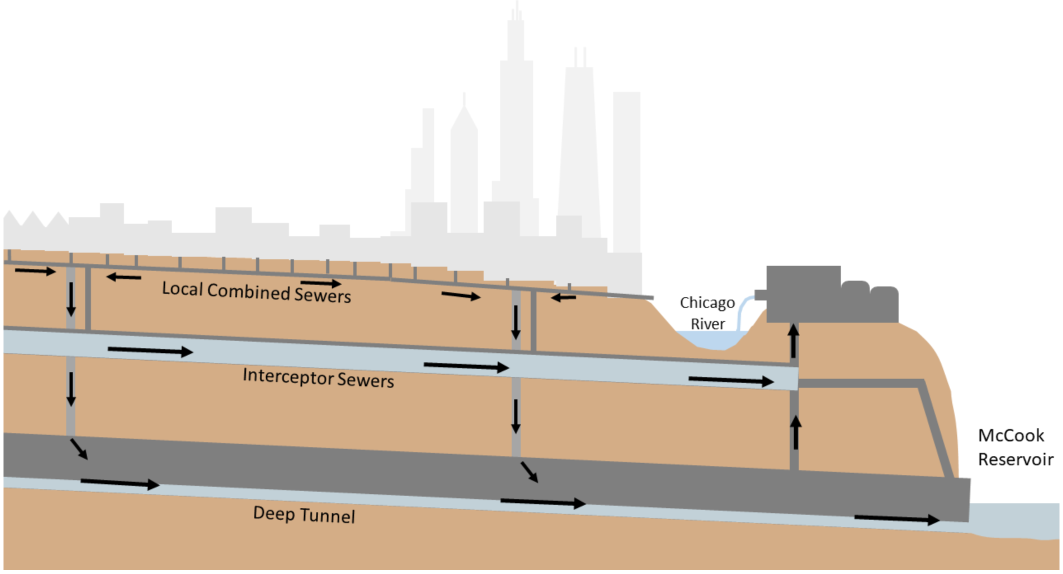

Figure 6. General overview of the combined sewer system and TARP of the Chicago area during a heavy rainfall event. If the capacity of the interceptor sewers is exceeded, water enters drop shafts to the deep tunnels, eventually reaching the large storage reservoirs.

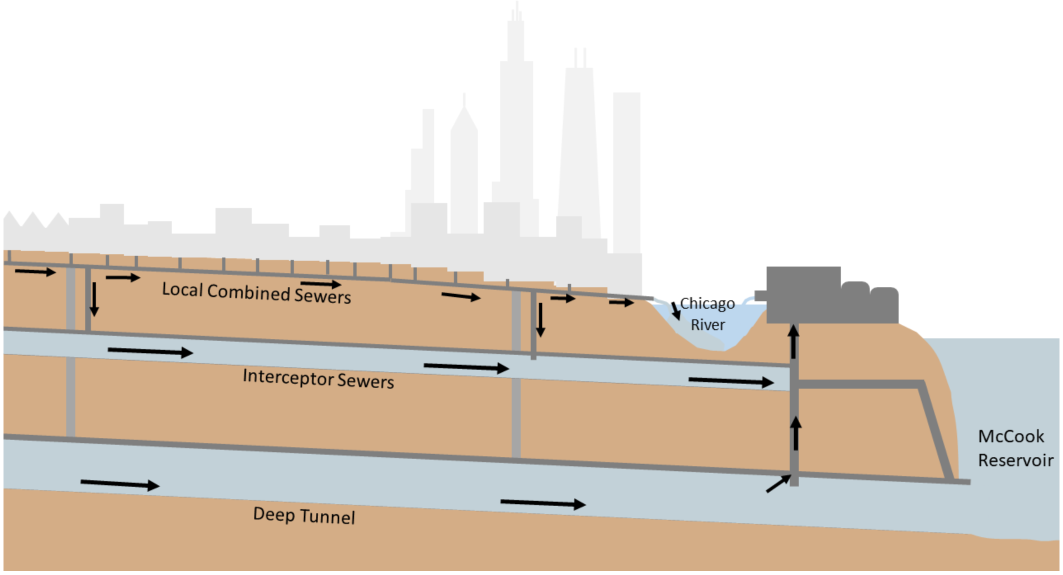

Figure 7. General overview of the combined sewer system and TARP of the Chicago area during a heavy rainfall event. If the storage capacity of the deep tunnels and reservoirs is exceeded, untreated wastewater and runoff is diverted to rivers during a combined sewer overflow event.

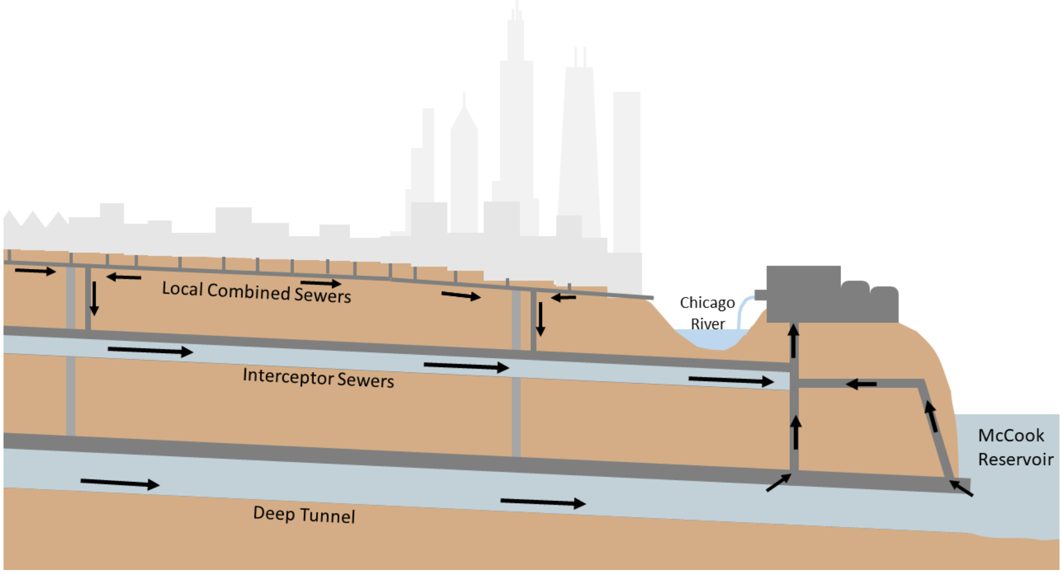

Figure 8. General overview of the combined sewer system and TARP of the Chicago area after a heavy rainfall event ends. Water levels in the interceptor sewers, deep tunnels, and reservoirs fall as water is treated by the water reclamation plants.

2.0 Chicago River Hydraulic Model

A simplified hydraulic model was created to evaluate potential run times and performance of such a model for operational forecasting. The first goal was an attempt to replicate the output of the USACE model used for the GLMRIS study. In that study, the Chicago River and associated waterways were modeled using design storms rather than actual events. Boundary condition input data for these design storms - the hypothetical 10-yr, 25-yr, 50-yr, 100-yr, and 500-yr rainfall events - were extracted from the model and then used as input to a simplified hydraulic model. With the same model inputs being used, the only difference between models would be the geometry, which would help isolate just the uncertainty from using the simplified modeling approach.

The channel bathymetry and terrain data in the simplified model were based upon that which was used in the USACE study model. The modeled time span was also set to match that of the USACE model. A review of early model output suggested several problems that could cause inaccurate results. Problems were noted with the underlying model terrain as well as the gridded land cover data used to derive surface roughness (Manning's n values). These issues with the model terrain may not have caused issues for the 1D approach used for the GLMRIS study, but would lead to issues when using a 2D modeling approach. After fixing issues with the terrain and land cover, output from the model was compared to model results from the GLMRIS study. The following sections discuss the numerous adjustments made to the model domain, the mesh cell spacing, the Manning's n values, and boundary conditions in an attempt to find the best combination for replicating results in the GLMRIS study.

2.1 Developing the Model Terrain and Land Cover

During some of the first test runs of the simplified model, modeled water levels and streamflow values suggested issues with the model terrain and land cover. For the model terrain, most of these issues would not have caused significant problems for a 1D hydraulic model, such as small sections of erroneous channel narrowing. In such cases, cross-sections in a 1D model could be placed away from the constriction, basically skipping it on the upstream and downstream sides, which would greatly reduce any impacts from the issue. In a 2D model, however, channel constrictions and issues with bathymetry would show up in storage and conveyance calculations for any modeled cells of the mesh covering that area. The model terrain issues noted during early testing included:

- Artificial channel constrictions in the model terrain
- Channel misalignments between model terrain and LiDAR elevation data
- Areas of missing channel bathymetry

The channel and surface roughness values (Manning's n values) in a 2D hydraulic model are handled by a land cover grid that covers the entire terrain matched to a lookup table. This is in contrast to a 1D hydraulic model where roughness values can be derived from the gridded data, but also can be manually set at individual cross-sections. Because the simplified hydraulic model was using 2D modeling, any issues with the land cover dataset would have to be manually fixed. One notable issue with the land cover dataset was the depicted width of the Chicago River and Chicago Sanitary and Ship Canal. This narrow width caused areas of much higher roughness (overbank areas) to encroach into the river channel, artificially slowing up streamflow and increasing river crests. Cells in the land cover grid were manually altered to widen the depicted river channel. The Manning's n values associated with the land cover also had to be considered, as there are a range of values possible for a given land cover type. Three different set of Manning's n values were considered:

- The mean value for a given land cover type indicated in the HEC-RAS User's Manual (US Army Corps of Engineers, 2016a; US Army Corps of Engineers, 2016b)
- Values recommended by Max Agnew of USACE in previous modeling studies (Lincoln 2018a; Lincoln 2018b)
- A blend (mean) between HEC-RAS values and Agnew values

See Appendix A for more detail about model terrain issues and the steps taken to fix them.

In addition to the issues with the model terrain and land cover mentioned above, other assumptions related to the model domain could impact the results and the processing time, including mesh cell spacing, the extent of the modeled 2D area into overbank areas, and the extent of the modeled 2D area away from the main area of interest. In certain situations, an increased cell spacing resolution could provide better model results, but this would be at the expense of longer processing time. Extending the 2D mesh into overbank areas would allow the model to better simulate extreme flood events and potentially show overbank inundation, but also would increase processing times. Extending the 2D mesh further upstream and downstream from the main area of interest could reduce the sensitivity of the model to some boundary conditions, but again at the expense of processing time. The simplified hydraulic model was tested under a variety of such scenarios.

2.2 Boundary Conditions

2.2.1 Streamflow from Combined Sewer Overflows

The combined sewer overflow (CSO) locations are the most important boundary condition to the hydraulic model. The CSOs represent runoff that is not treated and not stored and thus reaches the river channel during a heavy rain event. In the USACE model used for GLMRIS, runoff from the design storms is routed through a modeled local sewer, interceptor sewer, and tunnel network. When underground tunnels and reservoirs are full, excess runoff is sent to the waterways via CSO outfall locations. In the USACE HEC-RAS model, 87 unique boundary conditions were used, of which 76 represented CSO locations. Such a large number of streamflow inputs to the hydraulic model were implausible for an operational model, and also unnecessary because no explicit modeling of flow through the various tunnels and sewers would be performed. For the purposes of the operational model, the combined sewer overflow locations were merged into seven groups (Figure 9). Each of these groups corresponded to a major river reach or section.

In the simplified hydrologic and hydraulic modeling, only the total overflow would be modeled. The total overflow of the tunnel and reservoir storage would then be split into the relative proportion of streamflow typically seen in each of the CSO groups, as depicted by the USACE modeling for GLRMIS (Table 1).

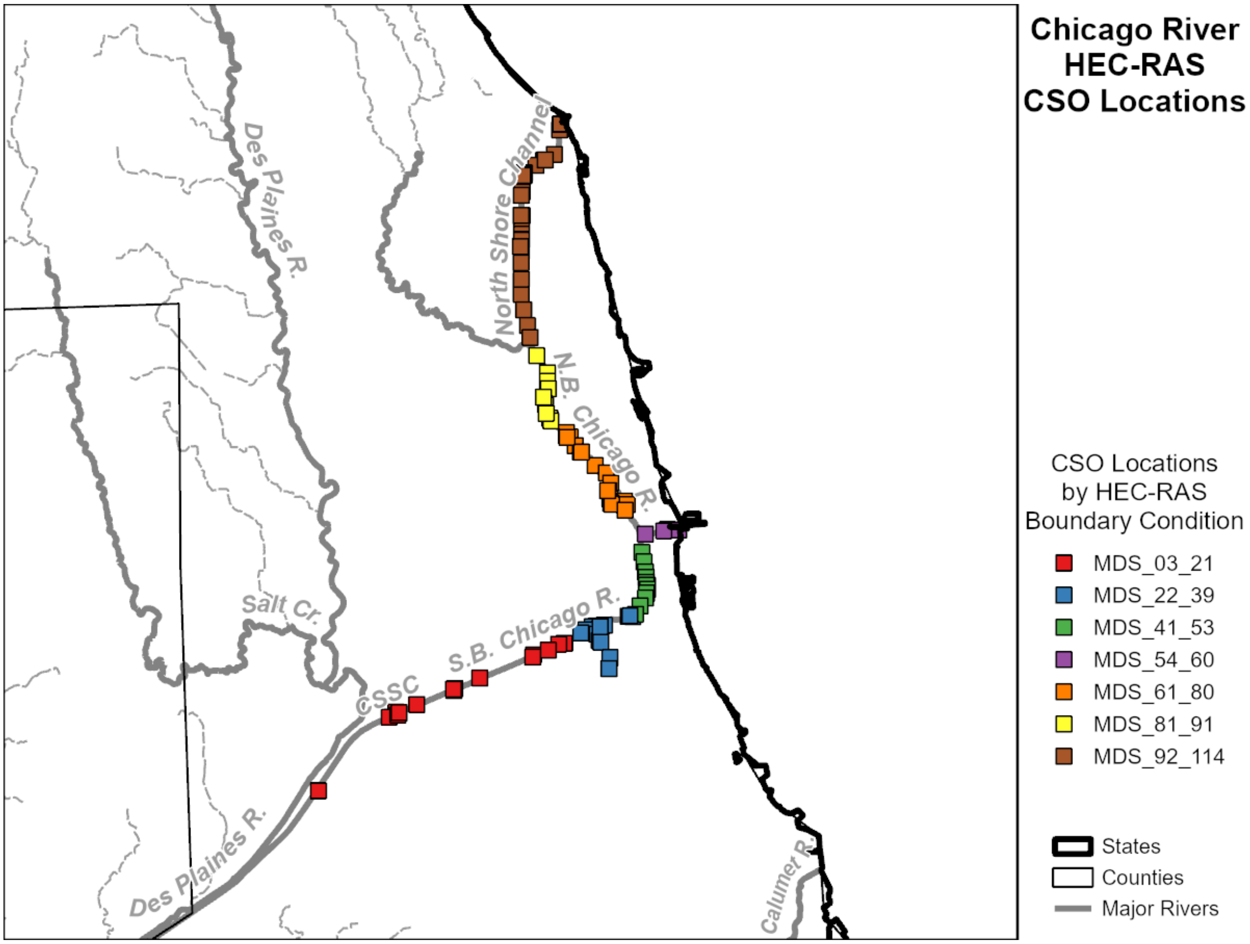

Figure 9. MWRD CSO locations along the Chicago River, North Branch Chicago River, South Branch Chicago River, North Shore Channel, and Chicago Sanitary and Ship Canal. CSO locations are colored based upon the HEC-RAS boundary condition they are tied to.

Table 1. Relative proportion of flows for each range of CSO locations during an overflow event. Range of flows based upon the hypothetical 10-yr, 25-yr, 50-yr, 100-yr, and 500-yr rainfall events modeled by the GLMRIS study model.

CSO Group	**Range of Proportion of Total Overflow**	**Assumed Proportion of Total Overflow in Operational Modeling**
MDS_3_21	0-19%	15% *0% was outlier among design storms in GLMRIS model results.*
MDS_22_39	18-21%	20%
MDS_41_53	8-21%	9% *21% was outlier among design storms in GLMRIS model results.*
MDS_54_60	0-2%	1%
MDS_61_80	9-19%	12% *19% was outlier among design storms in GLMRIS model results.*
MDS_81_91	3-14%	12% *3% was outlier among design storms in GLMRIS model results.*
MDS_92_114	7-31%	18% *31% was outlier among design storms in GLMRIS model results.*
NB_Chicago_NBPI2	9-17%	0% *Although GLMRIS model suggested 13% of total CSO flow went through these CSO locations, flow is assumed to be captured by streamflow at NBPI2 boundary condition. Thus, 13% of a modeled overflow is ignored by the model.*

2.2.2 Downstream Boundary at Lockport Lock

At the downstream end of the Chicago Sanitary and Ship Canal (CSSC) is Lockport Lock. Lockport Lock regulates the water level throughout the canal, with the backwater effect impacting the entire Cal-Sag Channel and also reaching the North Branch Chicago River upstream of the Chicago Loop. Multiple different approaches were tested for simulating the downstream boundary at Lockport Lock, including normal depth, a synthetic rating curve, and an explicit modeling of gates using simplified elevation-controlled gate rules.

Limitations exist with each of these methods. Using a normal depth boundary would cause the model to treat the downstream boundary as open river, which could lead to lower water levels than what would actually occur due to the existence of a lock. A rating curve boundary would require the development of an artificial, single value rating curve which would ignore the likely loop effect on the CSSC. Modeling of lock gates would likely be more realistic, but would increase processing time and also increase the complexity of the model because it would require a set of rules to dictate when to open and close the gates.

For the purposes of explicitly modeling gates at Lockport in the operational hydraulic model, the gates were simplified. In the USACE model for GLMRIS, Lockport Lock is depicted with nine sluice gate openings, each 14 feet high by 9 feet wide. Nearby, the Lockport hydroelectric facility is depicted with a single sluice gate approximately 10 feet high by 10 feet wide. These gate openings were merged into a single structure with a single gate opening 14 feet high by 85 feet wide. This does not add up to the total cross-sectional area of all gates on both structures to account for the difference in invert elevation at each. The modeled gate at Lockport Lock was tied to a simple elevation-based trigger, opening when the channel rises too high and closing when the channel falls too low, within a narrow elevation band. A few miles upstream of Lockport Lock, the CSSC is also regulated by the Lockport Controlling works. In the USACE model for GLMRIS, the Lockport Controlling Works is depicted with seven sluice gate openings, each 20 feet high by 30 feet wide. These gate openings were merged into a single gate opening 20 feet high by 210 feet wide. The modeled gate was also tied to an elevation-based trigger, set to be a few tenths of a foot higher than Lockport Lock.

In actual heavy rainfall situations, gates at Lockport Lock and Lockport Controlling Works would be opened prior to the onset of rainfall in an attempt to drawdown the CSSC and associated waterways. Because it would be particularly difficult to model drawdown behavior such as this, Lockport Lock was programmed to keep CSSC close to a narrow target elevation. Setting this target elevation too high would have the benefit of keeping water levels in the middle of the 2D mesh near Chicago closer to observed values most of the time, but could cause the model to over-simulate water levels during significant rainfall events. Setting this target elevation too low would cause the channel to be in a drawdown state all of the time, making water levels too low compared to observations the majority of the time, but reducing peak water levels during significant rainfall events. Because it takes some time for a drawdown to lower water levels to an equilibrium level throughout the CSSC and the Chicago River, on the order of many hours, finding the best single target value for an operational model is tricky. If a single target elevation must be used, the best approach likely would be a value between the typical water level and the drawdown water level in the CSSC. This would yield a simulated water level that is too low during dry periods but possibly too high during significant rainfall events (Figure 10). Once this model is set up in the operational forecasting system at North Central River Forecast Center, the ability to manually control the gate opening could be explored, which could allow forecasters to put a drawdown event into the model when heavy rainfall is forecasted.

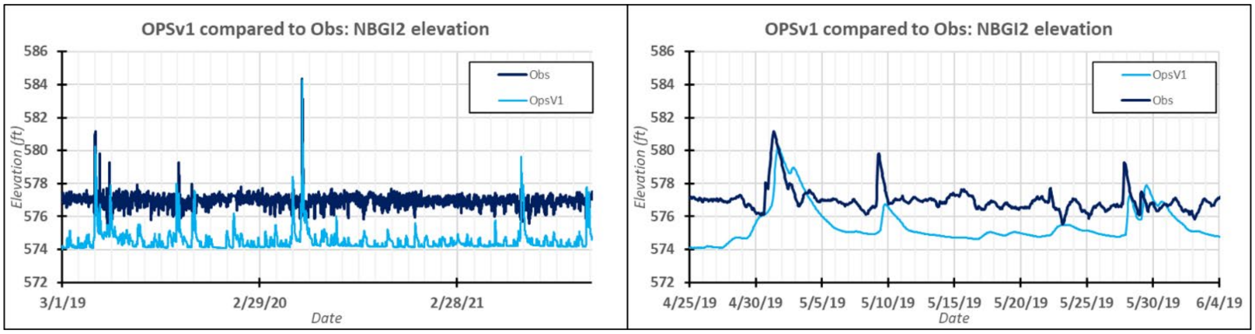

Figure 10. Example model output from the simplified hydraulic model showing the impact of a low target elevation at Lockport Lock. NBGI2 corresponds to the river gauge on the North Branch Chicago River at Grand Avenue.

2.2.3 Streamflow from the Calumet-Saganashkee Channel

Another somewhat downstream boundary of the Chicago River at CSSC is the Calumet-Saganashkee Channel (Cal-Sag). The Cal-Sag connects the CSSC to the lower end of the Calumet River and is regulated by O'Brien Lock. The Little Calumet River and several small creeks enter the Cal-Sag in this area. Two approaches were tested for simulating the boundary with the Cal-Sag, one approach where no flows from the Cal-Sag were modeled and another where streamflow from the Little Calumet River and the local drainage area were combined.

2.2.4 Boundary at Chicago Lock

The Chicago River at the Chicago Loop once flowed into Lake Michigan near the location of Chicago Lock. Because of Chicago Lock and the man-made hydrologic changes to the CSSC and Chicago River, flow generally moves away from the lock except in rare situations. When the Chicago River reaches flood stage (+3.0 ft on the Chicago City Datum, or about 582.2 ft NAVD88) near the Chicago Loop, the Chicago Lock and associated sluice gates are opened to create an additional path for water to leave the system. The Chicago Lock must be depicted in an operational model or simulated water levels near the Chicago Lock will be too high during the bigger flood events.

For the purposes of the operational hydraulic model, the gates at Chicago Lock were simplified. In the USACE model for GLMRIS, Chicago Lock is depicted with four separate structures, the main lock and three separate sets of sluice gates. The Chicago Lock itself is depicted as ten different weirs, each 40 feet high and 8 feet wide. Just to the north of the lock, there are four sluice gates each 10 feet high by 10 feet wide. Just to the south of the lock, there are two sluice gates each 10 feet high by 10 feet wide. To the west along the side of the channel there are four sluice gates each 10 feet high by 10 feet wide. For the purposes of the simplified, operational model, these various gates were merged into two structures. The Chicago Lock gates were merged into a single gate 40 feet high by 100 feet wide. The sluice gates near the Chicago Lock were merged into a single lateral structure with a single gate 10 feet high by 100 feet wide.

Because the rate of flow out of the 2D mesh at Chicago Lock could be limited by the water level of Lake Michigan, a small 2D area representing the lake was created on the opposite side of the lock. A stage boundary condition was created for this small 2D area which was tied to observed water levels for the lake. Although the Chicago Lock gates are generally opened around 582.2 feet elevation, this is prevented when Lake Michigan is very high. When the simplified hydraulic model is moved to the operational system of North Central River Forecast Center, additional rules for the gate opening trigger will need to be specified which only open the gates if the water level is both above the typical trigger *and* above the water level of Lake Michigan.

2.2.5 Boundary at Wilmette Controlling Works

At the north end of the engineered Northshore Channel is the Wilmette Controlling Works. The Wilmette Controlling Works is most often used to divert a small amount of water from Lake Michigan into the Chicago River basin for dilution purposes, but during significant rainfall events, some flow can be released into Lake Michigan.

In the USACE model for GLMRIS, Wilmette Controlling Works is depicted with one sluice gate 31 feet high and 32 feet wide. For the purposes of the simplified, operational model, this gate was replicated “as-is.” Due to some issues with the gridded land cover and terrain datasets near the location of the gate that caused model instability, the modeled location of Wilmette Controlling Works was moved about 600 feet inland on the Northshore Channel. A small 2D area representing Lake Michigan was also created for this boundary condition, similar to the modeled boundary condition at Chicago Lock. Although the trigger elevation for gates at Wilmette is higher than at Chicago Lock, this boundary condition will also need to be reviewed at a later date to make sure the model does not open gates when Lake Michigan is higher than the Northshore Channel.

2.2.6 Streamflow from Treated Wastewater at Stickney, O'Brien, and Calumet Water Reclamation Plants

Because the sewer system covering Chicago and many nearby sewers is a combined sewer, both wastewater and runoff from precipitation enter the same sewer and flow through the sewer system toward the Stickney, O'Brien (not to be confused with O'Brien Lock), or Calumet Water Reclamation Plant. Water usage is generally similar throughout the year. Each of the water reclamation plants can treat water at a significantly higher rate than the rate of municipal water use, leaving some additional capacity for water treatment during periods of heavy rainfall.

Water usage and water treatment by the water reclamation plants is simulated by the hydrologic model. More information about how these flows were handled is covered in the relevant hydrologic modeling section.

2.2.7 Streamflow from North Branch Chicago River

Streamflow from the North Branch Chicago River is another important boundary condition to the hydraulic model. This streamflow represents runoff from precipitation in the Chicago River headwaters north of the city, and will be simulated by the hydrologic model. Streamflow from the North Branch Chicago River also must include CSO water from NDS 2 through NDS 19, which enters the river from just upstream of the Niles gauge to near the Pulaski Road gauge in Chicago. For the purposes of reviewing different hydraulic model approaches, streamflow values from USACE modeling for GLMRIS were used. For later calibration and validation against actual observations, observed streamflow values for the North Branch Chicago River were used to narrow down any model errors to be specific to the hydrologic/hydraulic modeling of the Chicago River itself.

2.2.8 Summary of Streamflow Boundary Conditions

Table 2. Streamflow boundary conditions for the HEC-RAS model.

Boundary Condition	**CSOs and Waterways Modeled**	**Description of Location**
MDS_3_21	MDS 3 through MDS 21	Chicago Sanitary and Ship Canal from near Summit to near Bubbly Creek
MDS_22_39	MDS 22 through MDS 39	Bubbly Creek, Chicago Sanitary and Ship Canal near Bubbly Creek
MDS_41_53	MDS 41 through MDS 53	South Branch Chicago River between Bubbly Creek and Chicago River
MDS_54_60	MDS 54 to MDS 60	Chicago River
MDS_61_80	MDS 61 through MDS 80	North Branch Chicago Avenue between Chicago River and Western Avenue
MDS_81_91	MDS 81 through MDS 91	North Branch Chicago River between Western Avenue and Northshore Channel
MDS_92_114	MDS 92 through MDS 114	Northshore Channel
NB_Chicago_NBPI2	Streamflow on NB Chicago River at Chicago Pulaski Road gauge. Assumed to include overflow from CSO locations NDS 2 through NDS 19.	North Branch Chicago River
CalSagFlows	Streamflow from Little Calumet River and local tributaries into the Cal-Sag Channel. Overflow from CSO locations along Cal-Sag and tributaries ignored.	Calumet Saganashkee Channel

2.3 Hydraulic Modeling Approach

The original hydraulic models provided by USACE and MWRD were one-dimensional hydraulic models, each with over 2000 explicitly modeled river locations (cross sections) and dozens of storage areas to represent overbank areas. Due to the complex nature of the Chicago River and associated waterways, a two-dimensional hydraulic model was chosen for the operational model. The 2D model would have the benefits of easier set-up than a traditional 1D model along with the ability to also model the overbank storage areas and the often complicated, multi-directional streamflow that occurs in this area. Multiple different 2D meshes were tested, including one with 1000-ft spacing across the domain, one with 1000-ft spacing in overbank areas and 75-ft spacing in the river channels, and another with 1000-ft spacing in most areas except unlikely to flood overbank areas where 1500-ft to 2000-ft spacing was used.

2.4 Comparison of Simplified Hydraulic Model to GLMRIS Study Results

The hydraulic model was first tested to determine if it could yield similar results to the more sophisticated hydraulic model used for the GLMRIS study. Combined sewer overflow data used as the boundary condition for the GLMRIS study model was used as the boundary condition for the simplified hydraulic model. Different combinations of terrain, land cover, and downstream boundary conditions were tested to determine which provided the best results. An overview of various test simulations is shown by Table 3.

Table 3. Summary of multiple HEC-RAS scenarios run for testing purposes. Each scenario used a different combination of surface roughness (Manning’s n) values, 2D mesh spacing and extent, and downstream boundary conditions.

Simulation/ Test Number	**Land Cover**	**2D Mesh Spacing and Extent**	**Downstream Boundary Condition**
Simulation 1	Manning’s: Agnew recommendation	Spacing: 1000-ft Coverage: All areas <=590 ft elevation, excluding most of Cal-Sag and parts of CSSC upstream of Lockport Lock.	CSSC: Normal depth upstream of Lockport Lock Cal-Sag: None
Simulation 2	Manning’s: HEC-RAS manual	Spacing: 1000-ft Coverage: All areas <=590 ft elevation, excluding most of Cal-Sag and parts of CSSC upstream of Lockport Lock.	CSSC: Normal depth upstream of Lockport Lock Cal-Sag: None
Simulation 3	Manning’s: HEC-RAS manual	Spacing: 1000-ft Coverage: All areas <=590 ft elevation, excluding most of Cal-Sag.	CSSC: Stage hydrograph for Lockport Lock, constant 575.0 ft elevation Cal-Sag: None
Simulation 4	Manning’s: HEC-RAS manual	Spacing: 1000-ft Coverage: All areas <=590 ft elevation.	CSSC: Stage hydrograph for Lockport Lock, with 575.0 ft to 571.0 ft draw-down prior to event. Cal-Sag: Modeled flow hydrograph.
Simulation 5	Manning’s: Agnew recommendation	Spacing: 1000-ft Coverage: All areas <=590 ft elevation.	CSSC: Stage hydrograph for Lockport Lock, with 575.0 ft to 571.0 ft draw-down prior to event. Cal-Sag: Modeled flow hydrograph.
Simulation 6	Manning’s: Agnew recommendation	Spacing: 1000-ft, except 75-ft spacing in channel Coverage: All areas <=590 ft elevation.	CSSC: Stage hydrograph for Lockport Lock, with 575.0 ft to 571.0 ft draw-down prior to event. Cal-Sag: Modeled flow hydrograph.
Simulation 7	Manning’s: HEC-RAS manual	Spacing: 1000-ft, except 75-ft spacing in channel Coverage: All areas <=590 ft elevation.	CSSC: Stage hydrograph for Lockport Lock, with 575.0 ft to 571.0 ft draw-down prior to event. Cal-Sag: Modeled flow hydrograph.
Simulation 8	Manning’s: Agnew recommendation	Spacing: 1000-ft Coverage: Most areas <= 590 ft elevation, with extent narrowed along lower CSSC.	CSSC: Stage hydrograph for Lockport Lock, with 575.0 ft to 571.0 ft draw-down prior to event. Cal-Sag: Modeled flow hydrograph.
Simulation 9	Manning’s: Agnew recommendation	Spacing: 1000-ft Coverage: Most areas <= 590 ft elevation, with extent narrowed along lower CSSC.	CSSC: Elevation-controlled gates at Lockport Lock, with 574.5 ft target elevation. Cal-Sag: Modeled flow hydrograph.

2.4.1 Evaluation of Downstream Boundary Condition

The simplest approach for handling the downstream boundary would be to use a normal depth assumption near Lockport Lock. With typical river hydrology, the energy slope value for the normal depth is approximated by the river bed slope, which in this case was about 0.001. When modeled using normal depth, the CSSC near the Lockport boundary was significantly lower for a given streamflow in the model than would occur in reality. This was most evident when using longer simulation run times due to the amount of time taken to drain water in the center of the 2D mesh, away from the boundary. Significantly reducing the energy slope could be used to raise the modeled water level at and just upstream of the boundary, but this was at the expense of a significant reduction in modeled streamflow values. With exceptionally low energy slope values, not enough water would leave the 2D mesh even during dry periods, causing the 2D mesh to continually accumulate water. No value was found that would provide a good balance between reasonable streamflow values at the downstream end of the 2D mesh as well as reasonable water elevations. The normal depth value near 0.001 likely produced the best results, but still left the modeled water levels much too low throughout most of the 2D mesh the majority of the time, likely causing an under-simulation of water levels during heavy rainfall events (Figure 11).

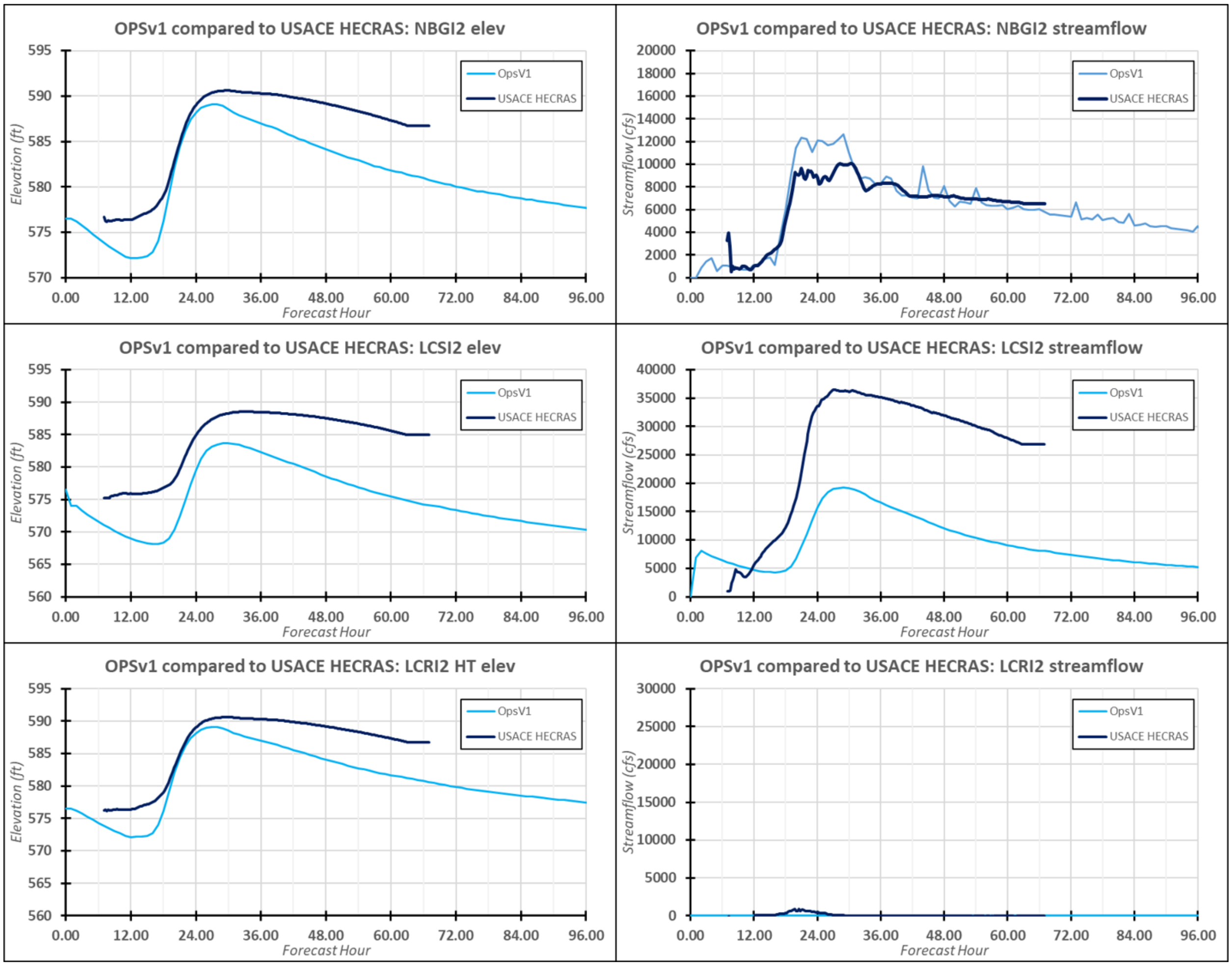

Figure 11. Model results for a 0.2% annual chance (500-yr ARI) design storm in the Chicago Basin with normal depth used as a downstream boundary at Lockport Lock. Compared to the output from the USACE model used for GLMRIS, the water level in the Chicago basin drops very quickly due to the very low simulated water levels near Lockport. NBGI2 corresponds to the river gauge on the North Branch Chicago River at Grand Avenue, LCSI2 corresponds to the river gauge on the Chicago Sanitary and Ship Canal near Lemont, and LCRI2 corresponds to the river gauge on the Chicago Lock separating Lake Michigan (pool side, HP) from the Chicago River (tailwater side, HT).

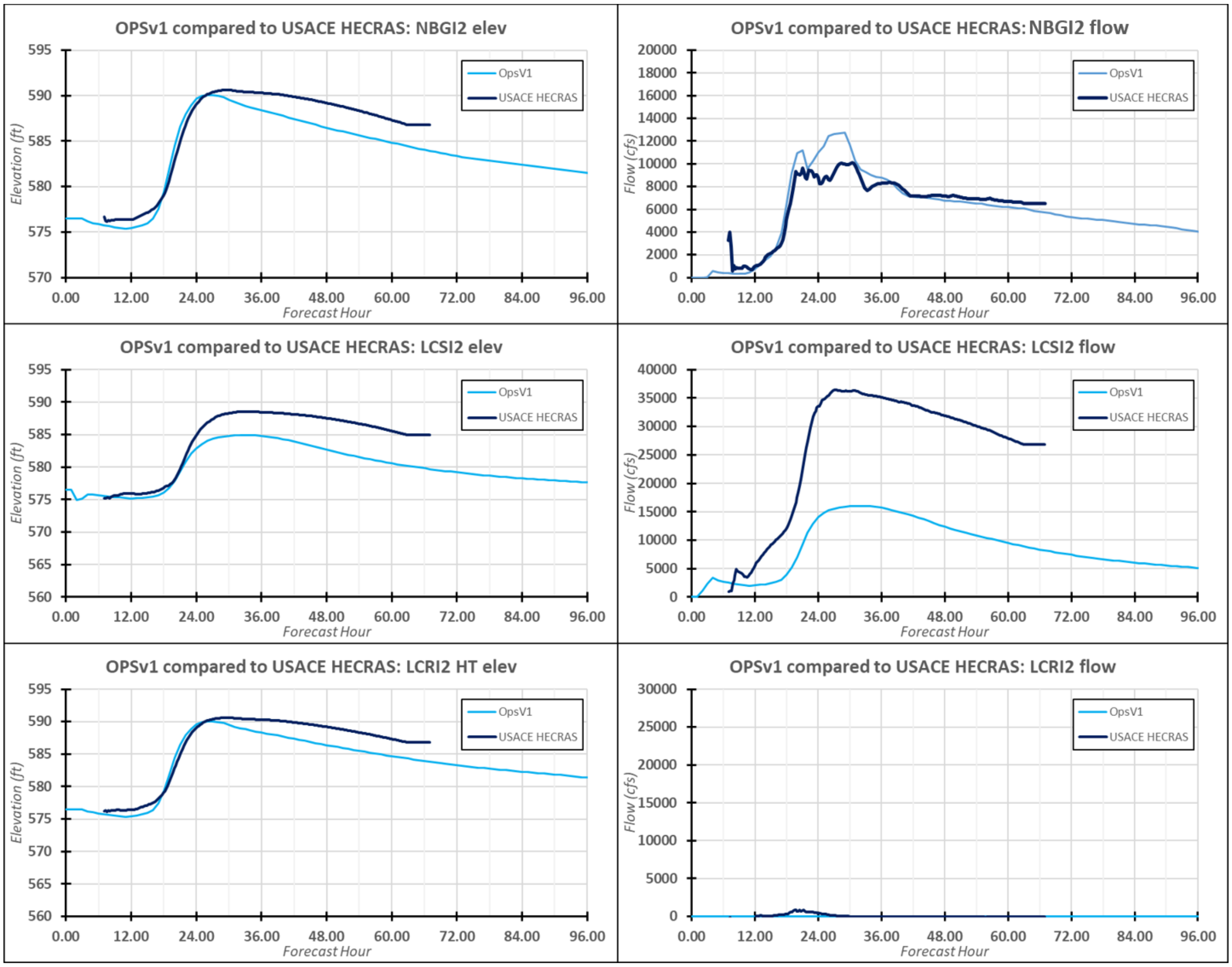

Figure 12. Model results for a 0.2% annual chance (500-yr ARI) design storm in the Chicago Basin with a rating curve used as a downstream boundary at Lockport Lock. Compared to the output from the USACE model used for GLMRIS, the water level in the Chicago basin drops quickly, and the flow is too high in the middle of the mesh but too low closer to the downstream boundary. NBGI2 corresponds to the river gauge on the North Branch Chicago River at Grand Avenue, LCSI2 corresponds to the river gauge on the Chicago Sanitary and Ship Canal near Lemont, and LCRI2 corresponds to the river gauge on the Chicago Lock separating Lake Michigan (pool side, HP) from the Chicago River (tailwater side, HT).

Another approach that was tested was to use a synthetic rating curve for the downstream boundary near the location of Lockport Lock. Using a synthetic rating curve would cause the modeled water elevation near Lockport to rise and fall based upon the streamflow heading toward the boundary. A synthetic rating curve was created based upon a relationship fit to modeled flow and water elevation values upstream of Lockport on the CSSC. The synthetic rating curve was very approximate due to the strong loop effect that occurs on the canal. Although some aspects of this approach appeared to produce reasonable results, using a rating curve boundary ignores the loop effect and likely contributes to the noted issues with streamflow and water elevations in the falling limb.

Based upon these results, it was determined that the simplified, operational hydraulic model would likely need some method of explicitly modeling the gates at Lockport Lock. Modeling gates as the downstream boundary would have the benefit of keeping water levels elevated in the CSSC and the Chicago River between periods of heavy rainfall. It would also better approximate the loop effect which occurs in the CSSC and allow for improvements to modeled streamflow, especially if a channel drawdown during heavy rainfall events could be modeled.

2.4.2 Evaluation of Cal-Sag Boundary Conditions

The addition of a boundary condition on the Cal-Sag which brought additional streamflow to the CSSC caused notable changes in the modeled results. In particular, the water level upstream of Lockport increased, and a significant increase in streamflow upstream of Lockport was noted. This increase in water levels and streamflow upstream of Lockport also caused a reduction in streamflow values in the Chicago Loop (likely due to a backwater effect), making modeled values in the simplified model much closer to the USACE model for GLMRIS. It was noted that streamflow values upstream of Lockport were still under-simulated, however, which may be due to diversions from Lake Michigan and treated wastewater at the Calumet Water Reclamation plant not being depicted (Figure 13).

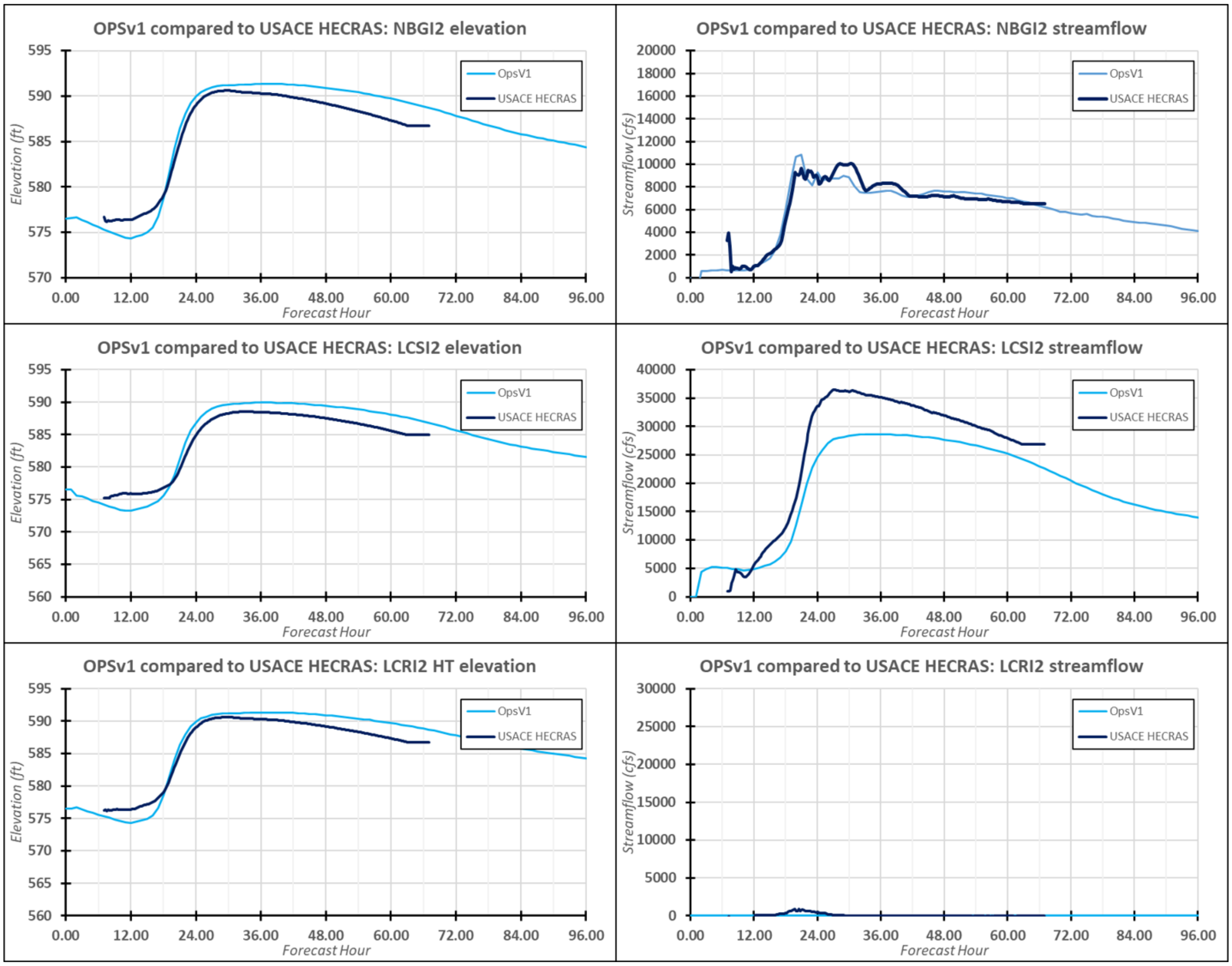

Figure 13. Model results for a 0.2% annual chance (500-yr ARI) design storm in the Chicago Basin with a streamflow boundary condition added on the Cal-Sag. Compared to the output from the USACE model used for GLMRIS, the water levels and streamflows as a whole are improved compared to the modeling approaches that ignore the Cal-Sag. NBGI2 corresponds to the river gauge on the North Branch Chicago River at Grand Avenue, LCSI2 corresponds to the river gauge on the Chicago Sanitary and Ship Canal near Lemont, and LCRI2 corresponds to the river gauge on the Chicago Lock separating Lake Michigan (pool side, HP) from the Chicago River (tailwater side, HT).

2.4.3 Evaluation of Increased Cell Resolution in River Channels

Model results using the 75-ft cell spacing in river channels caused water levels to peak sooner and lower across the 2D mesh. Streamflow was increased along the North Branch Chicago River near the Chicago Loop and also on the CSSC upstream of Lockport. Streamflow values also peaked sooner, but reached higher values than with the coarser resolution and then fell much more quickly. Despite getting streamflow values on the CSSC upstream of Lockport closer to the peak magnitude found in the USACE GLMRIS model results, the overall model results appeared to perform more poorly (Figure 14; Figure 15). There was also a significant increase in processing time due to the increase in mesh cells.

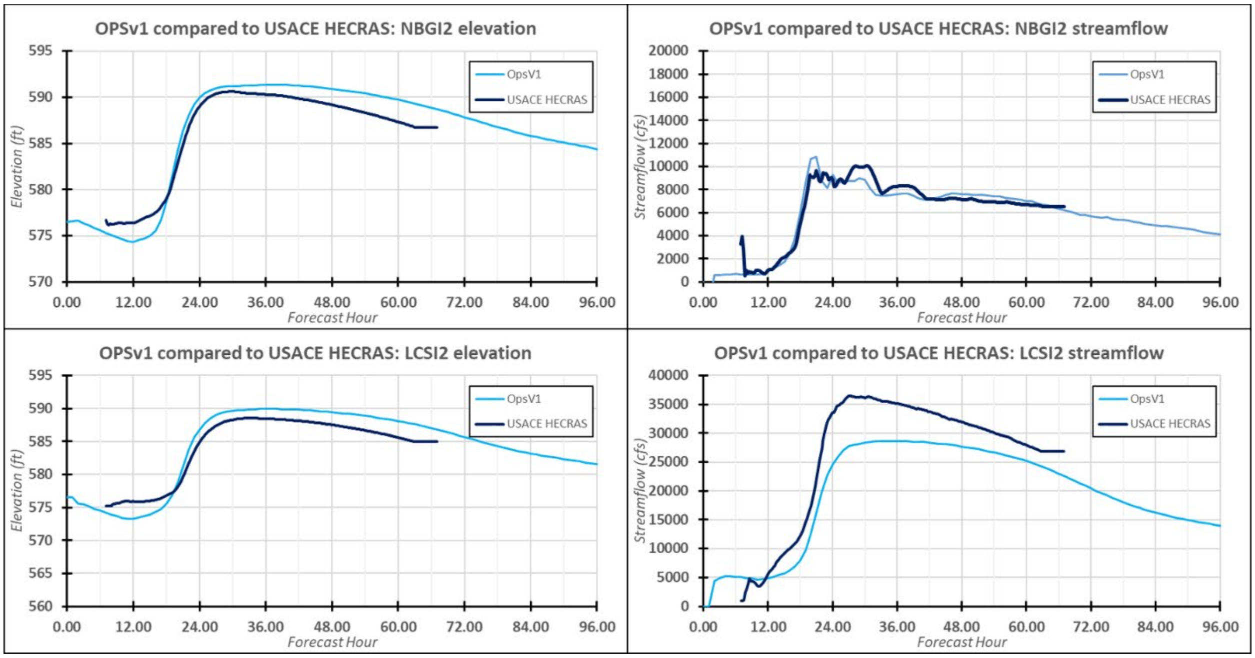

Figure 14. Model results for a 0.2% annual chance (500-yr ARI) design storm in the Chicago Basin with an approximate cell spacing of 1000 feet used throughout the modeled 2D area. NBGI2 corresponds to the river gauge on the North Branch Chicago River at Grand Avenue and LCSI2 corresponds to the river gauge on the Chicago Sanitary and Ship Canal near Lemont.

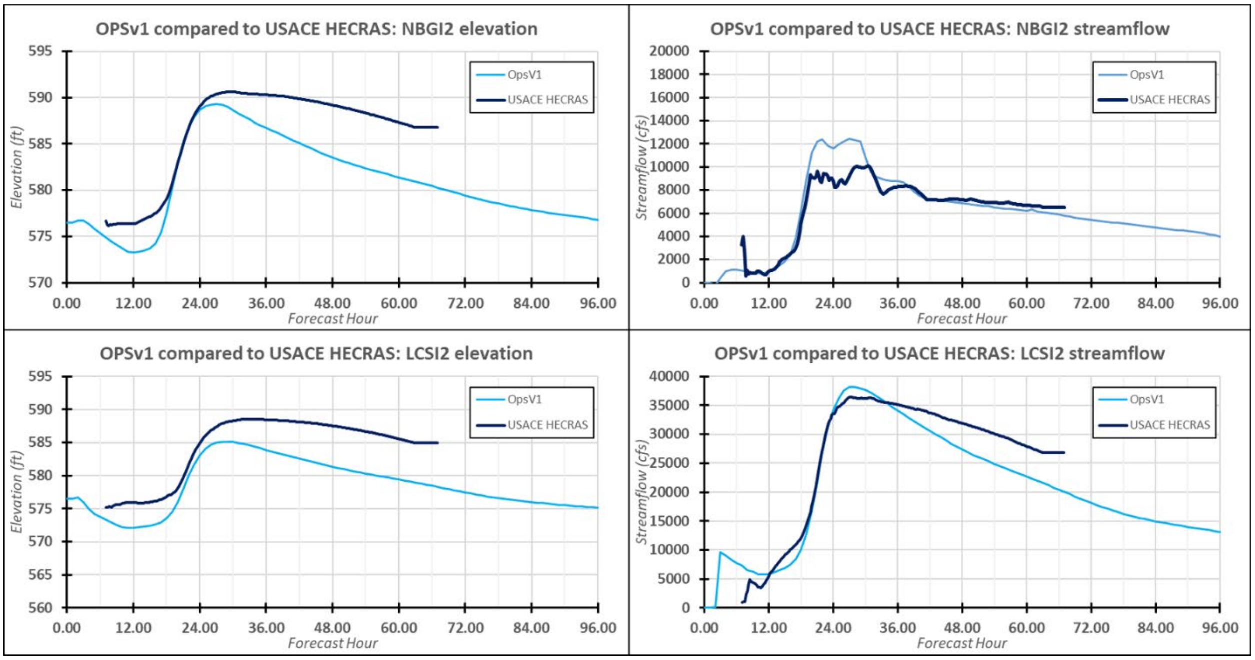

Figure 15. Model results for a 0.2% annual chance (500-yr ARI) design storm in the Chicago Basin with an approximate cell spacing of 1000 feet used in all areas except the river channels, where an approximate cell spacing of 75 feet was used. NBGI2 corresponds to the river gauge on the North Branch Chicago River at Grand Avenue and LCSI2 corresponds to the river gauge on the Chicago Sanitary and Ship Canal near Lemont.

2.4.4 Summary

The model results were most sensitive to the land cover roughness (Manning’s n values) and the downstream boundary conditions. Changes to land cover roughness had the effect of changing both the peak water level, the peak water level timing, and the streamflow. Changes to the downstream boundary condition had a smaller effect, especially to peak water level magnitude, but could cause significant changes to the streamflow in the CSSC. A subjective review of the test simulations is provided by Table 4.

In general, models using Manning’s n values recommended by USACE modelers (Max Agnew 2016, personal communication) performed better than models that used the Manning’s n values found in the HEC-RAS manual. Models that included Lockport Lock with an observed stage hydrograph generally performed better. Models that included the streamflow contribution from the Cal-Sag also generally performed better. Models with a significantly increased mesh resolution in the river channels did not have significantly improved results, but did have a significantly longer processing time. The modeling approach with the best balance of results and processing time was simulation 8, where Manning’s n values recommended by Max Agnew were used along with a known elevation for Lockport Lock, modeled streamflow entering the CSSC from the Cal-Sag, and no increase in 2D mesh resolution in the channel. The modeling approach used by simulation 9 was very similar to that of simulation 8, although there was an increase in complexity (and run time) due to the addition of gates at Lockport Lock.

The hydraulic modeling approach based upon simulation 9 is hereafter referred to as Operational Modeling Candidate 1. It is likely, however, that the results of using either simulation 8 or simulation 9 will yield similar results, and the exact approach to select for possible future operational modeling should be based upon balancing complexity and run times against the need to explicitly control gate settings. The next step in model development was to create a hydrologic model to simulate CSO events and test the combined hydrologic/hydraulic model with actual observations.

Table 4. Summary of model performance for each of the HEC-RAS scenarios run for testing purposes. Possible candidates for future model development are indicated.

Simulation/ Test Number	**Notes on Model Performance**	**Candidate for Future Development?**
Simulation 1	NBGI2: Stage crest within a couple feet with reasonable streamflow. LCSI2: Stage crest under-simulated and streamflow significantly too low.	No
Simulation 2	NBGI2:Stage crest very close with reasonable streamflow. Streamflow crest several hours later than with simulation 1. LCSI2: Stage crest under-simulated, but within a couple feet. Streamflow significantly too low and decreased compared to simulation 1.	Possibly
Simulation 3	NBGI2:Stage crest very close with reasonable streamflow. Hydrographs changed only a small amount from simulation 2. LCSI2: Stage crest also under-simulated, but within a couple feet. Streamflow significantly too low. Hydrographs changed only a small amount from simulation 2.	Possibly
Simulation 4	NBGI2: Stage crest significantly too high and many hours too late. Streamflow under-simulated early in the event followed by more reasonable streamflow. LCSI2: Stage crest significantly too high and many hours too late. Streamflow significantly too low, but increased compared to simulations 1, 2, and 3.	No
Simulation 5	NBGI2:Stage crest very close but a few hours too late. Streamflow very reasonable. LCSI2: Stage crest very close, but a few hours too late. Streamflow under-simulated, but much more reasonable compared to simulations 1, 2, 3, and 4.	Yes
Simulation 6	NBGI2:Stage crest within a couple feet, but a few hours too early and drops off too fast after event. Streamflow reasonable. LCSI2: Stage crest under-simulated and a few hours too early, followed by too quick of a drop off after crest. Streamflow crest very reasonable, but drops off too quickly after crest.	Possibly
Simulation 7	NBGI2:Stage crest very close but a few hours too late and drops too slowly afterward. LCSI2: Stage crest very close, but a few hours too late and drops too slowly afterward. Streamflow under-simulated, but much more reasonable compared to simulations 1, 2, 3, and 4.	Yes
Simulation 8	NBGI2:Stage crest very close, but with over-simulated larger floods. LCSI2: Stage crest very close. Streamflow reasonable.	Yes
Simulation 9	NBGI2:Stage crest very close for flood events, but under-simulated for typical and low flow conditions. LCSI2: Stage crest very close. Streamflow reasonable.	Yes

3.0 Chicago River Hydrologic Model

In real-time operations, contributions to the Chicago River from combined sewer overflows would not be known and would need to be modeled. A simple hydrologic model was developed in HEC-HMS to represent the infiltration/runoff processes, the movement of runoff into and through the sewer system, and the storage of water in the Mainstream Deep Tunnel and McCook Reservoir. Output from the HEC-HMS model could then be easily tied to the HEC-RAS model as boundary conditions.

3.1 Overview of Simplified Modeling Approach

The complex behavior of the drainage network in the Chicago River basin was drastically simplified for operational modeling purposes. In reality, a complex series of processes and events occurs during a heavy rainfall event, and can be different depending upon the rainfall amount, rainfall intensity, and antecedent conditions. A general summary of how the stormwater drainage system in the Chicago River Basin responds to a runoff event is provided by section 1.3 General Overview of Chicago River Hydrology. In the GLMRIS study, many of these complex processes were modeled; for an operational river forecasting model, these processes would need to be lumped together whenever possible. For a more detailed overview of how the TARP system handles stormwater, see section 1.3 General Overview of Chicago River Hydrology.

The first step for operational modeling of the Chicago River would be the modeling of infiltration and runoff due to precipitation. A hydrologic model takes hourly precipitation for each of the Chicago River, North Branch Chicago River, and Little Calumet River basins and estimates runoff and infiltration based upon land cover and soil characteristics, including an estimation of soil moisture. Runoff for the North Branch Chicago River basin and Little Calumet River basin are each sent directly to the hydraulic model. Runoff for the Chicago River basin is processed further by the hydrologic model.

Runoff for the North Branch Chicago River is sent to a simple flow routing method that is meant to depict the movement of water through the various sewers and tunnels. It then reaches a modeled reservoir which represents the combined storage capacity of McCook Reservoir, the Mainstream Deep Tunnel, the interceptor sewers, and the local near-surface sewers. Water leaves the modeled reservoir via two means, either an elevation-discharge relationship that depicts the background rate of water treatment by the Stickney and O'Brien Water Reclamation plants, or by a spillway at the top of the reservoir which effectively causes all inflows to immediately leave the reservoir when it reaches capacity. This spillway overflow is meant to represent a combined sewer overflow event. Reservoir overflows and the treated water are sent to the hydraulic model to determine the impact to the Chicago River. An overview of the simplified hydrologic modeling steps is illustrated by Figure 16. More details on these various model components can be found in the following subsections.

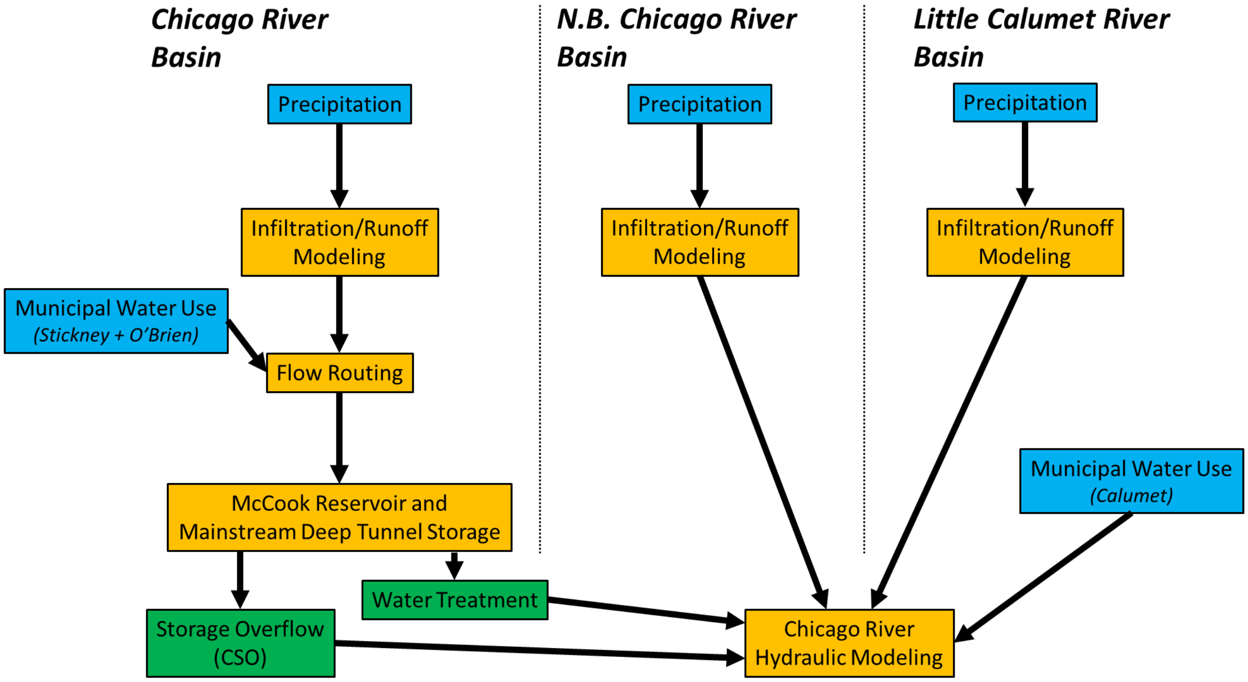

Figure 16. General overview of the hydrologic modeling approach for Chicago River operational forecasting. A significant amount of complicated modeling performed for the GLMRIS study is lumped together and simplified, becoming the “Flow Routing” and “McCook Reservoir and Mainstream Deep Tunnel Storage” components shown here.

3.2 Delineation of Basins

Generating the correct magnitude of flow for a given basin depends not only on the precipitation estimate and the runoff/infiltration modeling, but also depends upon an accurate accounting of the basin’s contributing area. Typically, river basins can be delineated using terrain data and GIS methods. Due to numerous complexities of the Chicago River basin, delineation of contributing areas is much more difficult. Construction of man-made canals and channels that move water across natural drainage divides can cause problems with automated delineation techniques. Underground drainage networks that span drainage divides also violate the assumptions of automated delineation tools. Further complicating the situation is the flow behavior of water in the underground drainage network which may move in different directions, and toward different treatment plants, depending upon the amount of storage in the system and the rainfall pattern. Because hydrologic modeling assumes one-directional flow (water always moves upstream to downstream), a simplified model of the Chicago River basin for operational forecasting will be subject to considerable uncertainty.

To provide the best possible approximation of contributing drainage areas to the Chicago River basin, a multi-step approach was followed. First, basins were delineated through the typical method of analyzing surface elevation. Next, basins were compared to the intercepting basins and the interceptor sewer lines defined by MWRD. The intercepting basins depict the areas serviced by a given water reclamation plant, assuming that flow remains in the near-surface sewers and interceptor sewers. The basin delineations were further refined by looking at the combined sewer area serviced by MWRD. In the combined sewer area, both stormwater and sanitary water would enter the same sewer, eventually heading toward the interceptors and sometimes the deep tunnels prior to being treated by a water reclamation plant. Outside of the combined sewer area, sanitary water moves toward the interceptors, but stormwater is handled separately, likely following topography to the nearest waterway.

The updated basin delineation (Figure 17) shows the contributing area of the North Branch Chicago River at Pulaski Road being reduced as most runoff between the Niles gauge and the Pulaski Road gauge would likely be captured by the combined sewers, bypassing the river channel. The Chicago Urban basin was expanded to include the areas in neighboring basins where interceptor sewers captured runoff in the combined sewer area. Considerable uncertainty remains with regard to the western extent of the Chicago Urban basin. Some interceptor sewers in the Des Plaines River basins likely cross the drainage divide into the Chicago River basin, but are not yet directly connected to the Mainstream Deep Tunnel or McCook Reservoir. Water entering these systems may thus reduce the rate at which Stickney can treat water stored in McCook and the Mainstream Deep Tunnel, but the exact magnitude, and means of modeling hydrologically, is not clear. The best estimate of the area of the Chicago Urban Basin is 214 mi^2, but could range from 192 mi^2 to 255 mi^2, a large difference with significant implications for modeled runoff.

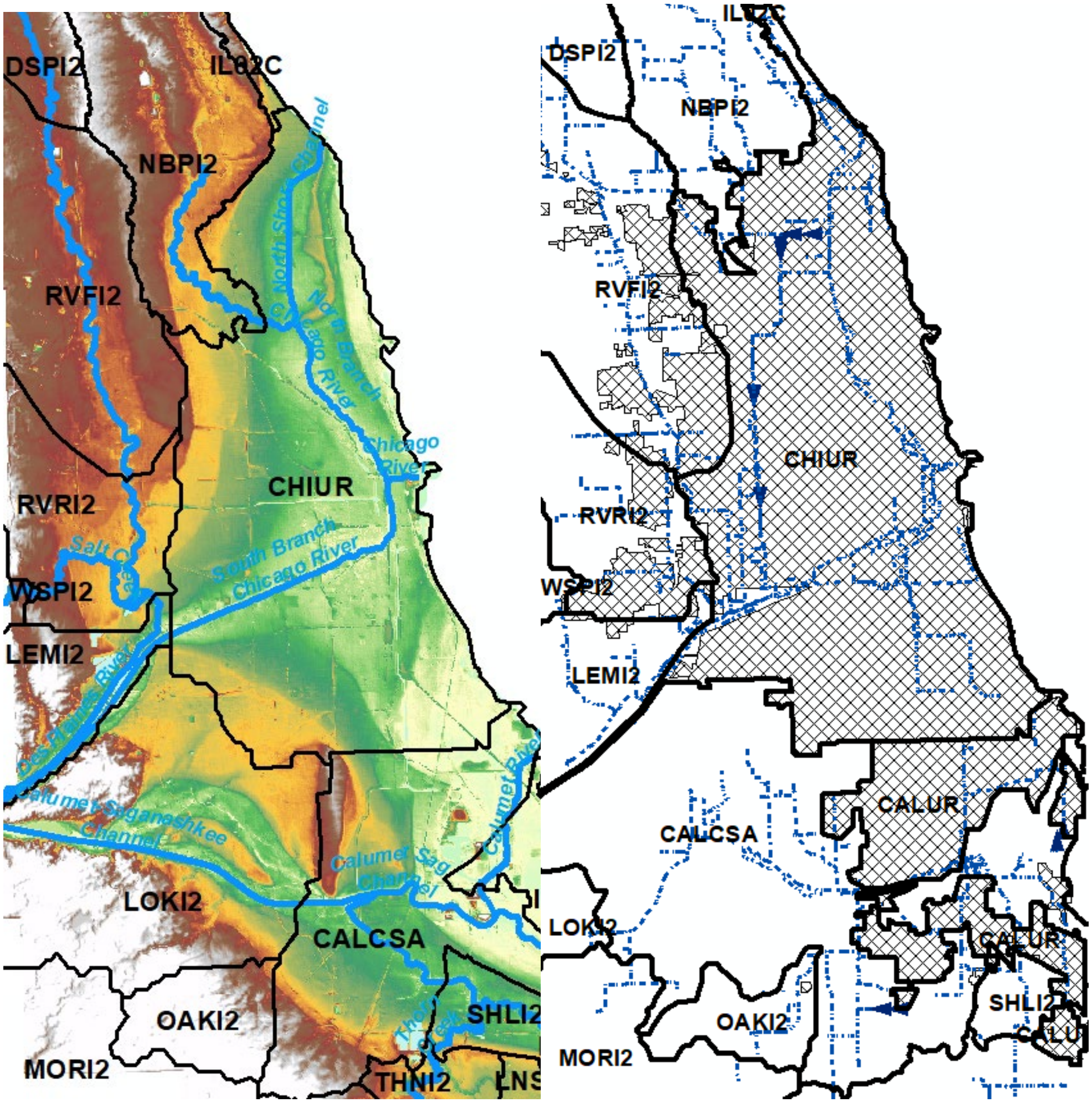

Figure 17. River basins delineated from elevation data alone (left), and river basins further refined based upon the location of intersector sewers and general flow directions (right). Municipalities with combined storm and sanitary sewers (hatching) were also used to refine the basin delineations because areas outside of the combined sewer area would have separate storm sewers which likely followed the surface topography to nearby waterways. The North Branch Chicago River at Pulaski Road basin uses the “NBPI2” identifier, the Little Calumet River at South Holland basin uses the “SHLI2” identifier, the Chicago Urban basin uses the “CHIUR” identifier, and the local contributions to the Cal-Sag Channel are indicated with the “LOKI2,” “CALCSA,” and “OAKI2” basin identifiers. A large portion of the uncertainty in basin delineation is related to whether or not combined sewer areas in the Des Plaines at River Forest (RVFI2) and Des Plaines at Riverside (RVRI2) basins are instead included as part of the Chicago Urban (CHIUR) basin.

3.3 Infiltration/Runoff Modeling

Infiltration and runoff processes were modeled using the Soil Moisture Accounting method in HEC-HMS. This is the closest infiltration modeling method to the SAC-SMA method used in NWS river forecasting. Parameters for the HEC-HMS method were estimated using a comparison between methods shown by Table 5. There are multiple similarities between the methods, including soil moisture being conceptualized as a combination of reservoirs or buckets which fill during precipitation and empty through evapotranspiration, percolation, or lateral movement to streams. Both methods break up these reservoirs into zones, with water infiltrating and percolating from upper zones to lower zones. Some parameters are not directly comparable, however, leading to likely uncertainties in the HEC-HMS calibration as well as the eventual conversion back to SAC-SMA parameters for operational modeling.

The SAC-SMA parameters currently used by NCRFC (Table 6) were converted to HEC-HMS parameters (Table 7) and then used as a starting point for further calibration. The HEC-HMS model also includes some modeling steps that are not available as part of SAC-SMA or the larger NWS river forecasting systems, including modeling of canopy interception and storage as well as soil surface storage. More detailed information about the SAC-SMA method and its variables can be found in Burnash (1995). Canopy storage was estimated using GIS datasets of tree canopy coverage and dominant tree types, combined with a look-up table of canopy interception, and then averaged by basin. Soil storage values were very crudely estimated and then updated through manual calibration. The runoff/infiltration for each modeled basin was then connected with municipal water use, and modeled routing, and a modeled reservoir, to complete the hydrologic model (Figure 18). More details about these other components will be covered in the following subsections.

Table 5. Comparison of soil moisture accounting parameters used by SAC-SMA and the parameters used by the HEC-HMS method.

HEC-HMS	**SAC-SMA**	**Comments**
Soil Storage	UZFWM+UZTWM +LZTWM	Maximum water content of the near-surface soil. Equivalent to the entire SACSMA Upper Zone max contents plus Lower Zone tension max contents.
Tension Storage	UZTWM+LZTWM	Portion of Soil Storage that does not drain due to gravity and can only be removed through transpiration. Equivalent to the SACSMA Upper Zone and Lower Zone tension max contents.
GW1 Storage	LZFPM	Maximum water content of the upper groundwater layer. Possibly equivalent to the Lower Zone Primary max contents.
GW2 Storage	LZFSM	Maximum water content of the lower groundwater layer. Possibly equivalent to the Lower Zone Supplemental max contents.
Max Infiltration	None	Max rate of infiltration from surface into Soil Storage. SAC-SMA has no limit to this rate. Good estimate may be saturated hydraulic conductivity, or some multiple thereof.
Soil Percolation	MAX_PERC	Max rate of percolation from Soil Storage to GW1 Storage. "Max Percolation" used with SAC-SMA is derived from the equation MAX_PERC=(LZFSM*LZSK)+(LZFPM*LZPK)*(1+ZPERC). Although assumed to be equivalent, the values appear quite large.
GW1 Percolation	*None*	Max rate of percolation from GW1 Storage to GW2 Storage. GW1 percolation is the constant rate of water moving from GW1 to GW2. SAC-SMA treats all lower zone buckets as existing in the same vertical space, so no water moves between them.
GW2 Percolation	SIDE	Max rate of percolation from GW2 Storage out of the system (into deep aquifers). SAC-SMA uses SIDE to determine the ratio of LZSK/LZPK water that leaves the system rather than going to baseflow. Another good estimate here might be soil percolation rate or saturated hydraulic conductivity.
GW1 Coefficient	*None*	Representation of lag between peak contents of GW1 Storage and peak baseflow contributions. In SAC-SMA, the baseflow contribution is estimated by a constant rate (LZPK/LZSK), so there are no direct equivalents.
GW2 Coefficient	*None*	Representation of lag between peak contents of GW2 Storage and peak baseflow contributions.
None	PFREE	
one	RSERV	
None	ADIMP	In SAC-SMA, this corresponds to additional impervious areas.
None	RIVA	

Table 6. SAC-SMA parameters currently in the operational forecasting system at NCRFC. Because HEC-HMS does not use SAC-SMA but instead its own soil moisture accounting model, SAC-SMA values were used to estimate HEC-HMS soil moisture accounting method values.

Parameter	**CHIURB**	**NBPI2**	**RVRI2**	**CALCSA**
UZFWM	55.0	55.0	45.0	45.0
UZTWM	55.0	55.0	25.0	25.0
LZFPM	100.0	100.0	50.0	50.0
LZFSM	30.0	30.0	14.0	14.0
LZTWM	200.0	200.0	120.0	120.0
UZK	0.52	0.52	0.03	0.30
LZPK	0.02	0.02	0.01	0.01
LZSK	0.15	0.15	0.11	0.11
ZPERC	210.0	210.0	135.0	135.0
REXP	1.7	1.7	1.2	1.2
PXADJ	1.0	1.0	1.0	1.0
PEADJ	1.0	1.0	1.0	1.0
PFREE	0.2	0.2	0.3	0.3
RIVA	0.0	0.0	0.0	0.0
RSERV	0.3	0.3	0.3	0.3
SIDE	0.00	0.00	0.00	0.00
PCTIM	0.15	0.15	0.10	0.02
ADIMP	0.00	0.00	0.00	0.00
ET-JAN	0.1	0.1	0.3	0.3
ET-FEB	0.3	0.3	0.5	0.5
ET-MAR	0.5	0.5	0.9	0.9
ET-APR	2.6	2.6	1.8	1.8
ET-MAY	3.4	3.4	3.4	3.4
ET-JUN	4.0	4.0	4.4	4.4
ET-JUL	4.1	4.1	4.5	4.5
ET-AUG	3.7	3.7	3.6	3.6
ET-SEP	3.3	3.3	2.6	2.6
ET-OCT	2.3	2.3	1.5	1.5
ET-NOV	0.1	0.1	0.7	0.7
ET-DEC	0.1	0.1	0.4	0.4

Table 7. Estimated HEC-RAS soil moisture accounting method parameters derived from SAC-SMA parameters. Values used as a starting point for Chicago River hydrologic modeling development and calibration.

Parameter	CHIURB	NBPI2	RVRI2	CALCSA
Soil Storage (in)	4.3	4.3	2.8	2.8
Tension Storage (in)	2.2	2.2	1.0	1.0
Max Infiltration (in/hr)	0.36	0.36	0.46	0.68
Soil Percolation (in/hr)	0.07	0.07	0.09	0.14
GW1 Storage (in)	7.90	7.90	6.70	6.70
GW1 Perc (in/hr)	0.07	0.07	0.09	0.14
GW1 Coeff (hr)	60.0	60.0	39.9	39.9
GW2 Storage (in)	5.1	5.1	0.6	0.6
GW2 Perc (in/hr)	8.27	8.27	5.31	5.31
GW2 Coeff (hr)	60.0	60.0	39.9	39.9
Impervious %	65.0%	35.0%	50.0%	45.0%
ET-JAN	0.1	0.1	0.3	0.3
ET-FEB	0.3	0.3	0.5	0.5
ET-MAR	0.5	0.5	0.9	0.9
ET-APR	2.6	2.6	1.8	1.8
ET-MAY	3.4	3.4	3.4	3.4
ET-JUN	4.0	4.0	4.4	4.4
ET-JUL	4.1	4.1	4.5	4.5
ET-AUG	3.7	3.7	3.6	3.6
ET-SEP	3.3	3.3	2.6	2.6
ET-OCT	2.3	2.3	1.5	1.5
ET-NOV	0.1	0.1	0.7	0.7
ET-DEC	0.1	0.1	0.4	0.4

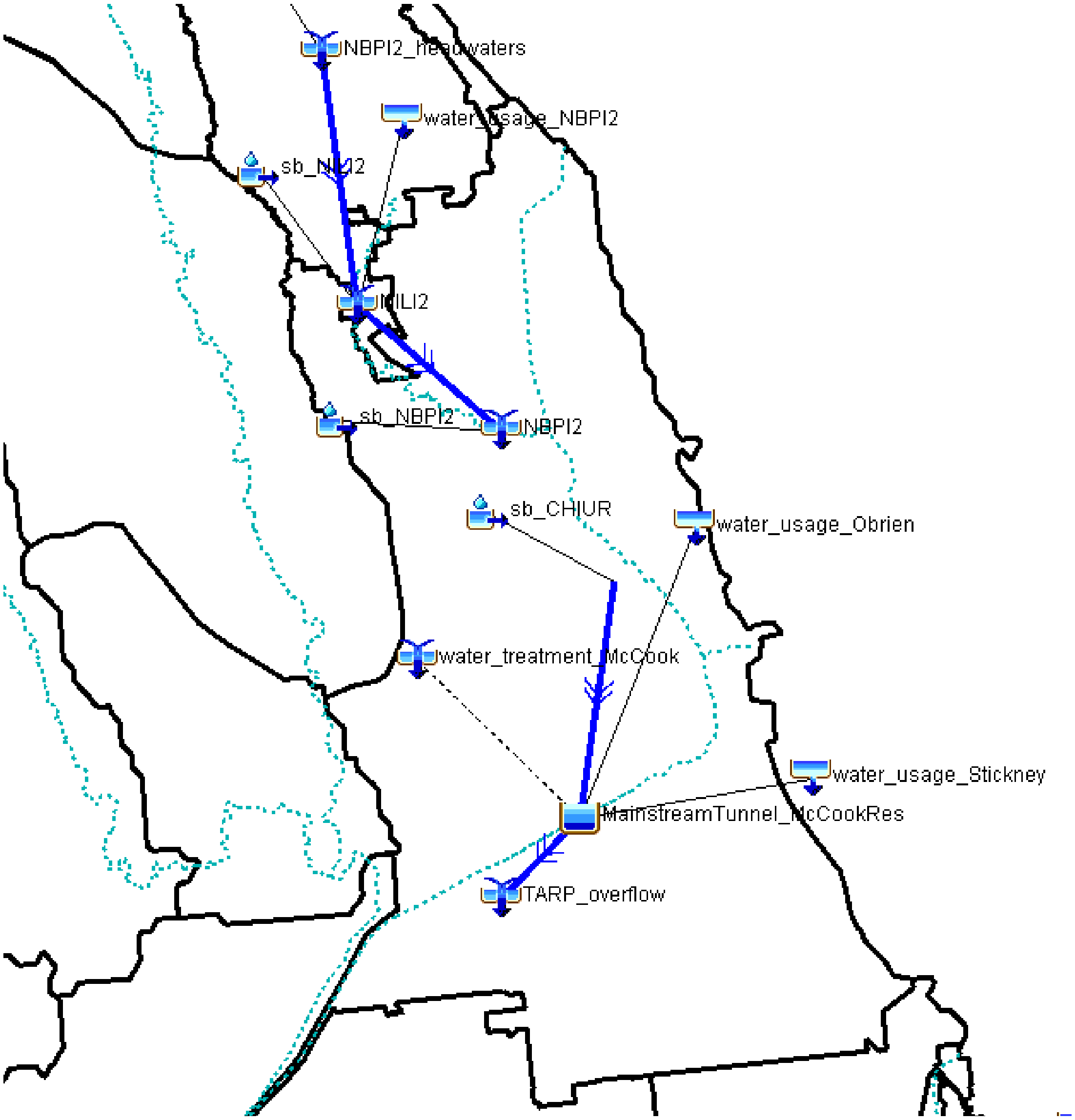

Figure 18. Schematic of elements in the HEC-HMS hydrologic model. The “sb” prefix indicates infiltration/runoff modeling for a given subbasin. The “water_usage” prefix indicates a set flow rate of water being added to the basins based upon water usage (and eventual treatment) from Lake Michigan.

3.4 Sewer and Tunnel Streamflow Modeling

Movement of water through the various sewers and tunnels is handled by a few different parts of the simplified hydrologic modeling. In the GLMRIS study, the sewers and tunnels are modeled more explicitly using specially designed pipe models and hydraulic models. Due to the complexity and time consuming nature of these modeling methods, the Chicago River operational forecast model must represent these processes in a much simpler way. Movement of water across the land surface and through the local combined sewer systems is approximated by a basin's unit hydrograph. Movement of water through the interceptors and deep tunnels is handled by the lag-k hydrologic routing method.

Unit hydrograph lag time for each basin was very crudely estimated, and then updated through manual calibration. The lag time between rainfall and tunnel/reservoir water level response was found to be quite short, so the routing method was initially given a lag of just 1 hour and a k value (averaging) of 0 hours.

3.5 Sewer, Tunnel, and Reservoir Storage Modeling

Although water moves through the combined sewers, interceptors, and deep tunnels, it is also effectively being stored in those areas. Storage of water is also simplified in the hydrologic model, with a single modeled reservoir representing the combined storage capacity of McCook Reservoir, the Mainstream Deep Tunnel, the interceptor sewers, and the local near-surface sewers. The elevation-storage relationship for McCook Reservoir and the Mainstream Deep Tunnel were provided by MWRD. Estimates for storage capacity of the interceptor sewers and local combined sewers were estimated through GIS means.

A shapefile of the interceptor sewers was provided by MWRD. For each feature (sewer section) in the shapefile, information about elevation, width, and height was provided. This shapefile was first clipped to the extent of the Chicago Urban (CHIUR) basin. Then the length of each line segment was calculated. The volume of each sewer section was then calculated based upon the length, width, and height.

No shapefile of local combined sewers was available. To approximate the location of local combined sewers, it was assumed that most local roadways would be co-located with a sewer. A shapefile of roadways was used with the interstate highways and expressways removed. Then, the shapefile was clipped to match the extent of the Chicago Urban (CHIUR) basin. Drainage regulations for the state of Illinois indicate that storm sewers should be at least 8-12 inches in diameter. It was assumed that most residential streets would have an 8-in diameter sewer, while major arterial roadways would have a 12-in diameter sewer. The length of each roadway segment was then calculated. The local combined sewer volume was thus estimated using the segment length with the cross-sectional area of the assumed diameter. This assumption is uncertain because much of the infrastructure of Chicago and nearby suburbs may have been built prior to these regulations being issued. On the other hand, these regulations represent a minimum capacity and are for storm sewers, not combined storm and sanitary sewers, which might suggest larger pipes are used.

The elevation-storage relationship for each component - McCook Reservoir, Mainstream Deep Tunnel, interceptor sewers, and local combined sewers - were combined to create a single elevation-storage curve for the hydrologic model. Because this single modeled reservoir was meant to represent storage in multiple locations at separate depths below the surface, the exact elevations of each of these components would not necessarily be applicable when creating the elevation-storage relationship required by the hydrologic model. The local combined sewers and the interceptors would generally be filled prior to water entering the deep tunnels and reservoirs, so it was assumed that the majority of the storage of these components should show up in the lower elevations of the relationship. This would effectively cause the modeled reservoir to rise more slowly at first for a given rate of water entering it, representing a storage amount that would need to be "overcome" prior to a substantial rise in the reservoir occurring (Figure 19).

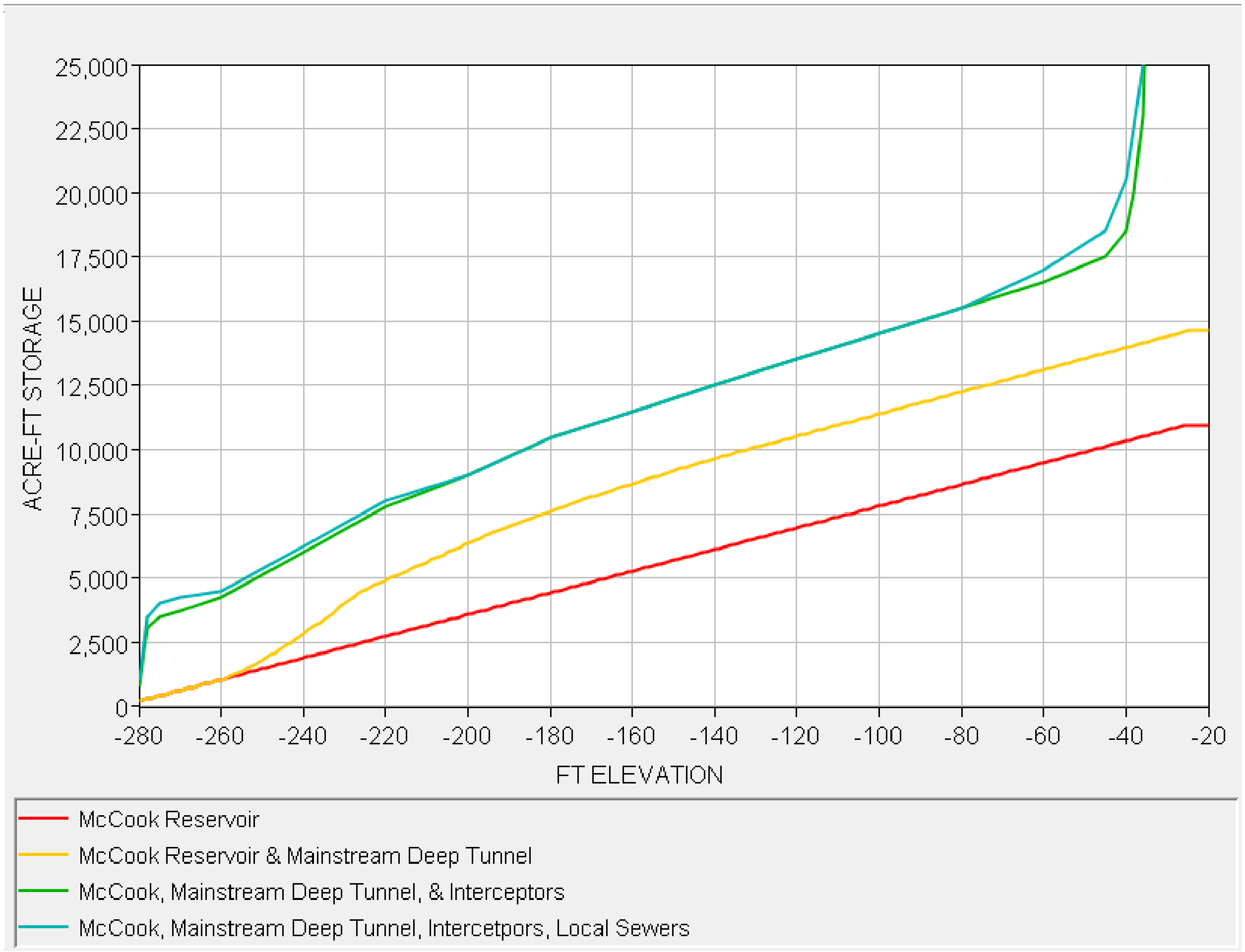

Figure 19. The elevation-storage relationship for various components of the Chicago Urban basin drainage network added together. Although McCook Reservoir is the single largest component by storage, storage in the Mainstream Deep Tunnel, interceptor sewers, and local combined sewers is non-trivial.

A large spillway was added to the modeled reservoir such that when it exceeded capacity, water would spill out. This was meant to approximate a combined sewer overflow event where McCook Reservoir is full, the Mainstream Deep Tunnel is full, and water in the interceptors no longer is sent down the drop shafts but instead is sent through outfalls to the river. The spillway was given a very large length and very high coefficients to minimize the lag introduced between excess runoff entering the reservoir and that runoff spilling out. The reservoir overflow was sent to the hydraulic model as a boundary condition, with the flow broken up into the CSO groups and multiplied by the relative proportion for each.

A smaller spillway with specified elevation-discharge curve was added to the model to represent water removed from the Mainstream Deep Tunnel and McCook Reservoir by the water reclamation plants. The elevation-discharge curve for this spillway was created using the published maximum capacities of the treatment plants - 1584 cfs and 366 cfs for the Stickney and O'Brien Water Reclamation plants, respectively. The curve was adjusted to make discharge 0 cfs when the modeled reservoir is empty.

3.6 Municipal Water Use Accounting

Water usage and water treatment by the water reclamation plants is simulated by the hydrologic model. Water usage was derived from the Illinois State Water Survey map of 7-day averaged, 10-year ARI streamflows for northeast Illinois, used to help plan for drought conditions (Illinois State Water Survey 2003). These maps highlight areas where water is removed from, and added to, area rivers which could impact the amount the streamflow during droughts. The Illinois State Water Survey analysis indicates 703 cfs, 265 cfs, and 213 cfs for the treated releases from Stickney, O'Brien, and Calumet Water Reclamation plants, respectively. A small seasonal cycle was added to these estimates (Figure 20). The estimated water use at the Stickney and O'Brien plants was added directly to the modeled reservoir representing McCook and the Mainstream Deep Tunnel, because those water reclamation plants generally serviced an area consistent with the Chicago Urban (CHIUR) basin. The estimated water use at the Calumet Water Reclamation Plant was added to the Little Calumet River streamflow, and then this combined streamflow was sent to the hydraulic model.

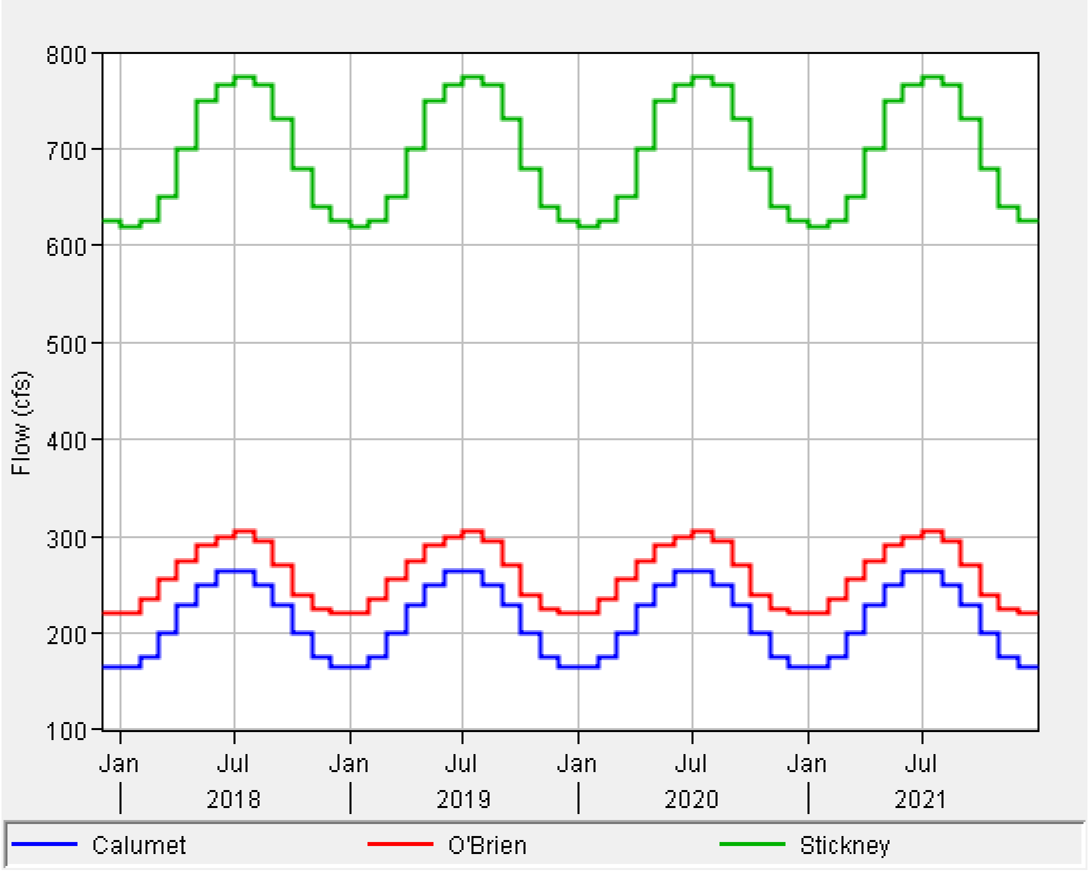

Figure 20. The estimated municipal water usage for the areas serviced by the Stickney, O'Brien, and Calumet Water Reclamation plants. Water usage was derived from published values by the Illinois State Water Survey with a season cycle added.

3.7 Comparison of Modeled McCook Reservoir Stages to Observations

To calibrate the hydrologic model, modeled elevations for the combined, simulated reservoir were compared to observations for McCook Reservoir (Figure 21). Because the modeled reservoir is meant to depict multiple areas of water storage within the drainage network of the Chicago Urban basin, perfect agreement between modeled water levels and observations would not be expected, especially at lower water levels where other storage areas would be filling up prior to McCook Reservoir. Despite the potential challenges, manual adjustments were made to the hydrologic model parameters to make modeled water levels better match observed water levels. Observation data for McCook Reservoir roughly spanned May 2019 through October 2021, and the model run started in March 2019 to allow for some “spin-up” time.

Calibration was a long, iterative process, involving both automatic calibration (MonteCarlo simulations) as well as manual calibration. In general, parameters were calibrated to have more storage and higher infiltration/percolation rates than expected from the original SAC-SMA parameters and area soil types. Slight adjustments were also made to the monthly evapotranspiration demand curve, including a reduction in peak summer values and increases to spring/fall values.

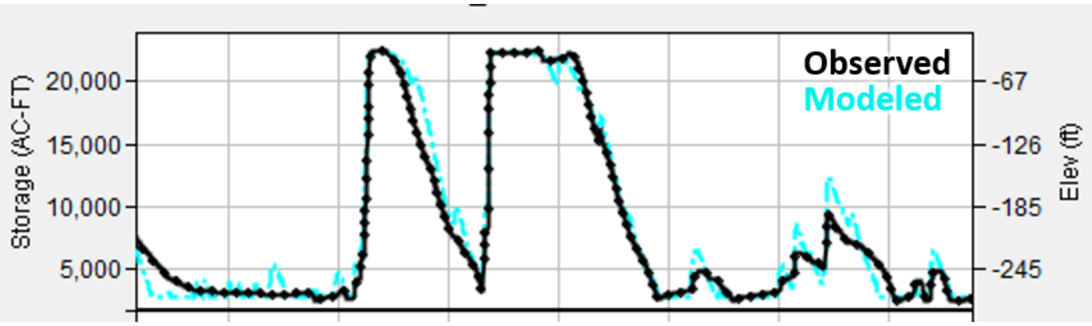

Figure 21. Example comparison between modeled water elevations in the combined, simulated reservoir of the hydrologic model and the observation water elevations for McCook Reservoir.

The unit hydrograph lag time was decreased to make the runoff reach the modeled reservoir faster and increase the rate of climb at the beginning of events. The specifications of the synthetic spillway at the top of the modeled reservoir was also adjusted to make “overflow” runoff leave the reservoir at a faster rate. Tweaks were made to groundwater capacities and percolation rates to reduce the amount of baseflow which entered the reservoir between rainfall events. Changes to the near surface soil capacity and infiltration rates were more difficult; changes were not made to these parameters without additional guidance from calibration of nearby basins.

Although streamflow from the North Branch Chicago River at Pulaski Road would be handled by the existing modeled subbasin in NCRFC’s forecasting system, this basin was also set up in the hydrologic model to evaluate the model performance. Parameters for this basin were derived in a similar fashion as mentioned above for the Chicago Urban basin. An automatic calibration was then set up in HEC-HMS. The MonteCarlo calibration approach was used, with multiple parameters allowed to vary as part of the calibration. Near-surface soil capacity, maximum infiltration rate, percolation rates, and groundwater capacities were all calibrated. After multiple calibration runs of thousands of simulations, no convergence occurred, meaning the calibration routine was not able to find a stable set of parameters matching a target threshold. Output from the calibration routine did show an improvement in the simulated water levels against observations over the calibration period, however. Parameters with improved modeling results included high infiltration rates, high percolation rates, and increased soil storage capacities (compared to the values estimated from those derived from NCRFC's SAC-SMA).

4.0 Verification of Combined Hydrologic and Hydraulic Model

Once a suitable hydrologic model was found from manual and automatic calibrations, it was connected to the previously developed hydraulic model. The best combination of model terrain, land cover, boundary conditions, and 2D mesh geometries was used to create the final draft model for operational use, referred to as Operational Modeling Candidate 1. Operational Modeling Candidate 1 was then compared to observed water levels in the Chicago River over the March 2019 through October 2021 period for verification.

For comparison purposes, a second hydrologic model was created which was essentially the hydrologic and hydraulic models merged together. Not only were reservoir, deep tunnel, and sewer storage handled by the hydrologic model, but the Chicago Waterway itself was modeled as a reservoir. This modeling approach was referred to as Operational Modeling Candidate 2. This model was also compared to observed water levels in the Chicago River over the March 2019 to October 2021 period.

Operational Modeling Candidate 1

Operational Modeling Candidate 1 was based upon Simulation 9 (see Table 4 in section 2.4.4). Simulation 9 included explicitly modeled gates at Lockport Lock, which were based upon gate dimensions in the GLMRIS study models, but substantially simplified. The Chicago waterway was modeled in a continuous drawdown state with a target elevation of 574.5 ft (typical values approximately 576.5-577.0 ft, with drawdowns reaching approximately 574.0-574.5 ft). More discussion on this boundary condition can be found in section 2.2.2. A comparison of modeled water levels to observed water levels over the March 2019 through October 2021 period is shown by Figure 22.

Model performance for individual rainfall events was generally reasonable. During the late-April through early-June 2019 period, multiple heavy rainfall events occurred which triggered combined sewer overflow events and river rise. Spring 2019 contained multiple examples of model performance during relatively minor sewer overflow and river rise events (Figure 23). Although streamflow at Lemont was under-simulated, especially early in the event during drawdown periods, the highest stage crest was within 1 foot. Fall 2019 contained examples of model performance for multiple rain events with little-to-no observed river rise (Figure 24). In contrast, the modeled crest for the significant flood event of May 2020 was within inches of observations, despite continued streamflow under-simulation (Figure 25). During the mid-June through mid-July 2021 period, a multi-day period of rainfall occurred that was heavy enough to completely fill McCook Reservoir, but not heavy enough to lead to a significant river rise; model performance was reasonable for streamflow but over-simulated stage crests (Figure 26).

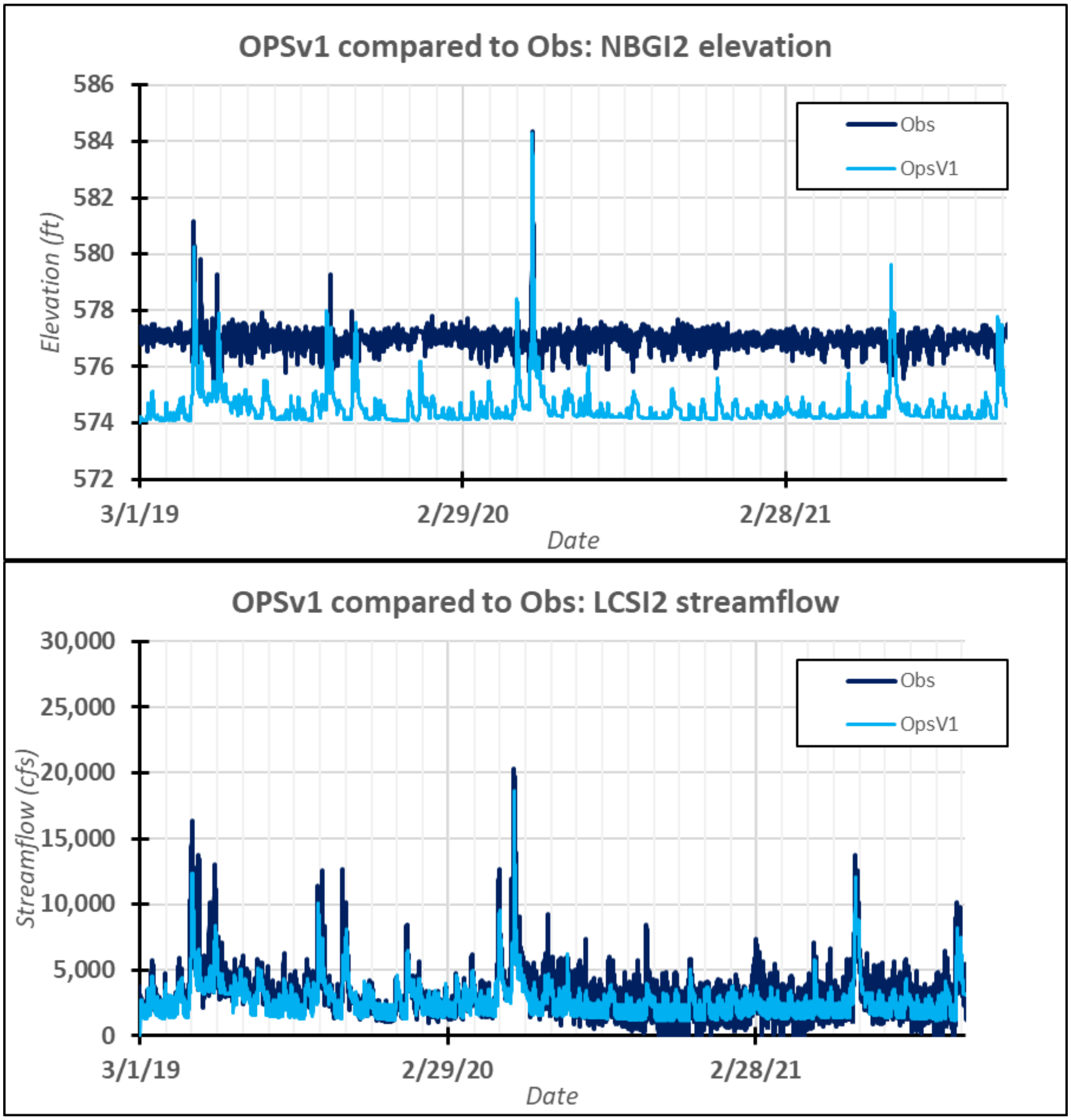

Figure 22. Modeled values using Operational Modeling Candidate 1 compared to observations for the NB Chicago River at Grand Avenue elevation (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont streamflow (LCSI2; bottom). Plots cover the entire verification period from March 2019 through October 2021.

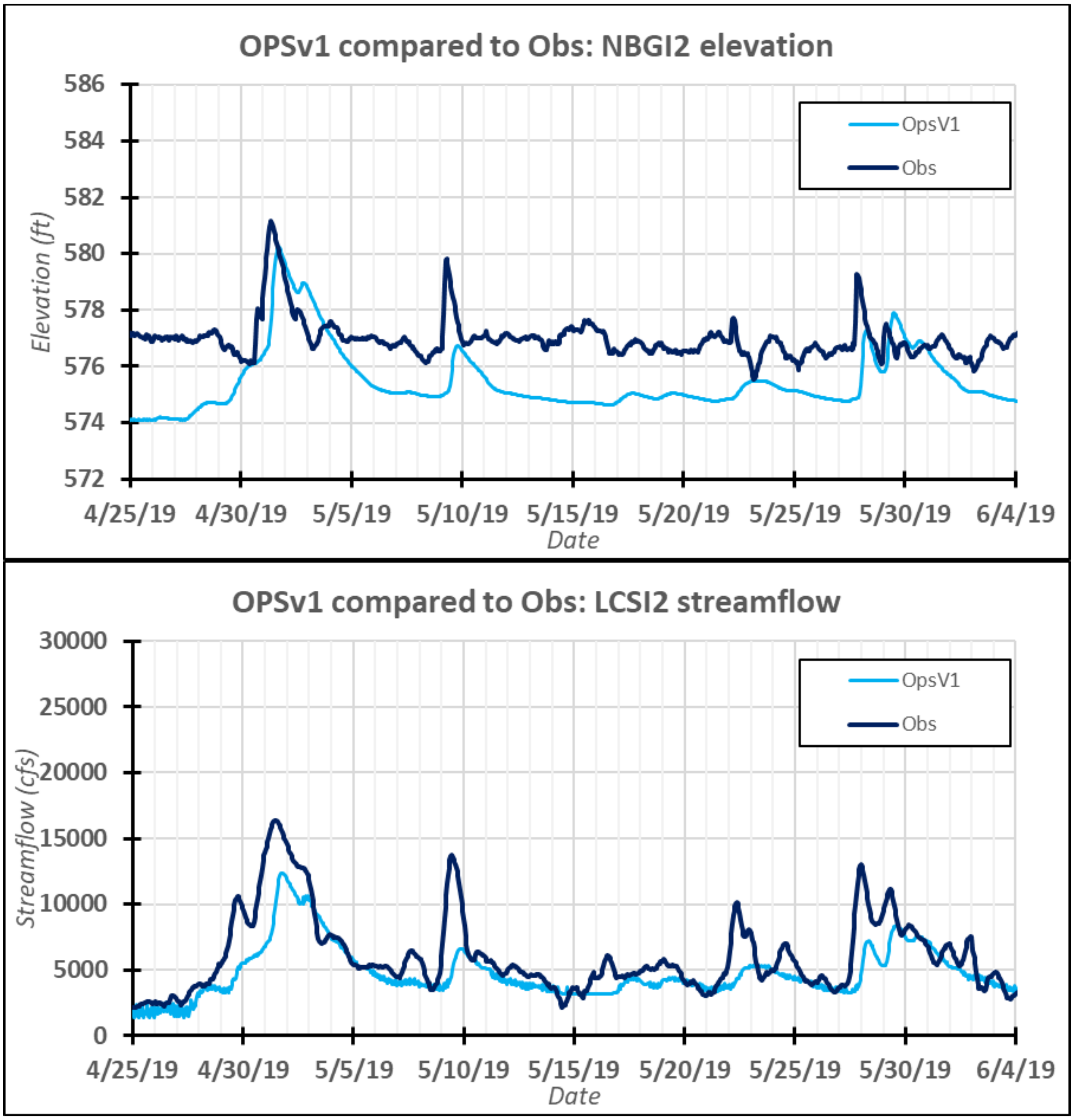

Figure 23. Comparison of Operational Modeling Candidate 1 to observations for a 40-day period in spring 2019, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for multiple relatively minor sewer overflow and river rise events.

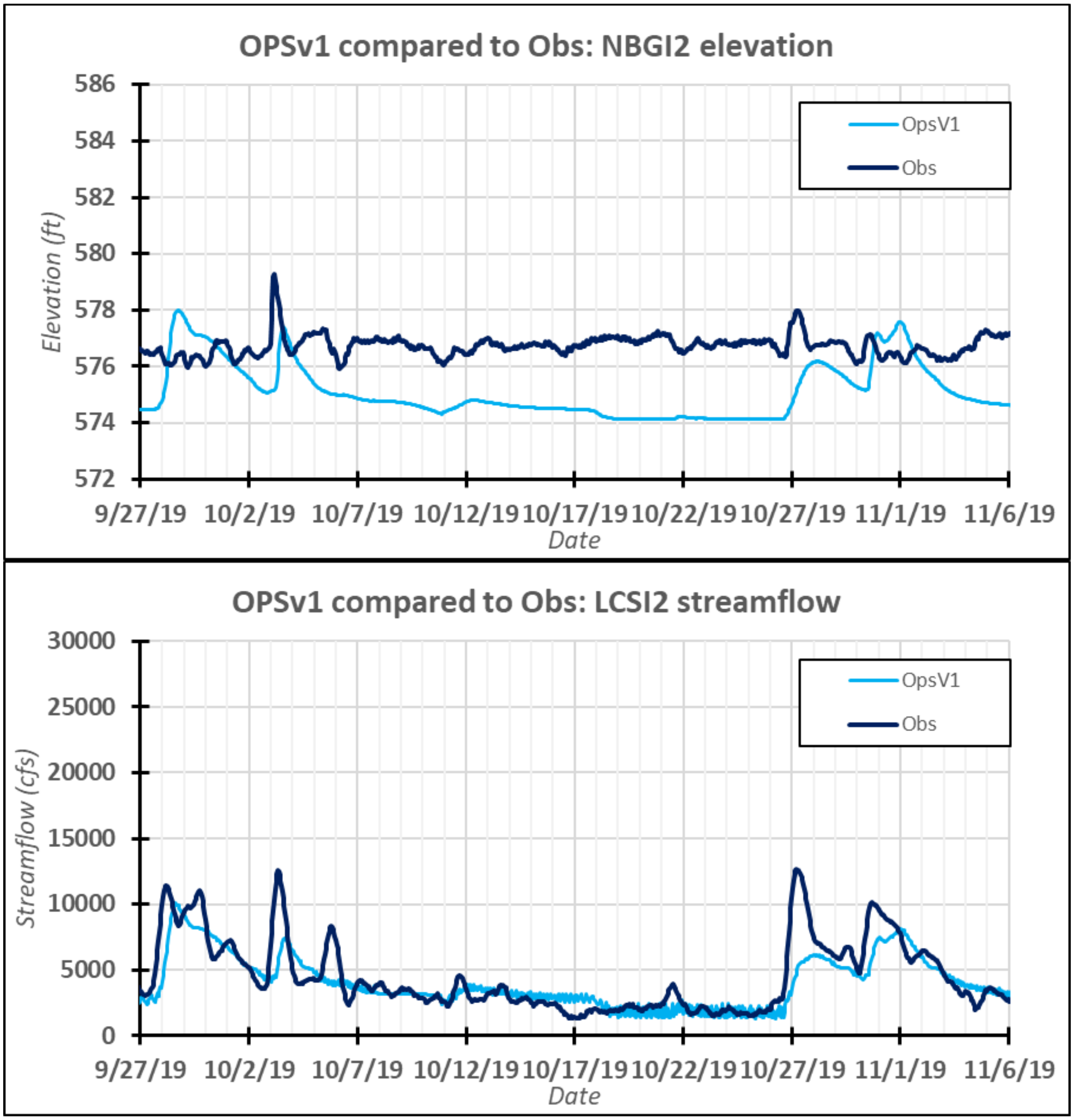

Figure 24. Comparison of Operational Modeling Candidate 1 to observations for a 40-day period in fall 2019, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for multiple rain events with little-to-no observed river rise.

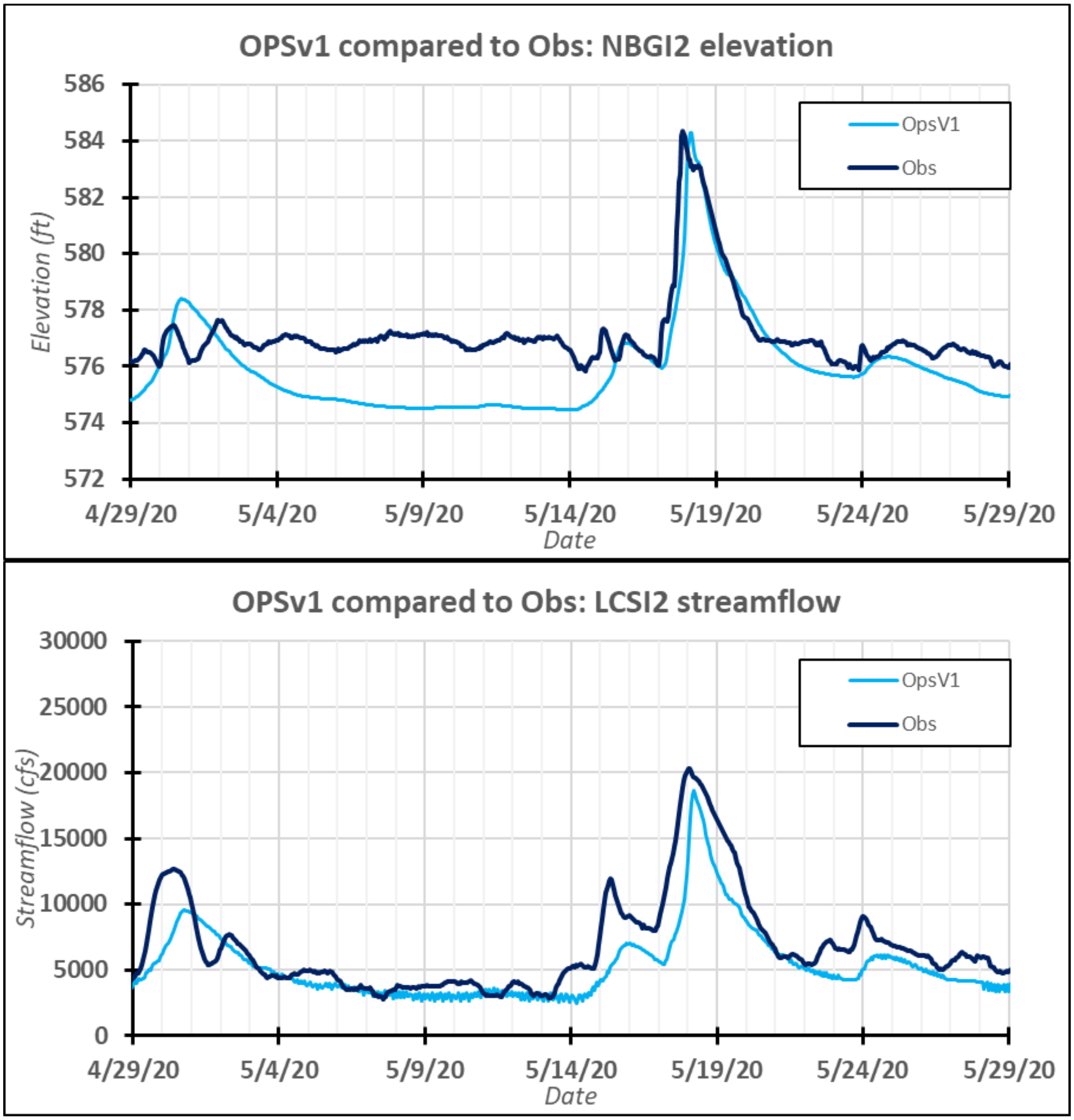

Figure 25. Comparison of Operational Modeling Candidate 1 to observations for a 30-day period in spring 2020, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for an impactful flood event that triggered the opening of Chicago Lock.

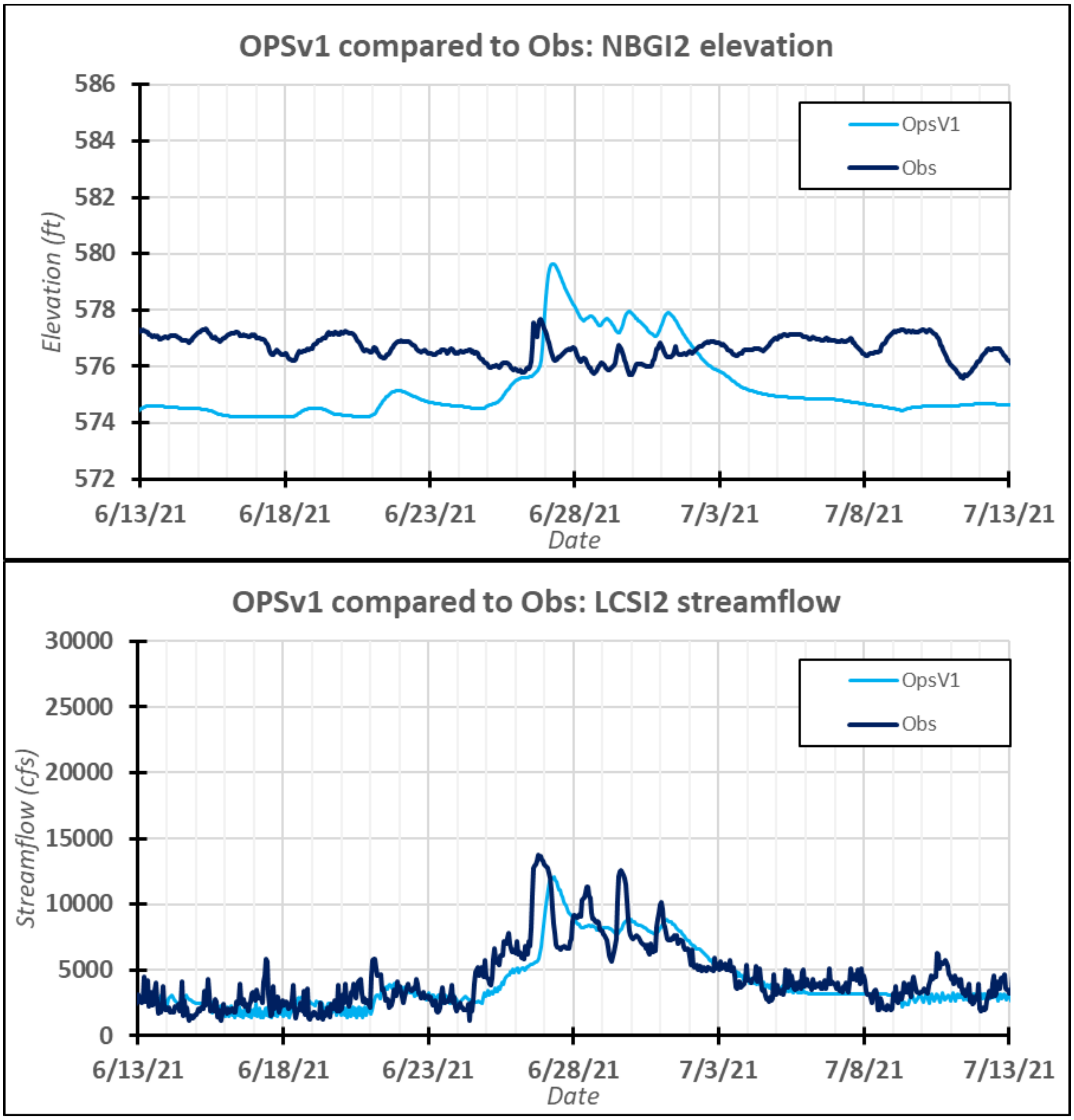

Figure 26. Comparison of Operational Modeling Candidate 1 to observations for a 30-day period in summer 2021, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for a multi-day period of heavy rain which was enough to cause McCook to reach capacity, but not large enough for a significant river rise.

Operational Modeling Candidate 2

Operational Modeling Candidate 2 was not expected to perform better than a hydraulic modeling approach, but was still tested to see how much forecast skill would be lost in exchange for greatly reduced processing times, as well as development and setup times. Operational Modeling Candidate 2 did have a reduced processing time compared to Operational Modeling Candidate 1 (less than 1 minute compared to approximately 13-16 minutes to simulate a 32-month period), and in many instances provided reasonable results (Figure 27).

Model performance for the late-April through early-June 2019 period, late-September to early-November 2019 period, May 2020, and the mid-June through mid-July 2021 period are shown by Figures 28-31.

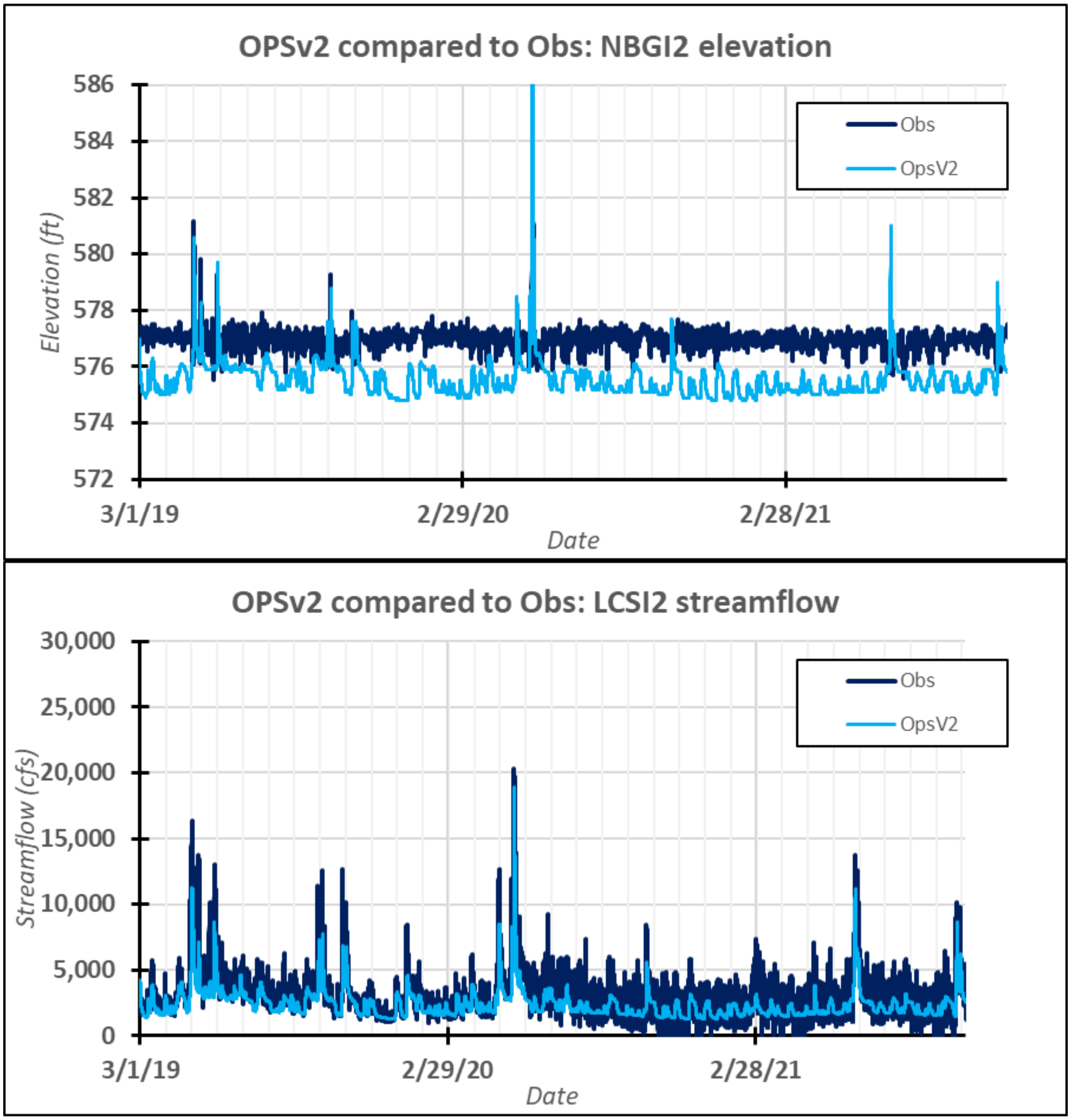

Figure 27. Modeled values using Operational Modeling Candidate 2 compared to observations for the NB Chicago River at Grand Avenue elevation (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont streamflow (LCSI2; bottom). Plots cover the entire verification period from March 2019 through October 2021.

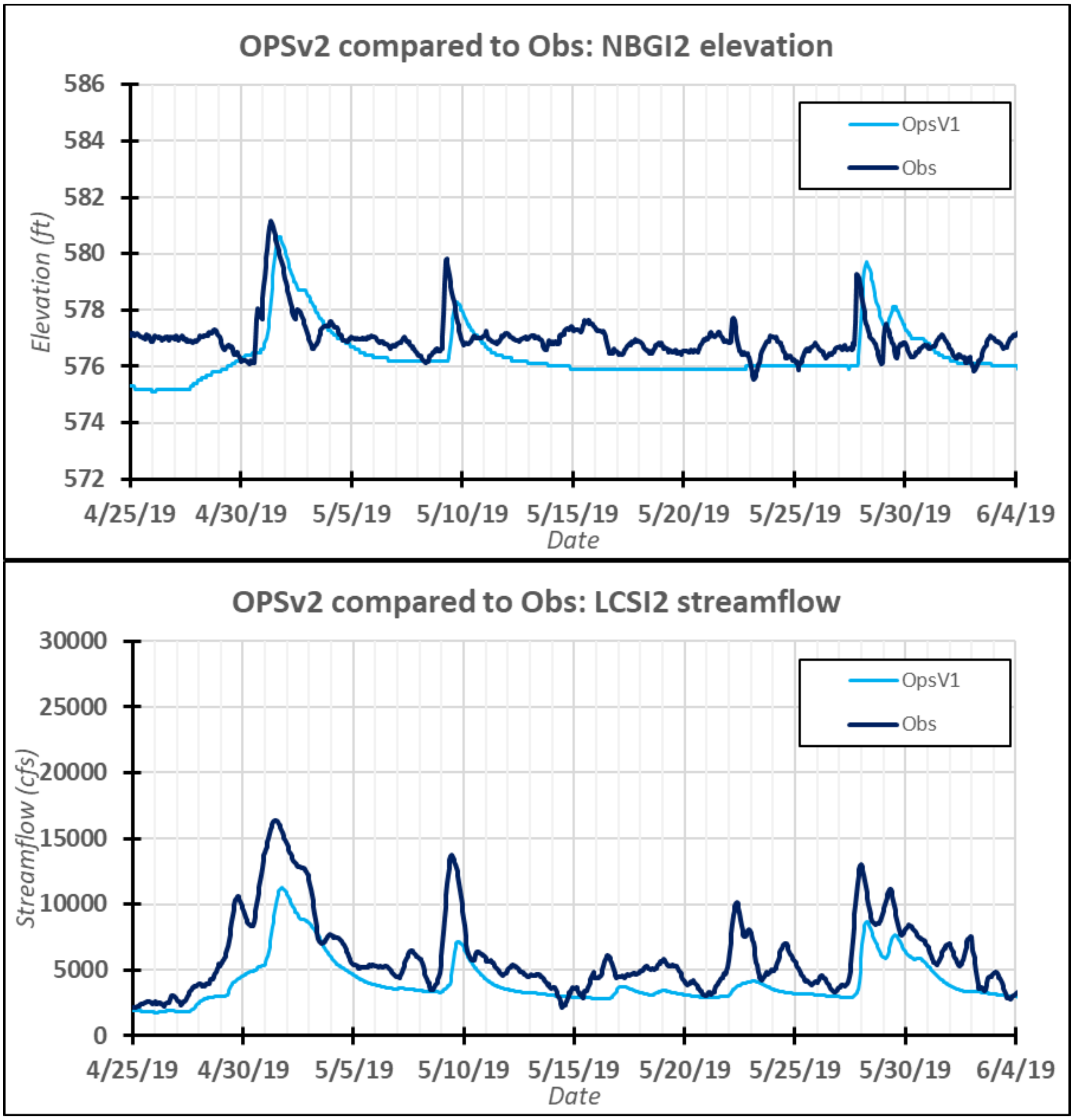

Figure 28. Comparison of Operational Modeling Candidate 2 to observations for a 40-day period in spring 2019, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for multiple relatively minor sewer overflow and river rise events.

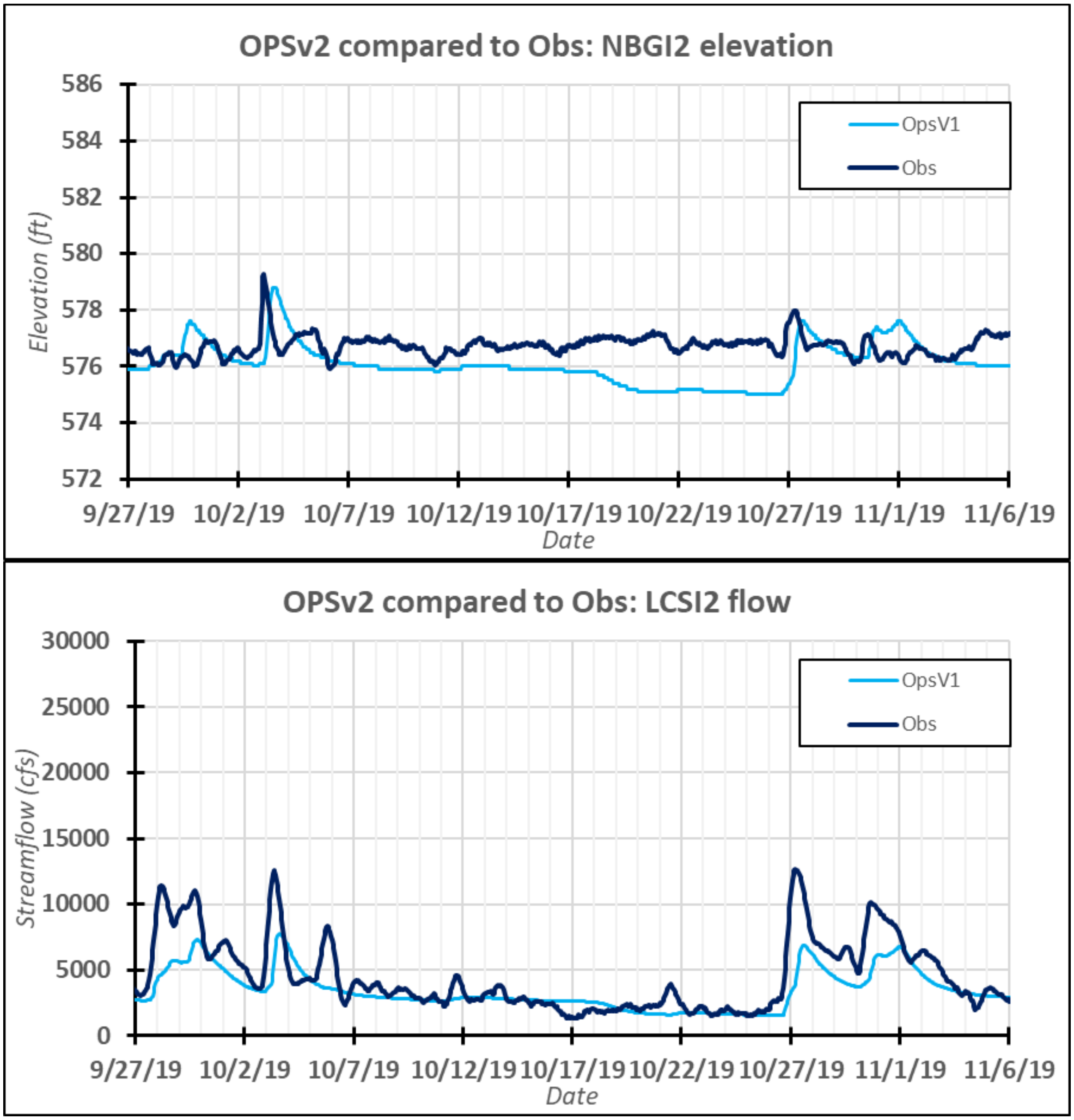

Figure 29. Comparison of Operational Modeling Candidate 2 to observations for a 40-day period in fall 2019, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for multiple rain events with little-to-no observed river rise.

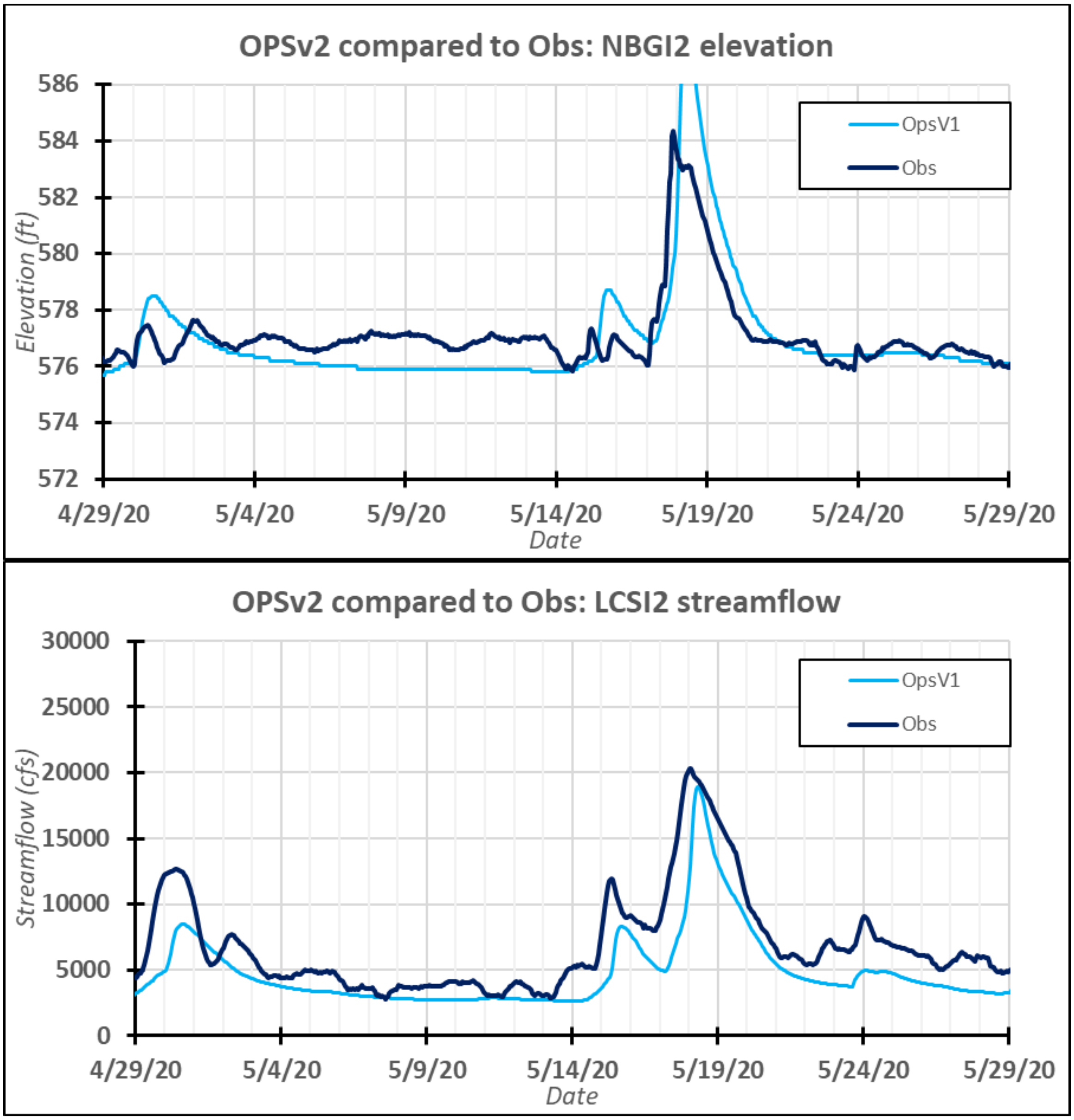

Figure 30. Comparison of Operational Modeling Candidate 2 to observations for a 30-day period in spring 2020, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for an impactful flood event that triggered the opening of Chicago Lock. Note that the entirely hydrologic Operational Modeling Candidate 2 does not have Chicago Lock modeled, which is likely a major cause of model crest over-simulation.

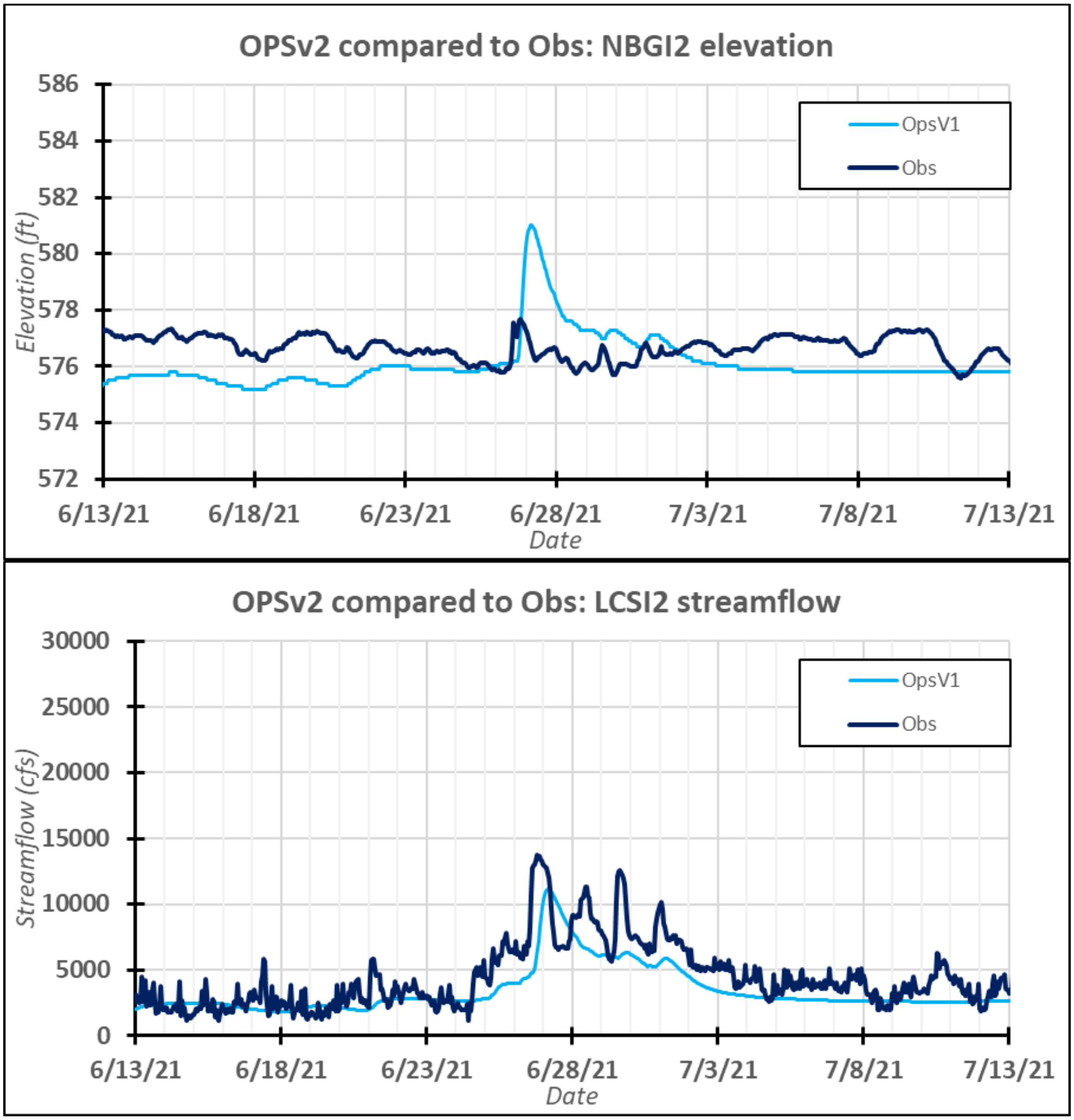

Figure 31. Comparison of Operational Modeling Candidate 2 to observations for a 30-day period in summer 2021, with NB Chicago River at Grand Avenue (NBGI2; top) and Chicago Sanitary and Ship Canal at Lemont (LCSI2; bottom). This period of time is an example of model performance for a multi-day period of heavy rain which was enough to cause McCook to reach capacity, but not large enough for a significant river rise.

5.0 Discussion

Many factors must be considered when developing an operational river forecasting model. The model must be accurate enough to provide meaningful warnings of flooding with reasonable lead time, but must have short run times. Model results should also be generally precise and consistent such that any biases can be corrected for by river forecasters. Weighing these factors for both Operational Modeling Candidate 1 (OpsV1) and Operational Modeling Candidate 2 (OpsV2) is tricky. The entirely hydrologic model, OpsV2, has a good balance of model run time and reasonable results. Unfortunately, study results showed OpsV2 would only be helpful in predicting the water level in downtown Chicago and couldn’t be used to model water levels and streamflows at multiple locations throughout the Chicago Waterway. OpsV2 also would be unable to explicitly show inundation during flood events.

OpsV1 generally has benefits that outweigh the negatives. Although OpsV1 has increased model run time compared to OpsV2, run times are still fast enough for operational forecasting needs. OpsV1 also provides much more information, such as water levels and streamflow at multiple locations throughout the 2D mesh. OpsV1 also has the capability to allow greater control by river forecasters, including explicit gate settings at Lockport Lock and Chicago Lock, which can improve modeling results and river forecasts. Based upon these considerations, OpsV1 was selected as the model for use in operational forecasting. The model was delivered to NCRFC in December 2021, and, as of the time of this report, is currently being developed for operational use in the existing modeling framework.

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Creating an Operational Forecasting System for the Chicago River

Appendix A: Creating Model Terrain for the Hydraulic Model

W. Scott Lincoln, NWS Chicago

1.0 Introduction/Background

A gridded topography/bathymetry elevation dataset is required for development of the Chicago River hydraulic model for operational forecasting. Some data already were available from existing models, but have some errors or lacks the spatial scope needed for development of an operational model. High-resolution elevation data for the overbank areas are also available from multiple sources. This report provides a summary of the data needs, existing data sources, challenges/problems with existing sources, and steps taken to develop the combined topography bathymetry elevation data set for the operational Chicago River model.

In addition to the terrain data, gridded land cover data is also required for model development as the land cover is used to estimate surface roughness (Manning's n values). The steps taken to prepare the necessary land cover data are briefly described.

1.1 Existing Data Sources

HEC-RAS models provided by US Army Corps of Engineers (USACE) Chicago District (LRC) and the Metropolitan Water Reclamation District of Greater Chicago (MWRD) each contained associated terrain data. These models also had bathymetry data at each of the modeled cross-section locations that could be interpolated and exported to a 2D grid. For the USACE model specifically, two versions exist, "8Sep" and "8Oct". Terrain elevation data are available from high-resolution light detection and ranging (LiDAR) data. LiDAR datasets are available from the state of Illinois (https://clearinghouse.isgs.illinois.edu/data/elevation/illinois-height-modernization-ilhmp). An overview of the available data sources is provided in the table below.

Elevation Data	Type	Spatial Scope	Resolution
USACE LRC HEC-RAS Model Terrain “8Sep”	Combined topography/bathymetry.	Portions of Cook, DuPage, Will, and Lake (IN) Counties. Includes bathymetry of NB Chicago River from near Pulaski Road to confluence with Chicago River, Northshore Channel, Chicago River, SB Chicago River, Chicago Sanitary & Ship Canal to Lockport, Des Plaines River from Lockport to near Joliet, Cal-Sag Channel, Calumet River, Grand Calumet River, Indiana Harbor Canal.	32.8 ft
USACE LRC HEC-RAS Model Terrain “8Oct”	Combined topography/bathymetry.	Portions of Cook, DuPage, Will, and Lake (IN) Counties. Includes bathymetry of NB Chicago River from near Pulaski Road to confluence with Chicago River, Northshore Channel, Chicago River, SB Chicago River, Chicago Sanitary & Ship Canal to Lockport, Des Plaines River from Lockport to near Joliet, Cal-Sag Channel, Calumet River, Grand Calumet River, Indiana Harbor Canal.	32.8 ft
USACE LRC channel data derived from cross-sections	Bathymetry	NB Chicago River from near Pulaski Road to confluence with Chicago River, Northshore Channel, Chicago River, SB Chicago River, Chicago Sanitary & Ship Canal to Lockport, Des Plaines River from Lockport to near Joliet, Cal-Sag Channel, Calumet River, Grand Calumet River, Indiana Harbor Canal	Variable (depends upon export settings set by user)
Cook County LiDAR	Overbank elevation/topography	Cook County, IL	3 ft
DuPage County LiDAR	Overbank elevation/topography	DuPage County, IL	1.5 ft
Will County LiDAR	Overbank elevation/topography	Will County, IL	2 ft
Lake County LiDAR	Overbank elevation/topography	Lake County, IN	5 ft

Gridded land cover data was available from the USGS National Land Cover Database (https://www.usgs.gov/centers/eros/science/national-land-cover-database). 2011 Land Cover data were used, which has a resolution of 30 meters (98 feet).

1.2 Documented Problems

A simplified model was created for test purposes to evaluate potential run times and performance of such a model for operational forecasting. The channel bathymetry and terrain data from the USACE GLMRIS model was used and the boundary conditions were set to match the boundary conditions used in the USACE model. Peak water levels for the “500-year ARI, Chicago Lock failure” scenario, as modeled by simplified model created by the National Weather Service, were at least a few feet higher than those from the USACE HEC-RAS model presented in their GLMRS study. A review of the detailed model output and underlying terrain data yielded the discovery of several problems. These problems may not cause serious problems in certain 1-D hydraulic models (depending on the selection of cross-section locations) but were at least partly to blame for the inaccurate test model results. Before performing additional model development, it was deemed necessary to further improve the terrain data.

1.2.1 Artificial Channel Constrictions

The first, and likely most serious, problem with the terrain data was found in the Chicago Sanitary & Ship Canal near river stations 299.0 to 300.0 in far western Cook County. Likely erroneous interpolations in the vicinity of small ports/harbors along the channel were encroaching on the main channel once the terrain data were resampled to a lower resolution (Figure 1).

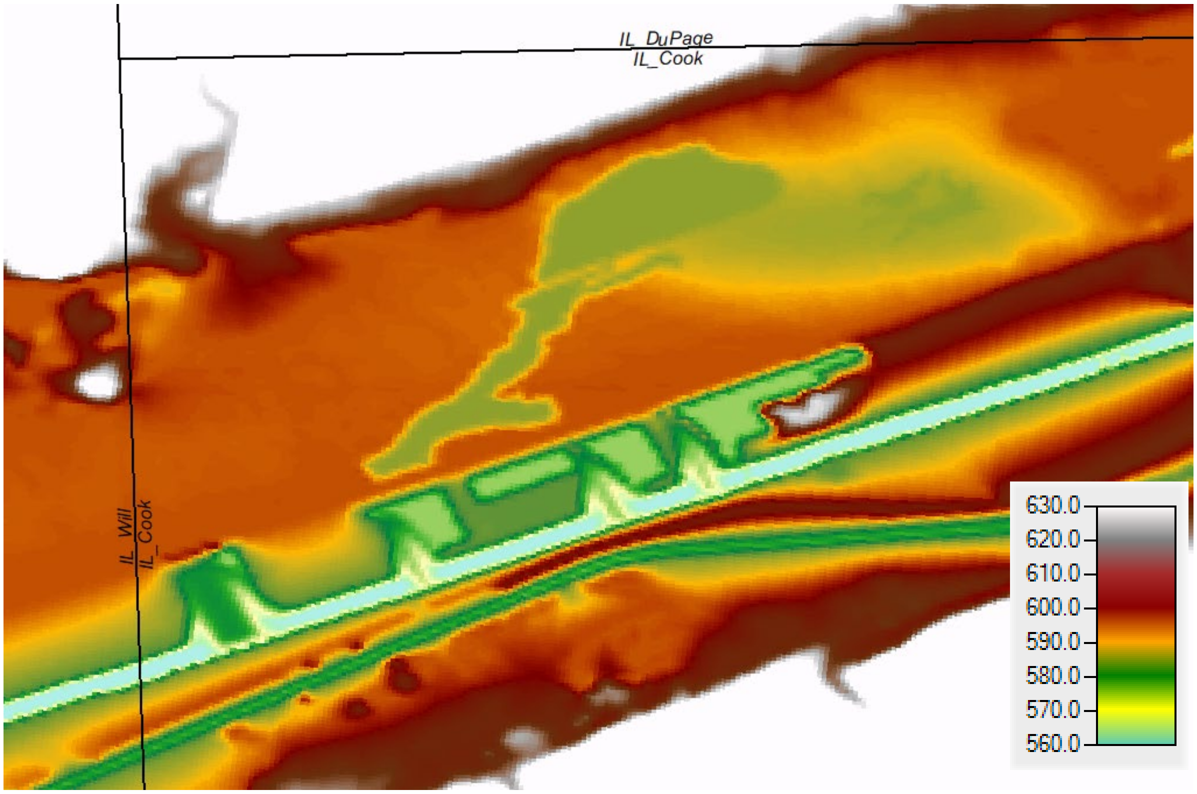

Figure 1. Combined topography/bathymetry data (elevation in feet) from USACE LRC's HEC-RAS model ("8Oct") showing likely erroneous data in far western Cook County. These artifacts at the location of the ports along the Chicago Sanitary and Ship Canal appear to have originated in the model cross-sections when they were interpolated/exported to a gridded bathymetry data set. When resampled to a lower resolution for creation of a model terrain, the artifacts encroached into the channel, causing a significant constriction.

1.2.2 Channel Mis-alignments with LiDAR Data

For the majority of channel sections throughout the study area, the channel data in the HEC-RAS models line up well with the expected channel location (based upon aerial imagery and the high-resolution LiDAR data). There is a notable misalignment of the channel data, however, just upstream of Lockport on the Chicago Sanitary & Ship Canal (Figure 2).

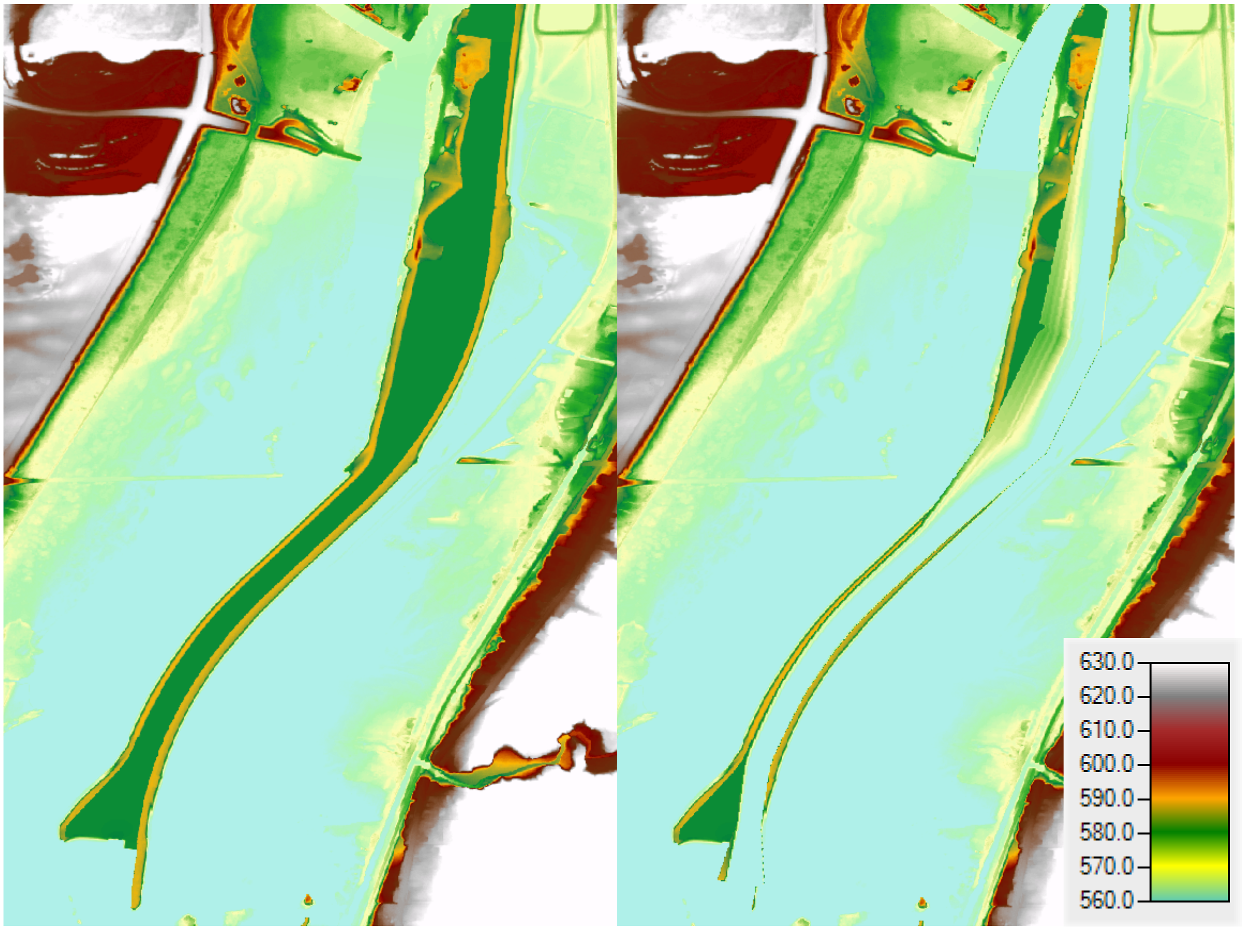

Figure 2. Will County LiDAR data (left) and Will County LiDAR data with exported/interpolated channel bathymetry overlaid (right). Channel bathymetry was exported at 10-ft resolution from the USACE LRC HEC-RAS model. The channel in the HEC-RAS model is likely too wide, causing portions of the bathymetry to show up at the location of the east levee of the Chicago Sanitary and Ship Canal.

1.2.3 Areas of Missing Data

Numerous areas exist in the model terrain where the entire channel is not depicted in the bathymetry (Figure 3). There are also some areas connected to the channel, such as ports and small turning basins, where bathymetry does not exist.

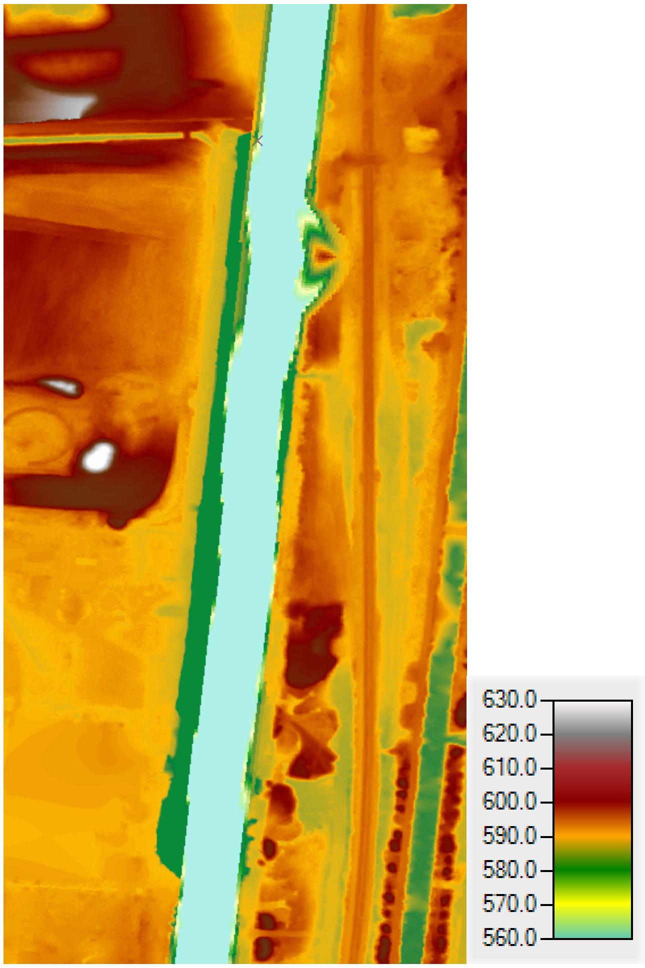

Figure 3. A section of the Chicago Sanitary & Ship Canal where channel bathymetry does not cover the entire channel. Portions of the west side of the canal (generally green colors above) are clearly part of the channel when looking at satellite imagery, but not indicated as part of the channel in the cross-section data, so they are not exported in the bathymetry data.

1.2.4 Other Minor Issues

In a few locations, minor imperfections in the combined terrain data (LiDAR plus interpolated channel bathymetry) were evident. Typically this would appear as strips of lower or higher elevation than expected near the banks of waterways (Figure 4). Although the effect on model performance would likely be quite low, these areas were also adjusted at the same time that the terrain data were improved in other areas.

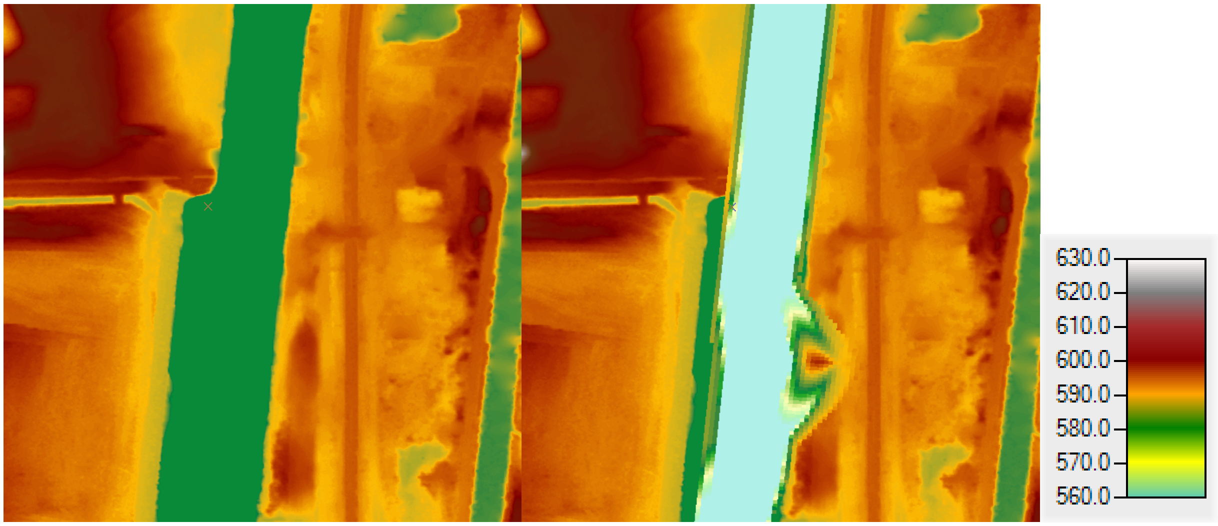

Figure 4. Will County LiDAR data (left) and Will County LiDAR data with exported/interpolated channel bathymetry overlaid (right). Channel bathymetry was exported at 10-ft resolution from the USACE LRC HEC-RAS model. Artifacts in the channel bathymetry data can be seen extending into the overbank area.

1.3 Overview of Model Terrain Creation Steps

The creation of the combined topography/bathymetry dataset for the model terrain involved multiple steps. First, the best (highest resolution) dataset available was determined for each part of the terrain - the channel bathymetry and overbank terrain. The terrain components were then manually edited to mitigate documented erroneous data and make the digital representation more accurate. The final step was to mosaic the bathymetry and overbank components into a single dataset.

2.0 Creating the Model Terrain

2.1 Selection of Datasets for Bathymetry and Overbank Topography

Due to the limitations and potential errors in the existing terrain datasets, a new combined terrain dataset was created. For the overbank areas, existing LiDAR elevation data were used. Channel bathymetry was based upon the model cross-section data from the USACE LRC HEC-RAS model, interpolated and exported on a 10-foot resolution.

2.2 Corrections and Improvements to Terrain Components

2.2.1 Exported Channel Bathymetry

To address issues with channel bathymetry, two different polygon masks were created:

- **Existing channel bathymetry mask**
  The first mask was derived from the exact raster extent of the exported channel bathymetry. This mask was then manually edited based upon satellite imagery and high-resolution LiDAR data to such that the mask did not extend into the overbank areas.

- **New bathymetry areas mask**
  This second mask was created to indicate the extents of additional areas along, and just off of, the channel which needed synthetic bathymetry added. This mask was also limited such that it did not extend into the overbank areas.

The existing channel bathymetry mask was used to remove bathymetry data that extended into areas where no bathymetry should exist (overbank areas). The areas where bathymetry needed to be added manually was represented by the new bathymetry mask. Estimated elevation values were added to a point shapefile within this mask polygon. These values were based upon a combination of nearby channel cross-section data, inferences from satellite imagery and LiDAR elevation data, and other experience.

An iterative process was used to create the final channel bathymetry for the model terrain. The point elevation values were interpolated using the spline method and masked to the extent of the new bathymetry areas mask (see above for a description). Results of the interpolation were compared to the existing/exported channel bathymetry in areas where values appeared reasonable. When a mismatch in elevation values or some other issue was discovered, the point values were adjusted numerically and spatially, and then the interpolation was run again.

In some instances, the new bathymetry mask was adjusted to help improve the interpolation results. This process continued until the values in the new bathymetry areas could generally blend into the values of the existing bathymetry.

Below are some examples where manual corrections and improvements were made to the channel bathymetry. Figure 5 shows an example where a reach of the river aligns so poorly with the satellite imagery and LiDAR elevation data that a simple clipping would cause issues (such as narrowing the channel too much). In this instance, the channel was shifted to better align with its true location. Figure 6 shows an example where a reach of the river with newly created artificial bathymetry was blended back into the original exported channel bathymetry. Figure 7 shows an example where small ports or turning basins off the main channel of the Chicago Sanitary and Ship Canal lacked bathymetry, so it was artificially added.

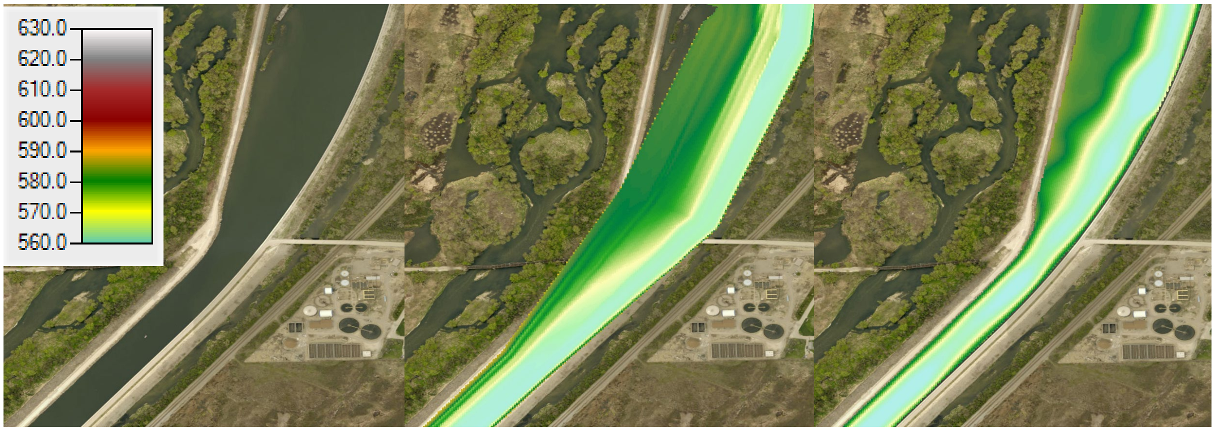

Figure 5. Aerial imagery showing a portion of the Chicago Sanitary and Ship Canal (CSSC) near Lockport (left), same as left image but with original channel bathymetry data (elevation in feet) as an overlay (middle), same as left image but with newly estimated bathymetry (right). Note how original channel bathymetry through most of this reach does not line up with the CSSC, and over an approximately 0.5-mile distance is depicted in a location completed outside of the east (left bank) levee.

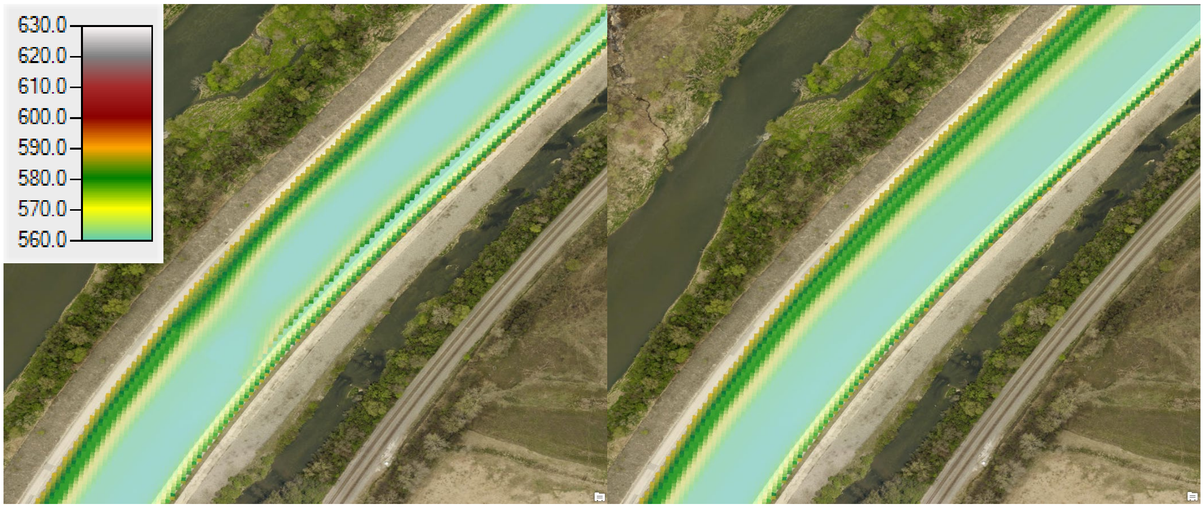

Figure 6. Aerial imagery showing a portion of the Chicago Sanitary and Ship Canal (CSSC) just upstream of Lockport Lock and Dam with original channel bathymetry (elevation in feet) as an overlay (left), same as left image but with newly estimated bathymetry added (right). Note the attempt to blend the synthetic bathymetry back into the original bathymetry.

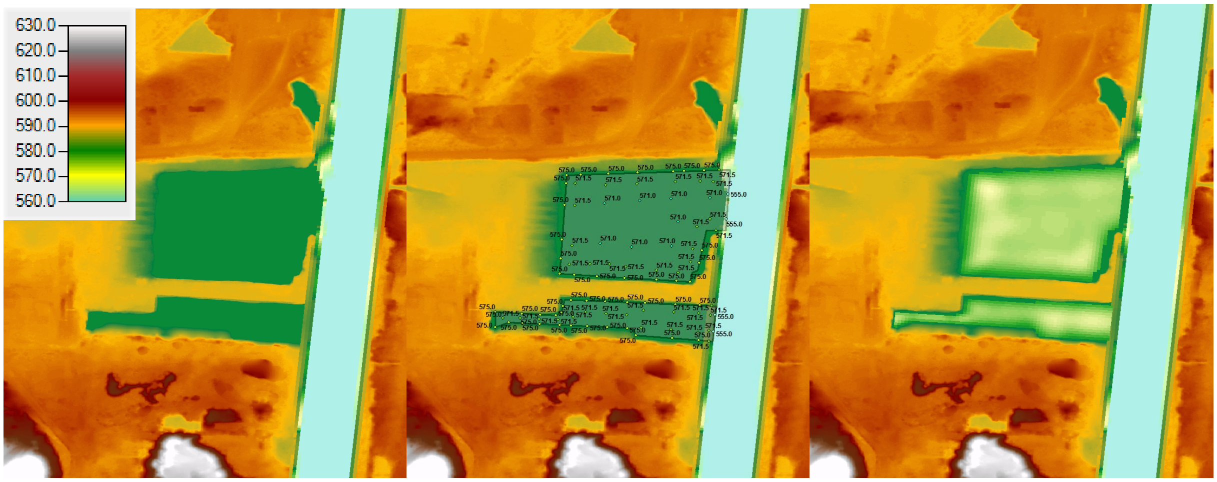

Figure 7. Combination of Will County LiDAR data combined with the original channel bathymetry data (left; elevation in feet), same as left image but with point elevation estimated and the new bathymetry mask added (middle), combination of Will County LiDAR data combined with original channel bathymetry data and newly estimated bathymetry of a connected turning basin (right).

Here is a list of instances where the original exported bathymetry data was altered, starting at Lockport Lock and Dam and moving upstream:

- In the immediate headwater area upstream of Lockport Lock and Dam, synthetic bathymetry was added to the west (right bank) side of the channel such that the channel extended to the levee. Bathymetry was clipped on the east (left bank) side because it extended across the levees.
- From about 0.5 miles upstream of Lockport Lock and Dam to about 0.5 miles upstream of Renwick Road/9th Street (2.0 total miles), synthetic bathymetry was created such that the channel was shifted west (toward the right bank).
- About 0.5 miles upstream of Renwick Road/9th Street, synthetic bathymetry was added for the area between the main channel and the Lockport Controlling Works.
- Synthetic bathymetry was added for ports/turning basins about 0.9 miles downstream of Romeo Road.
- Synthetic bathymetry was added for several ports/turning basins between I-355 and Lemont Road.
- Synthetic bathymetry was added for several ports/turning basins about 0.8 miles upstream of Lemont Road.
- Synthetic bathymetry was added to a small portion of the confluence of the CSSC and the Cal-Sag Channel.
- Synthetic bathymetry was added to a narrow stretch on the north (right bank) from 0.5 miles downstream of Harlem Avenue to 0.3 miles upstream of Harlem Avenue so the modeled bathymetry extended from bank to bank.
- Synthetic bathymetry was added for several ports/turning basins in the vicinity of the confluence with the South Branch Chicago River.
- Throughout the reach of the CSSC between Lockport Lock and Dam and the confluence with the Cal-Sag Channel, numerous small areas of synthetic bathymetry were added in locations where the original exported bathymetry did not extend to the edge of the channel (as depicted by aerial imagery and the LiDAR elevation data).
- Throughout the reach of the CSSC between Lockport Lock and Dam and the confluence with the Cal-Sag Channel, numerous small areas of the original exported bathymetry were clipped out that extended beyond the edge of the channel (as depicted by aerial imagery and the LiDAR elevation data).

The adjustments and corrections to the original exported bathymetry were deemed correct when the edges of the new bathymetry areas blended in reasonably well with the original exported bathymetry as well as the LiDAR elevation data (overbank areas).

2.2.2 LiDAR Elevation Data

The LiDAR elevation data from Cook, Will, and DuPage Counties were assumed to be accurate for the purposes of this model and used “as-is,” except for resampling the gridded data to match the channel bathymetry when appropriate.

2.3 Merging Components into Final Terrain

After making corrections and adjustments to the channel bathymetry, the various terrain components were merged together through a multi-step process.

1. The original exported bathymetry data were clipped to the existing channel bathymetry mask (see section 2.2.1 for a description).
2. New bathymetry data were merged with the original exported bathymetry data, with priority given to the new bathymetry in areas of overlap.
3. LiDAR elevation data for Cook, DuPage, and Will County were resampled to 10-ft resolution and clipped to areas near the channel with an elevation of about 600 feet or less.
4. New, combined bathymetry was merged with the LiDAR elevation data, with the lowest value taken from areas of overlap. The final result was a combined topo-bathy elevation dataset (Figure 8).

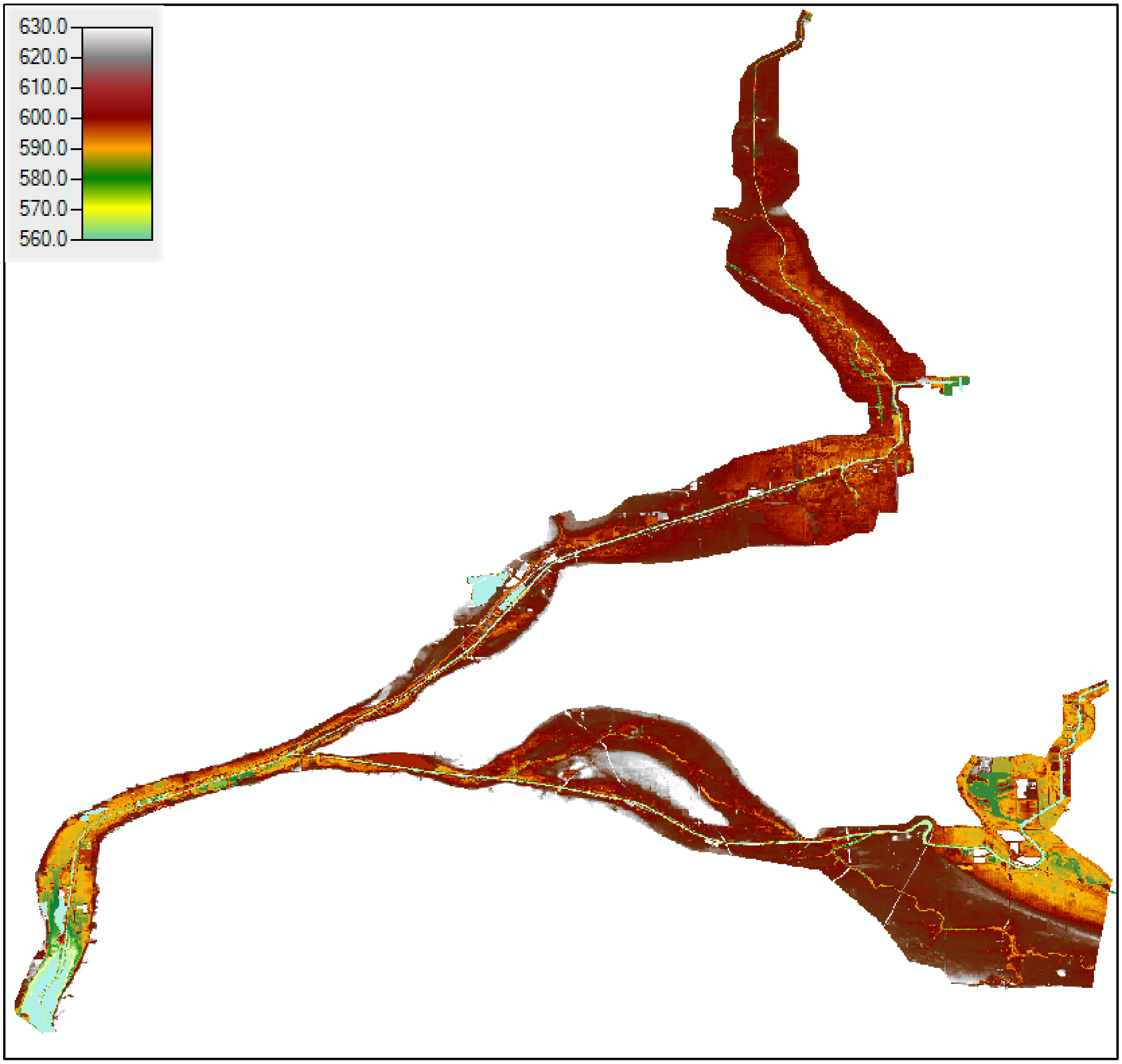

Figure 8. Combined topo-bathy terrain dataset using corrections and improvements made to the original exported terrain.

2.4 Differences Between New Terrain and Original Terrain

Several differences between the new terrain and the original terrain were noted, beyond the expected/planned differences (Figure 9). Some areas of excavation, such as quarries, were present in the new terrain data. Additional roadway and railroad embankments were present in the new terrain. It was also noted that the higher resolution of the new terrain caused the bottom of the Chicago Sanitary and Ship Canal to end up at a slightly lower elevation than that depicted in the original terrain. In areas with some of the largest errors in the original terrain's bathymetry, a significant improvement was noted (Figure 10).

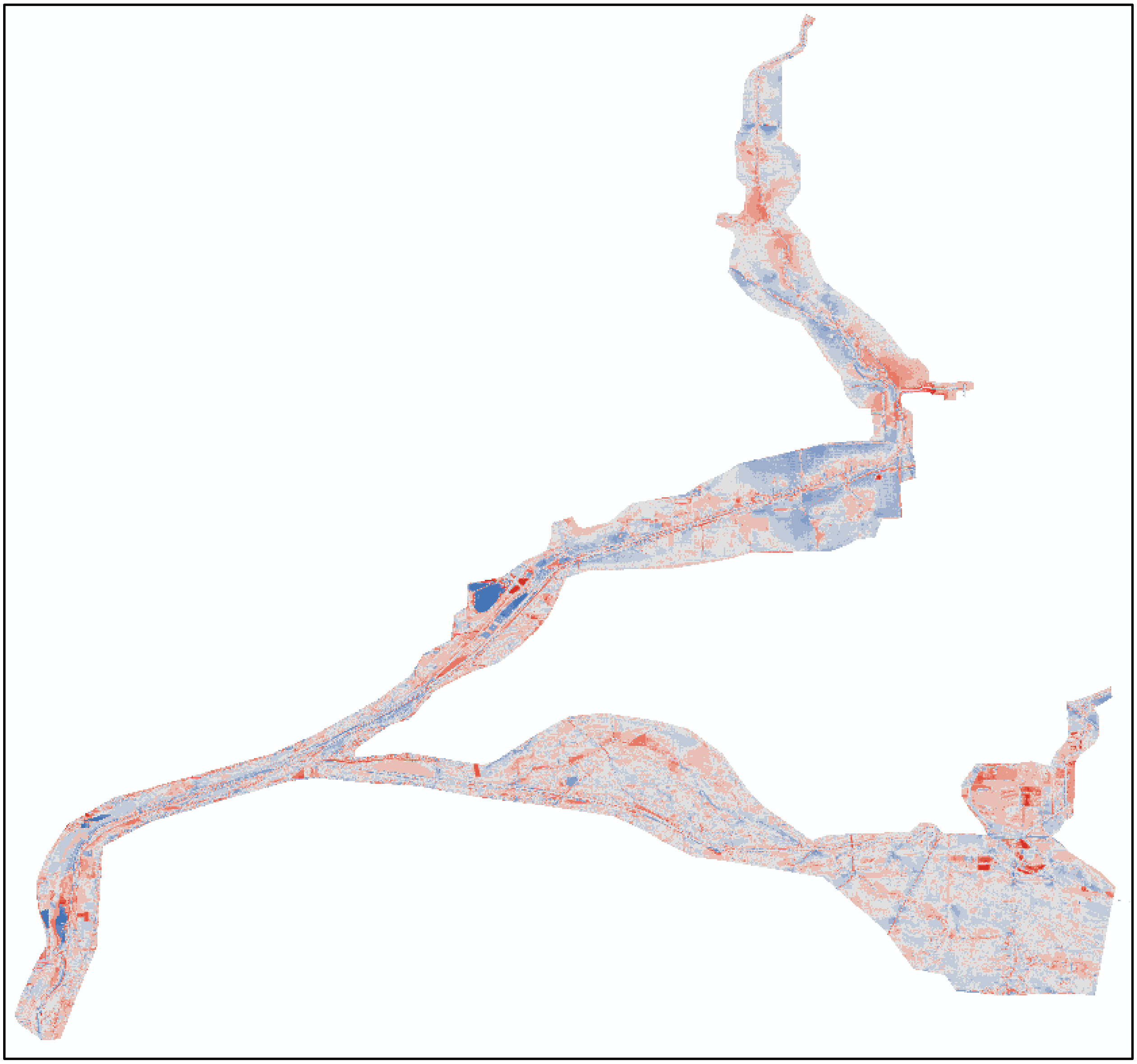

Figure 9. Difference between the new terrain and the original terrain. Blue colors represent areas where the new terrain is lower than the original terrain, and red colors represent areas where the new terrain is higher than the original terrain.

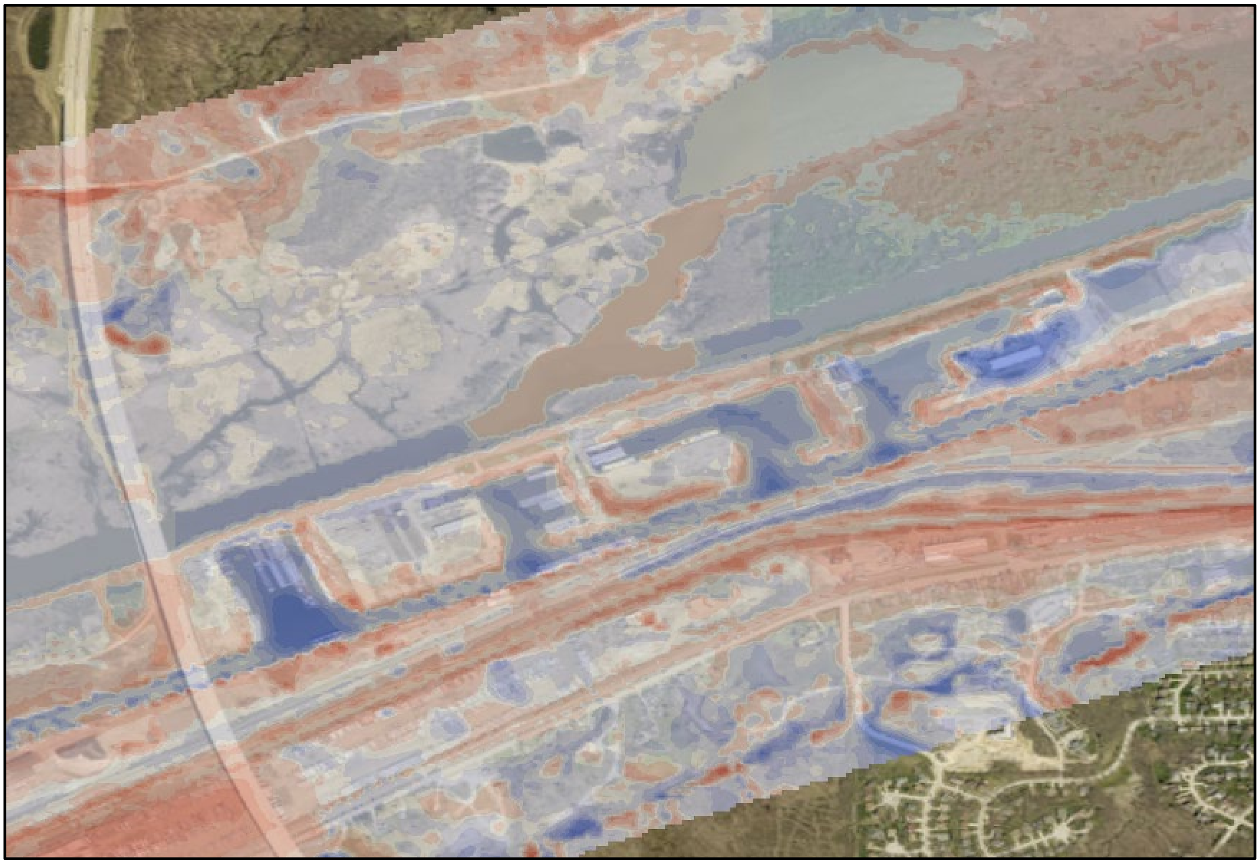

Figure 10. Difference between the new terrain and the original terrain along the Chicago Sanitary and Ship Canal near I-355. Blue colors represent areas where the new terrain is lower than the original terrain, and red colors represent areas where the new terrain is higher than the original terrain. This location was an example of some of the most serious issues with the original terrain, where flow would be artificially blocked by bathymetry values from the port/turn around areas extended into the channel.

3.0 Land Cover

Some of the noted issues with the model terrain were also noted with land cover data needed to derive surface roughness (Manning’s n values). Data from the NLCD 2011 dataset did not indicate a wide enough channel, and also had number bridges crossing the channel. Manning's n values were significantly higher for the bridge crossings and encroachments of overbank areas compared to values for open water. To address this, the NLCD 2011 land cover was manually adjusted. Due to the large difference in resolution between land cover data (98-foot) and the terrain data (10-foot), areas of the channel were depicted with a land cover of the overbank area. To make sure that the channel was completely covered with the “open water” land cover type, the channel area would need to be buffered by half the pixel width of the NLCD dataset.

The following steps were followed to create the land cover dataset for the HEC-RAS model:

- The river channel location, as depicted by the channel bathymetry masks created in an earlier section, was buffered by 15 meters (49 feet).
- The buffered polygon was converted to a raster with a value of 11 (the NLCD value for open water).
- This raster was then merged into the original NLCD 2011 dataset.

4.0 Conclusions and Future Work

Updates to the model terrain and land cover along and near the Chicago Waterway were necessary for creation of a Chicago River hydraulic model for operational forecasting. These updates corrected issues such as artificial channel constrictions and channel misalignment. Once these updates were made, additional model development and calibration work could be performed. More information about model development, calibration, and validation can be found in the main technical report on Chicago River operational forecasting.