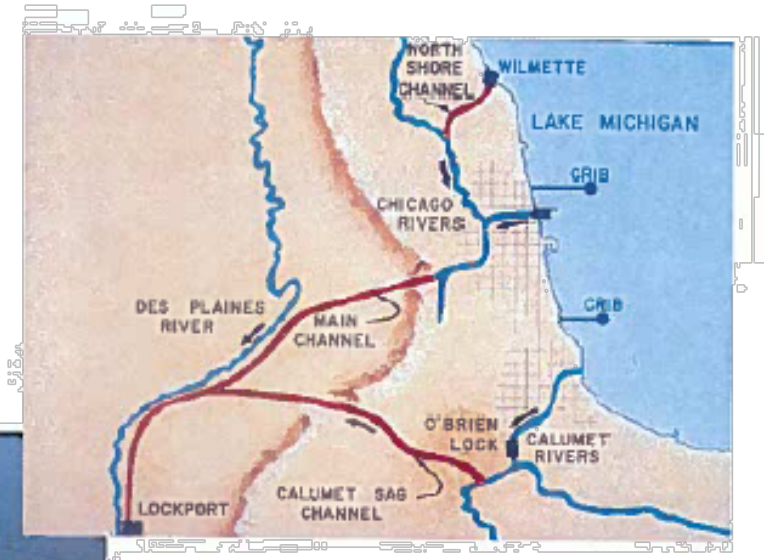
LAKE MICHIGAN DIVERSION COMMITTEE
Findings of the Eighth Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures



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May 2019

Acknowledgements

During the course of the Eighth Technical Committee's report preparation, a number of individuals and organizations were extremely helpful in assisting the developmental work. The Committee would like to express its' appreciation for the assistance of the U.S. Army Corps of Engineers (USACE), Chicago District, and especially Mr. Jeff Fuller, for their contributions in providing numerous reports and data, as well as for arranging and assisting the Committee in the delivery of the committee workshops and organizing informative field trips. The Committee also acknowledges the assistance of the following: USGS: Mr. James Dunker, Mr. Gary Johnson, Dr. Ryan Jackson, Mr. Kevin Johnson, Dr. Tom Over, Dr. David Soong, Ms. Amy Russell; ISWS: Ms. Erin Bauer, Mr. Dave Kristovich; IDNR: Mr. Dan Injerd; and The Lake County Stormwater Management Commission Chief Engineer, Mr. Kurt Woolford, for presenting the County's Des Plaines River Diversion Concept.

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Executive Summary

The Eighth Lake Michigan Diversion Technical Committee (8th TC) was appointed by the U.S. Army Corps of Engineers (USACE) in May 2018 to conduct an assessment and evaluation of the accounting procedures and methodology used in the determination of diversion from Lake Michigan, and to ascertain whether or not the methods are in accordance with the "best current engineering practice and scientific knowledge", as stipulated by the 1967 Supreme Court Decree and the 1980 modifications. Such a review is to be performed by a Technical Committee appointed every five years, and a report evaluating the accounting and operation procedures is to be presented to the USACE and to interested parties. The key topics reviewed by the 8th TC include the following: Lake Michigan Diversion Accounting (LMDA) Reports accounting for Water Years (WYs) 2010, 2011, 2012, 2013, 2014, and 2015 and Annual Reports 2016, 2017, and 2018; current diversion-related measurement techniques at the Lemont stream-gaging station, precipitation gages, and other pertinent structures; procedures used to calculate and verify flows that are not directly measured; and the status of recommendations from the Seventh Technical Committee. The Lemont Accounting is used to mean the same accounting system per the U.S. Supreme Court decree that flow measurement shall be made at Lockport. The actual flow measurement location over time has been shifted from Lockport to Romeoville to Lemont. The 8th TC has determined, that the LMDA (WYs 2010, 2011, 2012, 2013, 2014, and 2015) are in compliance with the 1980 Modified Decree, with respect to the **"best current engineering practice and scientific knowledge"**. The 8th TC is in general agreement with the findings and recommendations made by the Seventh Technical Committee. Actions have been taken in most cases to comply with the recommendations, and progress has been made since the Seventh Technical Committee recommendations were made. From the standpoint of **"best current engineering practice and scientific knowledge"**, the progress of the LMDA has been significant in a number of engineering/scientific areas: 1) hydrologic and hydraulic modeling and 2) flow measurements. The acoustical flow measurement technology has not only met the **"best current engineering practice and scientific knowledge"** but contributed through their pioneering efforts in the Chicago Sanitary and Ship Canal (CSSC) flow monitoring to the developing of cutting-edge protocols supported by the most advanced measurements technologies. The 8th TC expressed concern regarding if key components at the LMDA system might be in jeopardy for continued full operations (measurement of stage and discharge) as a result of budget cuts resulting in eliminating support for six of the streamflow gages currently used in the LMDA system. The USACE has indicated to the 8th TC that the USACE will continue to cooperate with U.S. Geological Survey (USGS) and other local stakeholders to ensure that an efficient streamgaging network is maintained that meets mission requirements.

<u>Cumulative Deviation of Lake Michigan Diversion</u>

The cumulative deviation of Lake Michigan diversion had increased from 1983 until 1994, when the trend reversed. The Lake Michigan Diversion is through WY 2015, based on flow at the USGS Lemont gage. Based on the data provided by the USGS and the USACE, the cumulative deviation has increased dramatically since 1999, and is +4699 cfs – years for WY 2015. This in part can be attributed to the levels of Lake Michigan and the reduction in leakage at the CRCW as a result of the repairs made to the lock gates and completion of the new turning basin all by the summer of 2000. The continued reduction in Lake Michigan pumpage since the early 1990s also reflects an aggressive campaign by the City of Chicago to repair leaky water mains which has also contributed to the reduction in the cumulative deviation from Lake Michigan diversion flows. The LMDA Reports (WY 2016, 2017, and 2018) have not been completed.

Activities for Fiscal Year (FY) 2010

The activities in FY 2010 included data collection for WY 2010, continuing modeling of diversion accounting for WY 2006 and WY 2007. Analyses of flow measurement data at Lemont and assessment of accounting changes resulting from relocating the Acoustic Velocity Meter (AVM) from Romeoville to Lemont were performed. Incorporating the Sixth Technical Committee's recommendations, the USACE requested that the USGS document the history of flow measurement for LMDA, the flow measurement instrument currently deployed at Lemont, and detailed analyses of flow measurement data collected at Lemont versus Romeoville. In 2010 the Corps contracted the Illinois State Water Survey to upgrade the field rain gage equipment with new data loggers, cellular telemetry and power supply. In 2010 the USACE requested that the USGS install an AVM in the Summit Conduit to measure the runoff from a 5.4 mi^2 Des Plaines River watershed to the CSSC. The State of Illinois completed repairs near the north basin wall of the Chicago River Controlling Works to reduce leakage.

Activities for FY 2011

The activities in FY 2011 included data collection for WY 2011, and completion of Lemont accounting computations for WY 2006 and WY 2007. The Corps installed new lock gates at the Chicago Lock that would help reduce leakage. In August 2011 the Corps met with model developers from the University of Illinois to discuss the current progress made on several hydrologic and hydraulic models. It is being evaluated that several of these models – in particular the Illinois Transient Model (ITM) and Illinois Conveyance Analysis Program (ICAP) – may take the place of the current Tunnel Network (TNET) models.

Activities for FY 2012

The activities in FY 2012 included data collection for WY 2012, and completion of Lemont accounting computations for WY 2008 and WY 2009. Revisions to the Diversion Accounting manual were incorporated into the electronic document as the document was brought up-to-date. The USGS published the report on "Comparison of Index Velocity Measurements Made with a Horizontal Acoustic Doppler Current Profiler and a Three-Path Acoustic Velocity Meter for Computation of Discharge in the Chicago Sanitary and Ship Canal near Lemont, Illinois." The USGS published the report on "Monitoring of Stage and Velocity, for Computation of Discharge in the Summit Conduit near Summit, Illinois, 2010-2012". The USGS published a report on the "Role of the U.S. Geological Survey in Lake Michigan Diversion Accounting in Illinois, 1984-2010". The USGS completed the discharge rating of the sluice gates at Lockport Controlling Works. A pilot study on the consumptive use was initiated using water supply and sewer flow measurement data in a northwestern suburb of Chicago (Elk Grove Village, IL). The University of Illinois is modifying their Tunnel and Reservoir Plan (TARP) modeling software to include the data Input/Output (I/O) interface with the Hydrologic Engineering Center-Data Storage System (HEC-DSS) and accept user-specified inflow hydrographs at the drop shaft locations.

Activities for FY 2013

The activities for FY 2013 include data collection for WY2012 and completing the Lemont accounting computations for WY 2010 and WY 2011. The Seventh Technical Committee was convened in May 2013. During FY 2013, Committee members attended workshops and meetings to be briefed on various activities and technical procedures related to Lake Michigan Diversion. The USGS published the report "Evaluation of the Potential for Hysteresis in Index-Velocity Ratings for the Chicago Sanitary and Ship Canal near Lemont, Illinois". The USGS installed a vertical Acoustic Doppler Velocity Meter in the CSSC at Lemont in July 2013.

Activities for FY 2014

During FY 2014, the annual diversion accounting reports for WY 2010 and 2011 were finalized. During FY 2014, a study on the inventory of green infrastructure and their potential impact on the runoff from the diversion watershed for Lake Michigan Diversion accounting was initiated. Updates to the water control manual for the Chicago Harbor Lock began in April 2014 and continued through the end of the fiscal year. The third workshop for the Seventh Technical Review Committee was held in October 2013. The Technical Committee completed their review and published their findings report in April 2014.

Activities for FY 2015

During FY 2015, the processing of the data collected for WY 2012 and 2013 continued through December 2014. Upon completion, the diversion accounting computations for WY 2012 and 2013 began. Although sufficient data were available to begin the computations for WY 2013, further progress was eventually hindered while awaiting responses from several local municipalities. The decision was made to split the publication of the two water years, moving forward with the WY 2012 accounting. The final column computations for WY 2012 were completed in May 2015, while the review of the WY 2012 report was completed in September 2015. The final diversion computations for WY 2013 were completed in September 2016. The USGS published the report "Analysis of Regional Rainfall-Runoff Parameters for the Lake Michigan Diversion Hydrological Modeling". This report provides a summary of the analysis undertaken by the USGS and USACE - Chicago District to assess the predictive accuracies of selected parameter sets. The Agency Technical Review (ATR) for the Chicago Harbor Lock's water control manual was completed in February 2015.

Summary of Hydrologic and Hydraulic Modeling

The 8th TC reviewed the hydrologic and hydraulic (H&H) models currently used in the LMDA procedures with regard to:

- The appropriateness of the individual models,
- The modeling strategy implemented to develop estimates of diverted flow quantities,
- The derivation of model input parameters and model performance metrics,
- Developments that have occurred since the review by the Seventh Technical Committee (7th TC), and
- Potential replacements for any of the models.

The 8th TC concludes the following:

a) "Regional" calibration of HSPF parameter sets and their application to nearby hydrologically similar watersheds is consistent with the **"best current engineering practice and scientific knowledge".**

b) The pervious and impervious percentages by land use category used since WY 1997 meet the standard of the **"best current engineering practice".**

c) The continued use of the land cover percentages in use since 1997 is reasonable and meets the standard of the **"best current engineering practice".**

d) Given the generally good performance of the 2008 USGS parameters found by Soong and Over (2015) for various gaged watersheds in the Chicago area, and, especially, the good performance

in estimating flows from the ungaged lower Des Plaines River and Summit Conduit watersheds, the 8th TC recommends that the USACE continue to use this parameter set in the LMDA computations.

e) The numerical instabilities in TNET computations have been reduced by modifications the USACE has made to TNET in recent years as detailed in Section 4.3.2. Thus, the 8th TC concludes that the current version of TNET applied in the diversion accounting meets the standard of the **"best current engineering practice".**

f) The models used to compute aspects of the diversion accounting meet the Supreme Court's requirement that the diversion accounting be done according to the **"best current engineering practice and scientific knowledge"**.

g) Unfortunately, now that all the major deficiencies in the hydrologic and hydraulic models used in the diversion accounting have been corrected, it is time to develop new models. The versions of the Special Contribution Area Loading Program (SCALP) and TNET currently used in LMDA are DOS-based and may have future hardware and computer operating system issues. With respect to SCALP, whereas there are numerous models that perform similar modeling of combined sewer interceptor systems, the effort necessary to apply and "calibrate/test" a new model to the interceptor systems feeding to the Water Reclamation Plants (WRPs) and TARP system in the diversion watersheds would be more substantial than the effort to recode and test the SCALP model. Thus, the 8th TC supports the USACE's plan to recode and test the SCALP model for continued use in the LMDA. With respect to TNET, two models developed by the University of Illinois (U of I) could potentially be useful to the USACE as they look to replace TNET, namely the (1) ICAP and (2) a U.S. Environmental Protection Agency (USEPA) Storm Water Management Model (SWMM) (Rossman, 2008) developed for the Calumet TARP system. Also, the USACE is considering developing new Hydrologic Engineering Center-River Analysis System (HEC-RAS) models of the TARP tunnels and reservoirs. The 8th TC recommends that the USACE work together with the U of I to modify ICAP to compute CSOs using actual pump operations, and evaluate the potential usefulness of ICAP for LMDA computations. The 8th TC also recommends that the USACE work together with the U of I to evaluate the potential usefulness of the USEPA SWMM of the Calumet TARP system for LMDA computations. The 8th TC feels that building and testing new HEC-RAS models of the Calumet and Mainstream/Des Plaines TARP systems from scratch will be a large undertaking. Thus, the 8th TC feels that the LMDA funding might be more effectively spent if the existing, tested ICAP or SWMM models of the TARP system could be adapted for LMDA computations. Whatever model is used to replace TNET—ICAP, SWMM, or HEC-RAS—it should be set up so that simulated water levels can be compared to measured water levels where available.

h) Given the importance of flow data at the Upper Des Plaines Pumping Station (UDPPS) to the LMDA, the USACE should do whatever it can to encourage the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) to make recording the UDPPS flow data a priority. Once more complete records of flow are available at the UDPPS the USACE should evaluate in detail the performance of the hydrologic and hydraulic models in estimating the flows reaching the UDPPS.

i) The high flows in the West Branch of the Grand Calumet River after dredging (completed in 2016), the high water levels in Lake Michigan in recent years, and the possibility of flows from the East Branch of the Grand Calumet River reaching the West Branch indicate a complete re-evaluation of flows from Indiana reaching Illinois needs to be done using a new hydraulic model

of the Grand Calumet River system. The 7th TC recommended that "After dredging is complete, HEC-RAS model should be updated and recalibrated. Regression equations used for LMDA should be reviewed and revised as appropriate." The 8th TC fully concurs with the recommendation that a new HEC-RAS model should be developed for the post-dredging Grand Calumet River system. Further, the derivation of new equations should be completely detailed in a report for review by a future Technical Committee. The U of I is developing a HEC-RAS model of the Grand Calumet River system for the MWRDGC. Thus, the 8th TC suggests that the USACE could work together with the U of I in the development of the new HEC-RAS model to minimize duplication of effort. Then using the new HEC-RAS model new relations should be developed between Lake Michigan water levels and Indiana water supply reaching the Chicago Area Waterway System (CAWS) through the Grand Calumet river. The detailed water surface elevation data collected in the Grand Calumet river system between late February 2017 and August 2018 may be sufficient to calibrate and verify the new HEC-RAS model for the Grand Calumet River system. However, the USACE should be aware that more data may be needed to fully calibrate and verify the model, and may want to have USGS re-establish the water-surface elevation data network for a limited period.

j) In October 2018, the USGS installed a new temporary gaging station at Columbia Avenue 1 mile upstream from Hohman Avenue. This gage is composed of a side-looking Acoustic Doppler Velocity Meter (ADVM) mounted on a 2-in. diameter aluminum pipe on the left bank upstream culvert guidewall 20 ft upstream of Columbia Avenue. The 8th TC commends the USGS on the establishment of this new gage, and it encourages the USACE to evaluate the use of the Columbia Avenue gage for the development of new relations to determine Indiana water supply reaching the CAWS (to be used as a deduction in the LMDA). This recommendation is necessary in view of the history of poor rating conditions at the Hohman Avenue gage discussed in Section 4.6.3

<u>Summary of Flow Measurement</u>

The 8th TC critically examined the flow measurement instrumentation and infrastructure as well as the data acquisition and processing protocols used in the LMDA since 2014 when the 7th TC review report was issued. In this reference period, there have been significant advancements on many aspects of the LMDA direct flow measurements and there are more developments currently on-going. As usual, the central attention for the flow measurement component of the LMDA has been the streamflow gaging station located at Lemont, IL, which accounts for 90% of the directly measured data for accounting purposes. Given the critical importance of these advancements and of the on-going developments for the overall assessment of the LMDA study, only aspects related to the Lemont station data acquisition are presented in this summary. Specific findings and suggestions for improving other aspects of the flow monitoring associated with the LMDA study are summarized in the Chapter 5 and in the 8th TC Recommendation section of the report.

Following a series of studies on the CSSC carried out in the last decade, the problem of time transients in the CSSC is currently well documented (Jackson et al. 2012, 2013; Muste and Lee, 2013; Jackson, 2018). Especially relevant is the study conducted by Jackson (2018) that summarizes results from more than 3.5 years of continuous monitoring with an up-looking Acoustic-Doppler Current Profiler (ADCP) deployed at the Lemont gaging station. This study enables examination of the monitoring at this station from a new perspective: one that is not possible with the horizontally oriented instruments deployed at the site. The study results fully document the variability in the velocity profile over a wide range of unsteady flows, as well as the impacts of tow passages and operations at the controlling structures in the CSSC. These data also reveal other flow complexities active in the CSSC such as the seasonal, density-driven underflows

triggered by a combination of environmental variables. The results ensuing from Jackson (2018) properly address most of the concerns expressed by the flow measurement experts of the 6th and 7th TCs regarding the current streamgaging practice.

The aforementioned findings were further investigated by Jackson (2018) to document the impact of the flow perturbations generated by various perturbation sources on the performance of the index-velocity method used in conjunction with the AVM and horizontal ADVM deployed at the Lemont gaging station. There is no question that the index-velocity is the best approach for continuous real-time measurements in complex measurement environments where flow unsteadiness and backwater might be present. However, the main concern for the present context is to assess if the performance of the one-to-one V_{index}-V_{mean} relationship, used at the Lemont station for estimation of discharges, is sufficient for LMDA purposes. Jackson (2018) illustrated that while the hourly and daily mean discharges measured at the station might be slightly off compared to direct discharge measurements (reference), the monthly and annual mean discharges are not statistically different. Given that for the purposes of LMDA, the assessment of the diversions from Lake Michigan is based on an annual mean discharge, Jackson (2018) concludes that the current index-velocity method used in conjunction with AVM and ADVM is an acceptable discharge estimation method. The 8th TC agrees with this conclusion.

In parallel with the verification of the flow monitoring activities at the Lemont gaging station, the LMDA monitoring team adopted internationally accepted standards for the conduct of uncertainty analysis (Over et al., 2017). This adoption enables to currently state with confidence that the LMDA is accomplished within specified uncertainties in a complex measurement environment that for many other agencies appear intractable. More valuable information on uncertainty sources are expected from the implementation of a new direct discharge measurement method (i.e., the Q-Track) installed by the USGS in the Spring of 2017. It is expected that the successful implementation of the Q-Track system will not only quantify unknown uncertainties but will offer a state-of-the-art methodology to directly measure discharges with high spatial and temporal resolution on par with the data directly acquired with ADCP transects currently used to build the ratings at the station. Once the methodology and implementation aspects are finalized, the Q-Track has the potential to become the primary measurement standard at the Lemont gaging station. The Q-track is more efficient than the current time- and cost-intensive index-rating hence the latter method can become the secondary (backup) measurement method at some time in the future.

Similar to the preceding review committees, the 8th TC is overall pleased with the efforts of the USACE to address the plethora of issues raised by the committees over time. The follow-up work carried out with attention and ingenuity by the USGS streamgaging team is commendable as it is a known fact that the measurement environment at Lemont, and in general in the whole CSSC system, represents a continuous challenge irrespective of the methods and instruments used for flow monitoring. From this perspective, the tasks tackled by the USGS under the coordination of the USACE is in many respects pioneering work in the hydrometry area. The technical level of these efforts exceeds the level of **“the best current engineering practice and scientific knowledge in hydrometry”**. Many of the lessons learned during the implementation of the cutting-edge technologies and protocols developed for streamflow measurement at the Lemont station became integral parts of the operation guidelines for other stations in the nation.

1.0 Introduction

1.1 History of Lake Michigan Diversion

When Maj. Stephen H. Long described the Chicago River on March 4, 1817, (Hill, 2000) he stated:

> "The Chicago River is but an arm of the lake [Lake Michigan], dividing itself into two branches, at the distance of one mile inland from its communication with the lake. The north branch extends along the western side of the lake about thirty miles and receives some few tributaries. The south branch has an extent of only 5 or 6 miles, and receives no supplies, except from the small lake of the prairie [Mud Lake, at the portage connection with the Des Plaines]… the river and each of its branches are of variable widths, from 15 to 50 yards and, for 2 or 3 miles inland, have a sufficient depth of water to admit of almost any burden."

Presented in Figure 1.1 is the 1830 map of the Chicago River outlet at Lake Michigan.

In 1822 Congress authorized Illinois to construct a canal between the Chicago and Illinois Rivers. On April 10, 1848, after several failed attempts and financial setbacks, the 96-mile Illinois and Michigan Canal was completed between Chicago and LaSalle, Illinois. Eventually, the demands of growing commerce led to changes in the river from the complete removal of the sandbar at its mouth to the replacement of the portage route with the Illinois and Michigan Canal, the fulfillment of a centuries-old dream. As the city grew, the river became polluted by the waste-disposal needs of both people and industry, requiring further changes to the river. Humans turned the river into a sewer; the pollution of the river threatened the life force of the growing metropolis. The river overflowed its banks, carrying the seeds of devastating illnesses out into Lake Michigan and polluting the city's drinking water supply. In 1865, the population of Chicago was 178,900. The Chicago River served as the receptacle for sewage and garbage. The conveyance capacity of the Illinois and Michigan Canal was insufficient to convey runoff from heavy rains resulting in flow back into Lake Michigan, threatening the city's water supply. In 1871, the canal was deepened to increase the capacity to convey flows away from Lake Michigan. In 1880, Chicago's population had grown to 503,185 and the canal's capacity, even with the deeper cut, was insufficient to carry the increased flow. Sewage flowed into Lake Michigan resulting in significant outbreaks of disease. The Chicago Sanitary District was created and on September 3, 1892, it began excavation of the Chicago Sanitary and Ship Canal (CSSC), a 28-mile canal between Chicago and Lockport, Illinois. (April 1899) (Figures 1.2 and 1.3). St. Louis determined that the CSSC was a probable threat and Missouri planned to file for an injunction. In the middle of the night of January 1, 1900, Commissioners of the Chicago Sanitary District breached Needle Dam Figure 1.4 allowing river water to enter the canal. Prior to approximately 1982 the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) was known as Metropolitan Sanitary District of Greater Chicago (MSDGC). In 1910, the 8-mile North Shore Channel was completed and in 1922 the 16-mile Calumet-Sag Channel was completed. The Chicago River Controlling Works (CRCW) were completed in 1938, allowing control of flow from Lake Michigan into the Chicago River. The O'Brien Lock and Dam were completed in 1965, controlling flow from Lake Michigan through the Calumet River into the Calumet-Sag Channel. (Figures 1.5-1.7). Opening the Chicago Waterway resulted in a series of disputes between Illinois, the War Department, other Great Lakes states, and Canada, dating back to 1900 and continuing to date, to address the issue of Illinois' diversion of water from Lake Michigan. Summarized in Figure 1.6 and 1.7 is The Chicago Sanitary and Ship Canal System before and after canal construction.

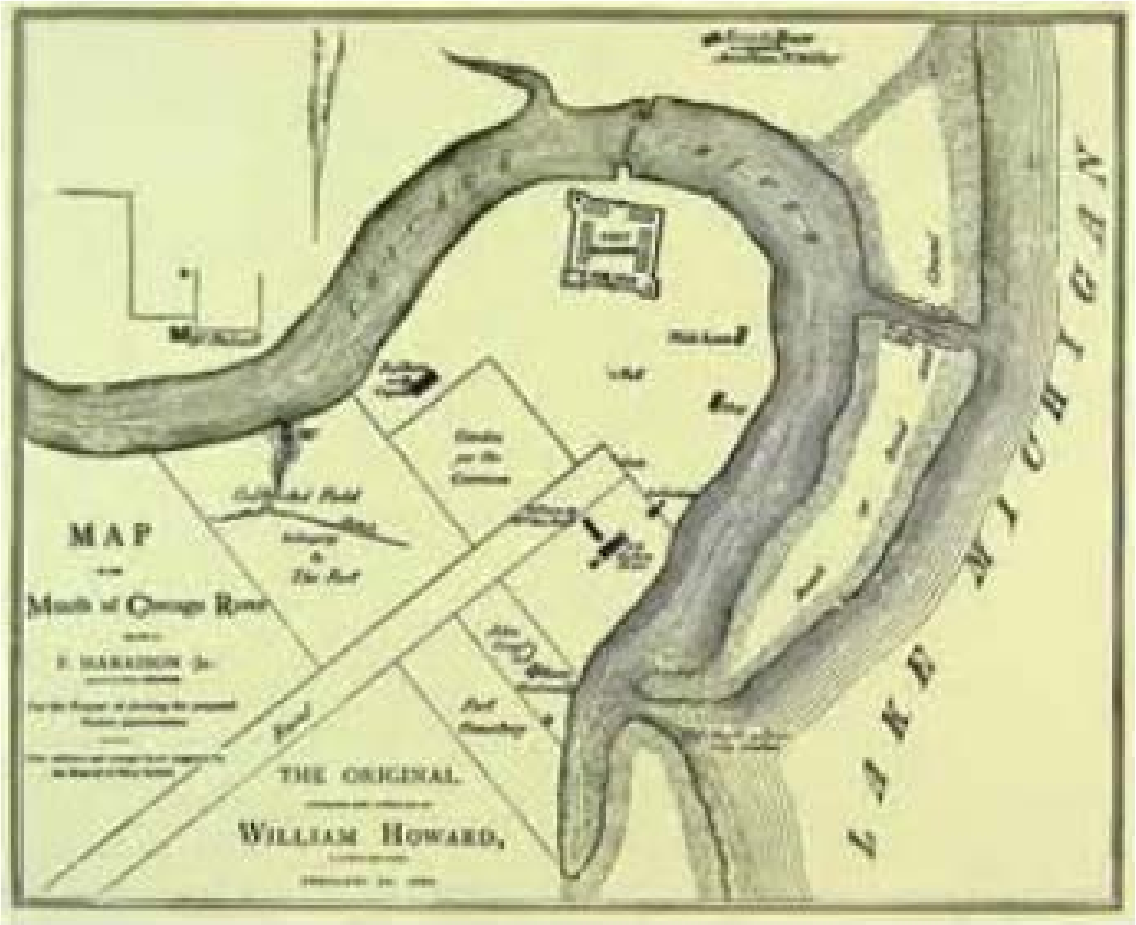

Figure 1.1. Chicago River - 1830

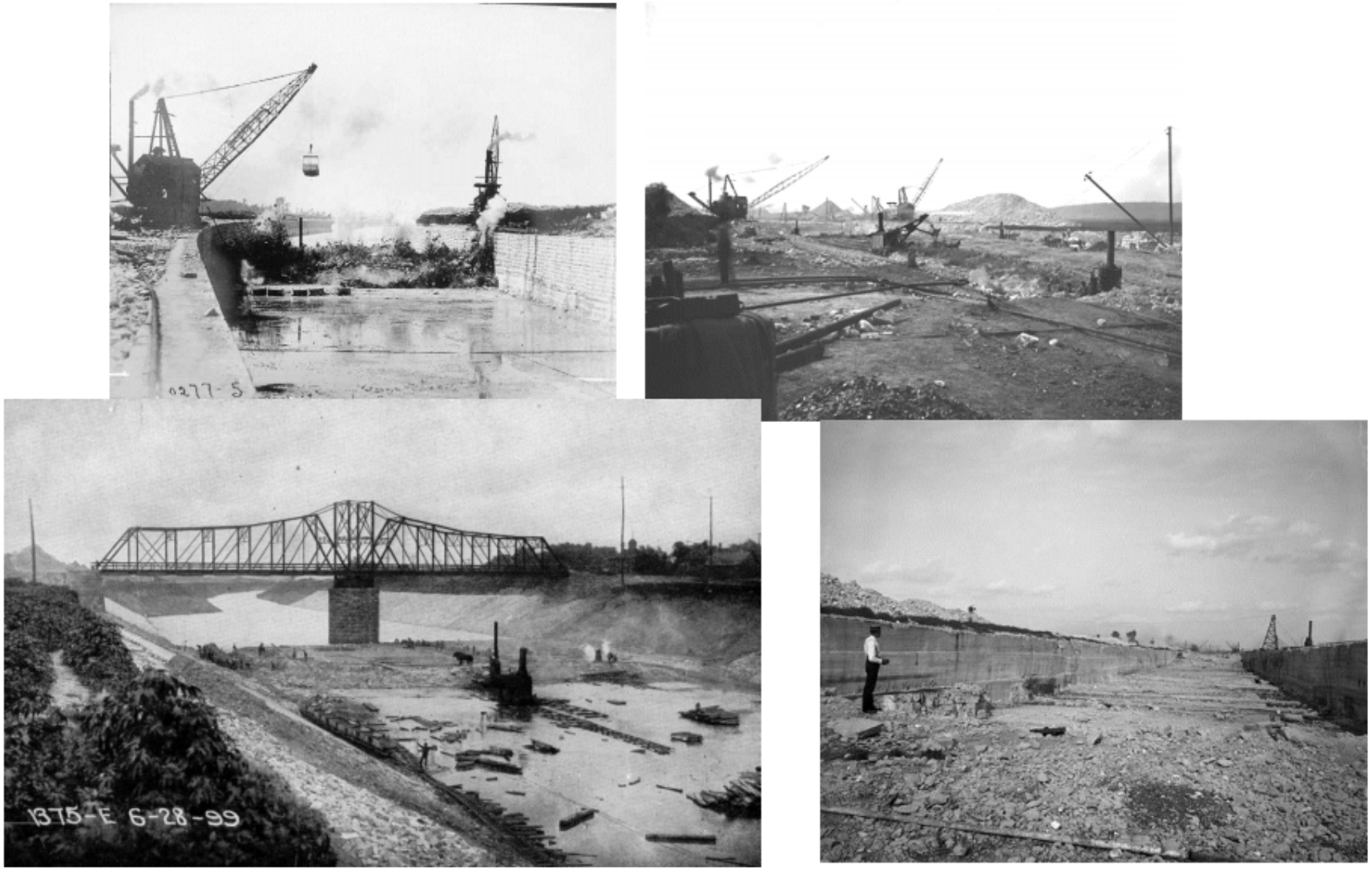

Figure 1.2. Photographs showing construction of the Chicago Sanitary and Ship Canal 1892-1900, referred to as "Chicago School of Earthmoving" (Courtesy of Lewis University Archives)

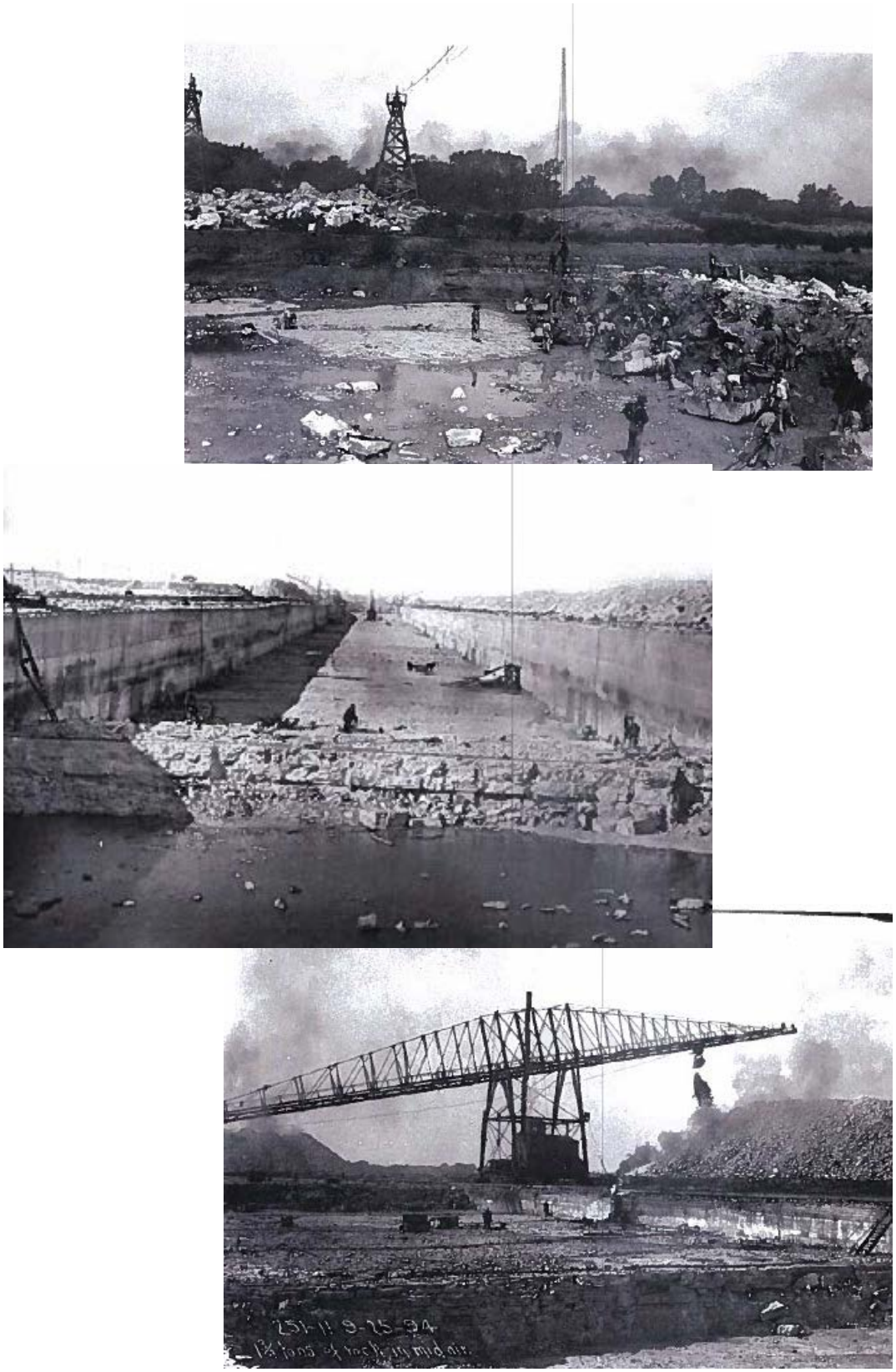

Figure 1.3. Photographs showing construction of the Chicago Sanitary and Ship Canal, 1892-1900, referred to as the "Chicago School of Earthmoving" (courtesy of Lewis University Archives).

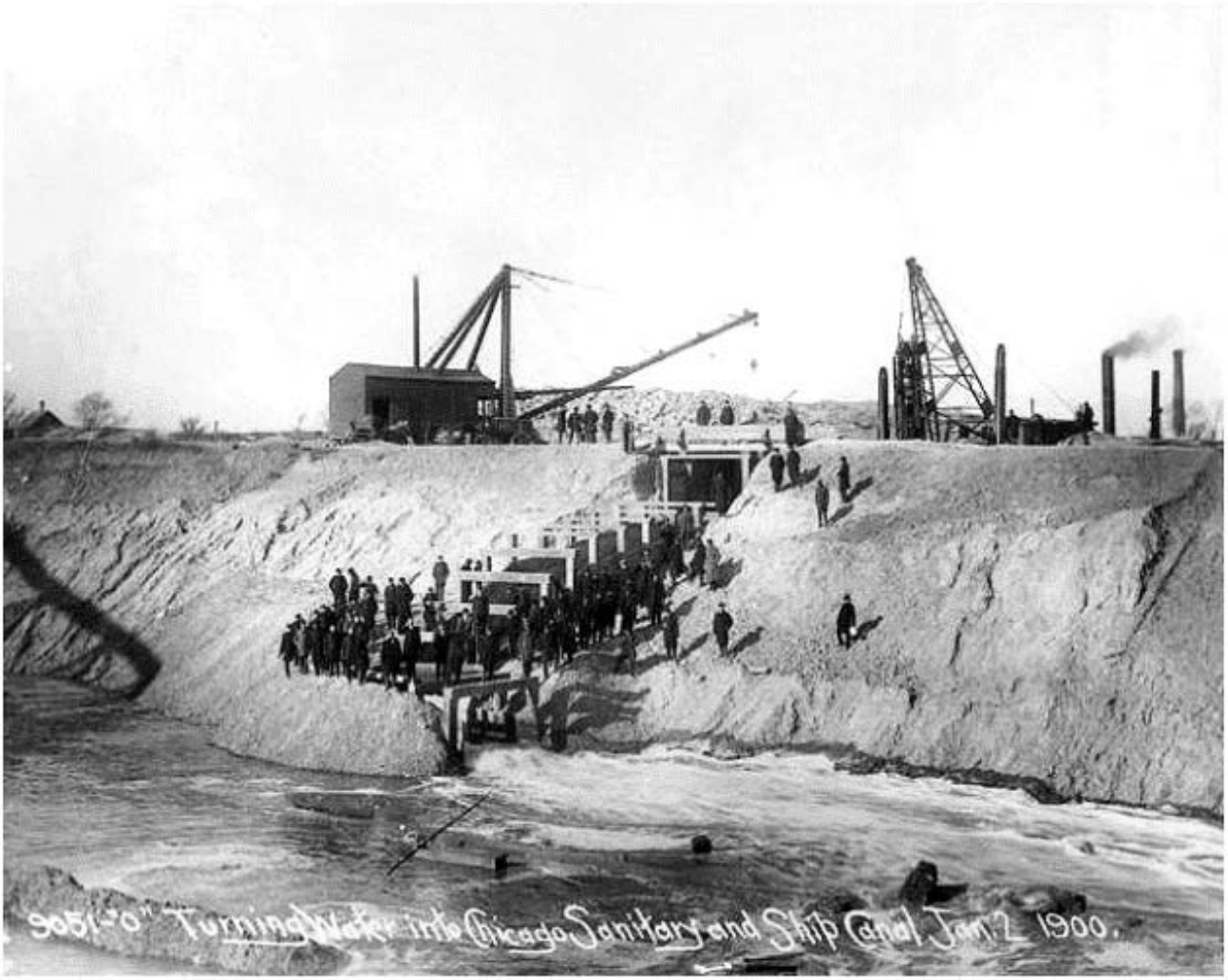

Figure 1.4. Breaching Needle Dam to allow flow into the Chicago Sanitary and Ship Canal, January 2, 1900. (Courtesy of Lewis University Archives)

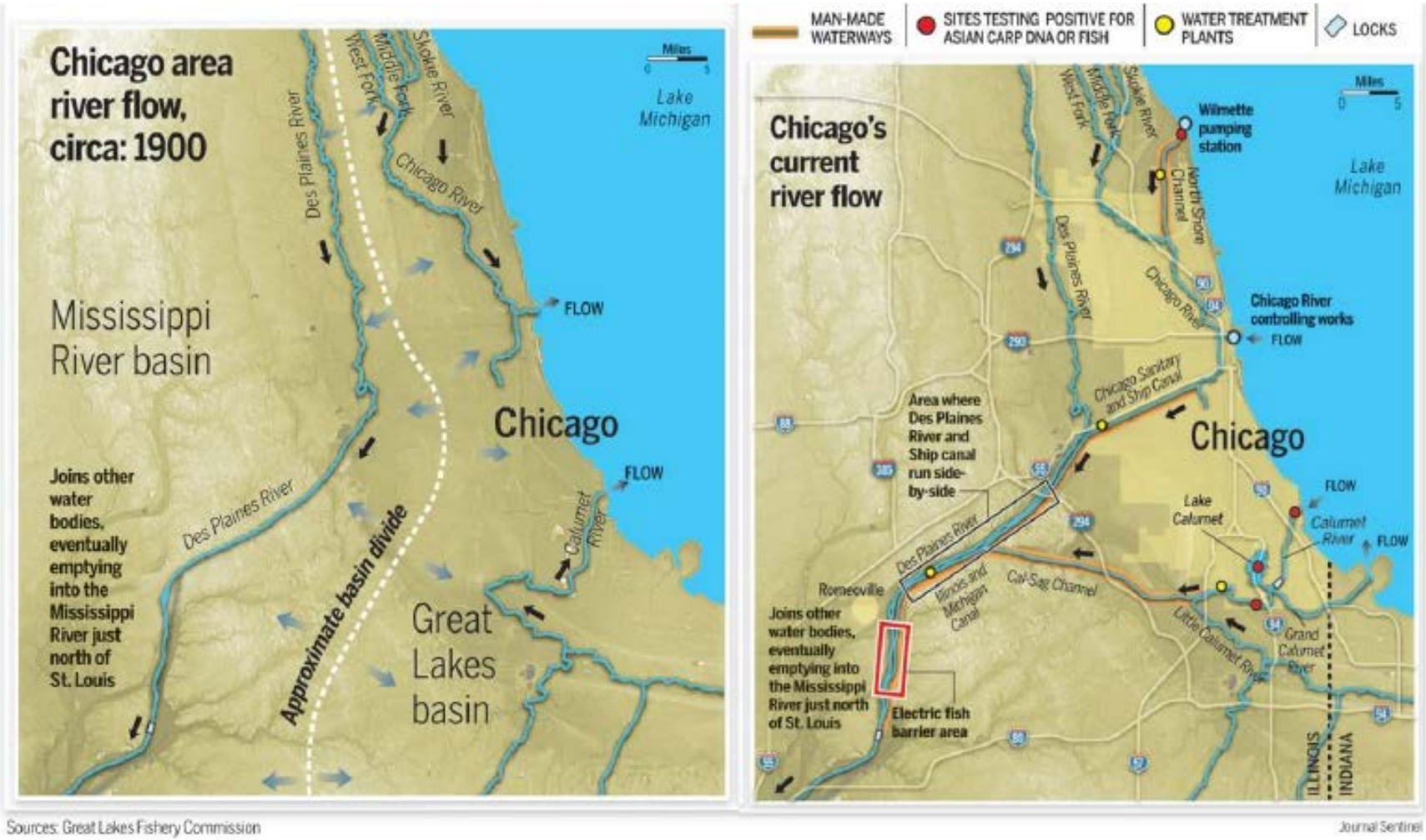

Figure 1.5. Lake Michigan Diversion Before 1900 – Present (note: Water Treatment Plants = Water Reclamation Plants)

Figure 1.6. Development of Chicago Sanitary and Ship Canal System – Before Canal Construction.

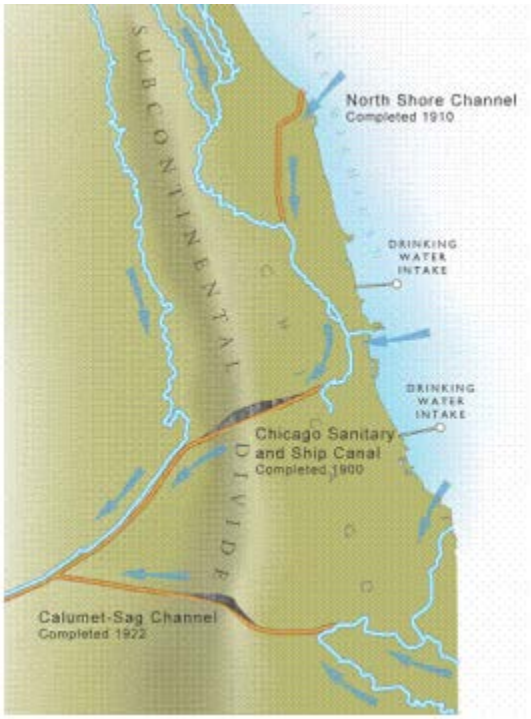

Figure 1.7. Development of Chicago Sanitary and Ship Canal System – Chicago Sanitary and Ship Canal System Completed.

In 1901 the MSDGC was authorized by the Secretary of War to divert 4,167 cfs in addition to domestic pumpage. In 1908 and again in 1913, the United States brought actions to enjoin the MSDGC from diverting more than the 4,167 cfs previously authorized in 1901. The two actions were consolidated, and the Supreme Court entered a Decree on January 5, 1925 allowing the Secretary of War to issue diversion permits. In March of the same year, a permit was issued to divert 8,500 cfs in addition to domestic pumpage, which was about the average then being used.

In 1922, 1925, and finally in 1926, several Great Lakes states filed similar original actions in the U.S. Supreme Court seeking to restrict diversion at Chicago. A Special Master, appointed by the Court to hear the combined three suits, found the 1925 permit to be valid and recommended dismissal of the action. However, the Supreme Court reversed his findings. Subsequently, the Court instructed the Special Master to determine the steps necessary for Illinois and the MSDGC to reduce diversion. Consequently, a 1930 Decree reduced the allowable diversion (in addition to domestic pumpage) in three steps: 6,500 cfs, after July 1, 1930; 5,000 cfs after December 30, 1935; and 1,500 cfs after December 31, 1938.

In 1967, a U.S. Supreme Court Decree limited the diversion of Lake Michigan water by the State of Illinois and its municipalities, including sewage and sewage effluent derived from domestic pumpage, to a five-year average of 3,200 cfs, effective March 1, 1970. This Decree gave full responsibility to the State of Illinois for diversion measurements and computations. The U.S. Army Corps of Engineers (USACE) was to have a role of "general supervision and direction." The first five-year accounting period began March 1, 1970 and ended to February 28, 1975. During this period, the average diversion was 3,183 cfs. The next accounting period began March 1, 1975 and ended February 29, 1980. During this period, the average diversion was 3,044 cfs. The U.S. Supreme Court amended its 1967 Decree on December 1, 1980. The amendment changes, in part, provisions of the 1967 Decree that prevented the State of Illinois from effectively utilizing and managing the 3,200 cfs of Lake Michigan water, which had been allocated previously by the U.S. Supreme Court. This amendment forms the current diversion criteria this report addresses. These criteria can be summarized as follows:

1. An increase in the period for determining compliance with the diversion rate limit of 3,200 cfs from a 5-year running average to a 40-year running average,

2. Changing the beginning of the accounting year from March 1 to October 1,

3. Limit on the average diversion in any annual accounting year shall not exceed 3,680 cfs, except in any two (2) annual accounting periods within a forty (40) year period, and the annual average diversion shall not exceed 3,840 cfs, and

4. Limit on the cumulative algebraic sum of the average annual diversions minus 3,200 cfs during the first 39 years to 2,000 cfs-years.

In addition, the modified U.S. Supreme Court Decree for the Lake Michigan Diversion at Chicago, Illinois, adopted by the Court on December 1, 1980, stipulates that the USACE convene a three-member Technical Committee at least once every five years to review and report on the methods of flow measurement and procedures for diversion accounting. The Committee review is to include:

1. an evaluation of the current procedures used for the measurement and accounting of diversion in accordance with the best current engineering practice and scientific knowledge; and

2. recommendations for any appropriate changes to those procedures.

1.2 Overview - Components of Lake Michigan Diversion (2010-2015)

The average annual value for each of the primary components of the Lake Michigan Diversion for accounting years 2010 through 2015 are listed in Table 1.1 including lockages, leakages, navigation makeup flow, discretionary flow. The primary components of Lake Michigan Diversion accounting are presented in Figures 1.8 and Figure 1.9 and are as follows:

- water supply taken from Lake Michigan intake cribs (the Harrison-Dever Crib one of the Lake Michigan Cribs is shown in Figure 1.9) and discharged into the river canal system or rivers in the greater Chicago area as Water Reclamation Plant effluent and occasional combined-sewer overflows (CSOs);
- storm runoff from the diverted watershed area of Lake Michigan, draining to the river and canal system in the greater Chicago area; and
- water from Lake Michigan entering directly into the river and canal system in the greater Chicago area. This component consists of the following three parts (Table 1.1, note: all the lakefront facilities are shown in Figure 1.8):

    a) water required for lockage at the Chicago Harbor Lock and the Thomas J. O'Brien Lock;

    b) leakage occurring at the CRCW, Lock, and turning basin walls (Chicago Harbor), O'Brien Lock and Dam, and Wilmette Pump Station and Sluice Gate; and

    c) direct diversions for navigational make-up and discretionary (water quality improvement) purposes made at the CRCW and O'Brien Lock and Dam, and discretionary purposes at the Wilmette Pump Station

Table 1.1. Total Average Annual Flow of Different Components of the Lake Michigan Diversion, 2010 - 2015

	2010		2011	
Description	**Average Flow (cfs)**	**Percentage of Total Flow**	**Average Flow (cfs)**	**Percentage of Total Flow**
Lake Michigan Pumpage by the State of Illinois	1253	44.4	1245	45.4
Runoff for Diverted Lake Michigan Watershed	1190	42.1	1146	41.8
Total Direct Diversions	382.2	13.5	352.1	12.8
Total Diversion (columns 11-13)	2825		2743	
Lockages	45.5	1.6	37.2	1.4
Leakages	35.0	1.2	16.6	0.6
Navigation Makeup Flow	24.0	0.9	28.2	1.0
Discretionary Flow	277.4	9.8	269.6	9.8
Total Diversion (columns 1-10)	2874		2791	

	2012		2013	
Description	**Average Flow (cfs)**	**Percentage of Total Flow**	**Average Flow (cfs)**	**Percentage of Total Flow**
Lake Michigan Pumpage by the State of Illinois	1288.5	57.8	1230.3	48.8
Runoff for Diverted Lake Michigan Watershed	623.3	28.0	946.9	37.6
Total Direct Diversions	317.4	14.2	342.4	13.6
Total Diversion (columns 11-13)	2229		2520	
Lockages	25.7	1.2	25.1	1.0
Leakages	18.2	0.8	11.5	0.5
Navigation Makeup Flow	5.4	0.2	29.2	1.2
Discretionary Flow	268.0	12.0	276.5	11.0
Total Diversion (columns 1-10)	2267		2431	

	2014		2015	
Description	**Average Flow (cfs)**	**Percentage of Total Flow**	**Average Flow (cfs)**	**Percentage of Total Flow**
Lake Michigan Pumpage by the State of Illinois	1220	44.1	1176	49.3
Runoff for Diverted Lake Michigan Watershed	1128	40.7	859.9	36.1
Total Direct Diversions	421.2	15.2	348.5	14.6
Total Diversion (columns 11-13)	2769		2384	
Lockages	53.8	1.9	64.4	2.7
Leakages	20.9	.8	29.1	1.2
Navigation Makeup Flow	31.0	1.1	34.6	1.5
Discretionary Flow	315.6	11.4	220.4	9.2
Total Diversion (columns 1-10)	2785		2390	

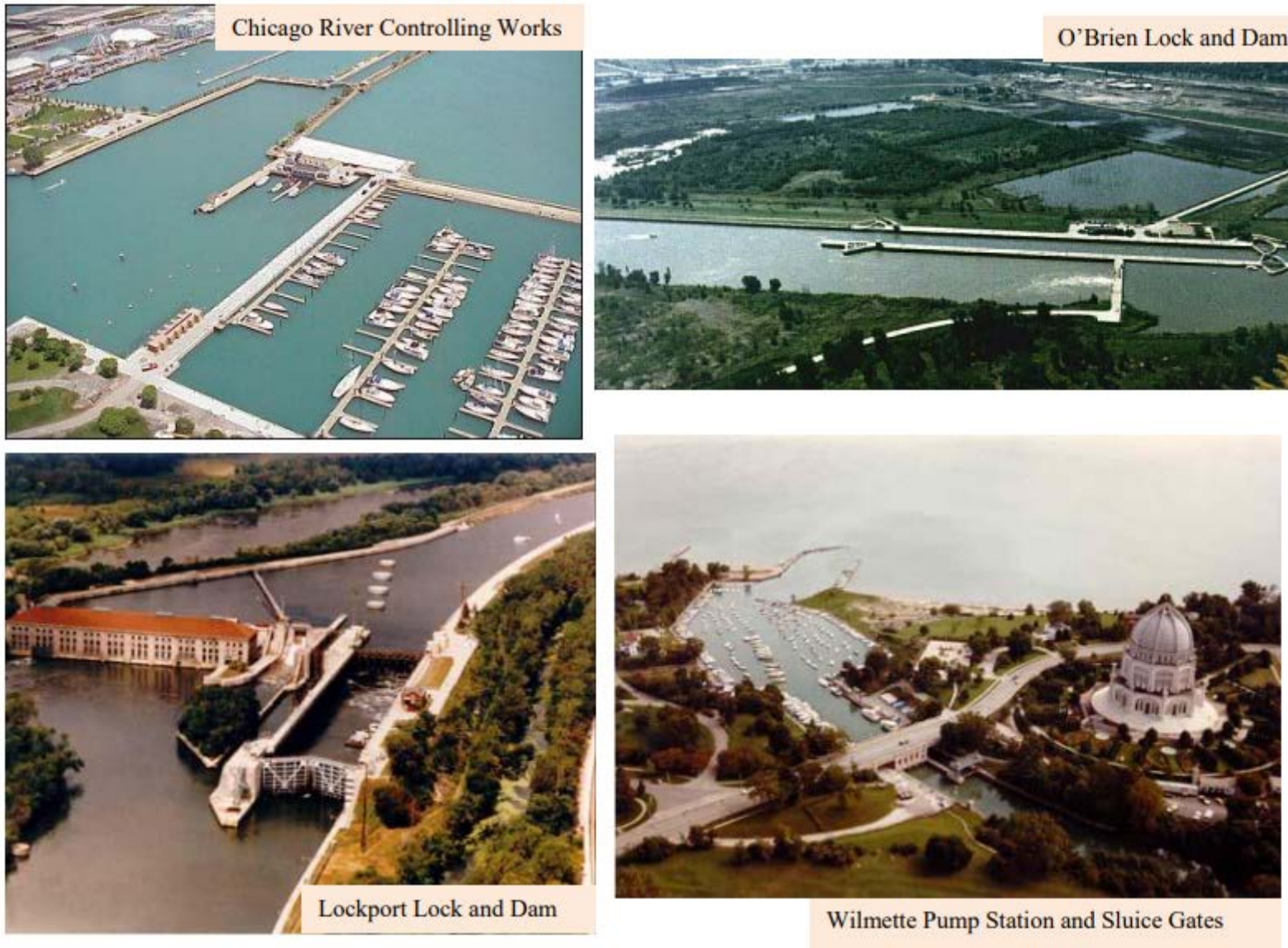

Figure 1.8. Chicago River Controlling Works

Figure 1.9. Harrison-Dever Cribs.

1.3 Summary of the First to Seventh Technical Committees' Recommendations and Findings

The Technical Committee has convened eight times since the modified U.S. Supreme Court Decree was adopted on December 1, 1980 for the purpose of reviewing flow measurement methods and procedures for diversion accounting. Each review has been documented in a final report that describes the review and associated findings, and provides recommendations. Each subsequent Committee reviews the preceding committee reports and investigates activities undertaken by the various parties involved in the accounting process to address the recommendations offered by previous committees.

Like the accounting methods and procedures, the findings and recommendations of the Technical Committee have evolved over time. The following sections summarize the primary findings and recommendations provided by each of the previous seven Technical Committees. The specific action taken by the USACE is discussed in each individual committee report.

1.3.1 First Technical Committee

The first three-member Technical Committee convened in June 1981, and issued their final report, dated October 1981. The committee's report presented a discussion of the history of diversion, the various components of the diversion, and the various flow measurements and computations used to determine Lake Michigan diversion as defined by the 1980 Modified Supreme Court Decree. The First Committee found virtually every aspect of the program to account for diversion from Lake Michigan to be in need of improvement. The diversion, measurement and accounting process "lacked credibility." The Lockport flow components, the cornerstone for diversion accounting, at that time, were determined to be deficient "in practically every aspect." The First Committee report was reviewed to establish a base of reference for the evaluation of diversion activities since 1981. The following is a brief summary of recommendations made by the First Committee:

1. Preparation of a Master Plan for diversion accounting,

2. Establishment of a Quality-Assurance program including an Operational Procedure Manual,

3. Consideration of alternatives to measurement at Lockport facilities,

4. Modifications and improvements to flow measurement practice for Lockport facilities, and

5. Modifications to flow measurement practices for Lockport Lock leakage.

1.3.2 Second Technical Committee

The Second Technical Committee was convened in July 1986 and reviewed accounting for Water Years (WYs) 1981 through 1983. The following is a brief summary of the major findings and recommendations of the Second Committee:

1. The Second Technical Committee was in general agreement with the findings and recommendations made by the First Committee (1981)

2. The Master Plan for diversion accounting and the Quality Assurance program are essential elements of the diversion accounting program that were still lacking,

3. The diversion accounting certification report should provide the reader a narrative description of the facts which support the certification evaluation,

4. At some appropriate time, probably no earlier than after the completion of WY 1987, the diversion records for water years after 1980, should be reviewed, and if appropriate, revised as necessary to account for the apparent errors in the Lockport discharge rating used during WYs 1981-1984,

5. Columns 7 and 9 of the Diversion Accounting Procedures representing the so-called sewer induced groundwater inflow should be withdrawn from the diversion accounting format,

6. Action should be initiated to address the deficiencies in the data bases for parameter values and model calibration, verification, and simulation, especially as they pertain to those drainage areas used directly in computing diversion,

7. Examine the constancy of the relation between water-supply pumpage and sewage treatment-plant inflows and its applications for the purpose of estimating the infiltration and inflow deduction for the Des Plaines watershed,

8. Reconsider the alternatives (modeling, etc.) for estimating the annual runoff from the Lake Michigan watershed,

9. The effort by the U.S. Geological Survey (USGS) to establish guidelines to promote improvement in the quality of the Acoustic Velocity Meter (AVM) records should be continued,

10. The current regressions of the daily discharges for the AVM against MSDGC's records for flow at Lockport, used for the AVM back-up, should be reconsidered, specifically giving attention to the actual Lockport operating configurations,

11. A technical review of the AVM flow records should be conducted annually by the participating agencies,

12. The flow records for the AVM and flows at Lockport reported by MSDGC should be reviewed and compared for consistency on an annual basis,

13. The mean bed elevation for the canal in the reach delimited by the AVM transducer location should be determined, as well as along the transducer paths,

14. The Lockport facilities of the MSDGC and USACE should be used for the back-up to the AVM system at Romeoville,

15. Execute a set of field measurements designed to verify the ratings developed by the USACE Waterways Experiment Station (WES) for both the Lockport Powerhouse sluice gates and the Lockport Controlling Works,

16. Infiltration and inflow of groundwater into the Tunnel and Reservoir Plan (TARP) tunnels should be treated as a deduction to the flows measured at Lockport, and

17. The runoff to the TARP system for the Lower Des Plaines combined sewer system should be determined and included as a deduction.

1.3.3 Third Technical Committee

The Third Technical Committee was convened in February of 1993 and reviewed WYs 1984 through 1989. This Third Technical Committee was gratified by the improvement achieved in the accounting procedures, particularly in the quality of the AVM records. The primary reason for the diversion exceeding the flow limits of the Supreme Court Decree as modified in 1980 is the improved accuracy of the accounting procedures. A major part of this improved accuracy can be attributed to the AVM system at Romeoville. In most instances, actions have been taken to comply with the recommendations and significant progress has been made. Some of the findings and recommendations made by the Third Technical Committee are still current are listed in italics to emphasize their importance.

1. The draft of the Master Plan for the Lake Michigan Diversion Flow Measurements and Accounting Procedures 14 April 2014 is needed.
2. The Master Plan should include an "Operational Procedures Manual" documenting technical procedures and methods used in the Lake Michigan diversion computations,
3. The draft – Plan (draft – October 1988) should be updated and finalized based on the present status of Lake Michigan diversion computational procedures and measurements,
4. Update the AVM Quality-Assurance Plan,
5. A technical review of the Romeoville AVM discharge ratings and flow records should be conducted annually,
6. The mean bed elevation of the canal at the AVM measuring reach should be surveyed periodically,
7. An examination of the range of discharge measurements indicates that about 80 percent of the measurements were made at gage heights between 24.7 and 25.7 ft. If at all possible, it would be very useful in the development of discharge ratings to obtain more discharge measurements at the 21 to 24 ft range,
8. The Acoustic Doppler Current Profiler (ADCP) (Broadband) system should be used to calibrate and verify the AVM Romeoville system operations. The ADCP can be a valuable tool for measurement during low flow and/or unsteady flow conditions,
9. Investigate the feasibility of developing ratings between the leakage flow through the gates at the lakefront and the water surface elevation of the lake, and
10. *Annual Lake Michigan diversion results should be published in a more timely fashion*, and field investigations of flow characteristics of the Upper Des Plaines Pumping Station (UDPP), including bypass flow, should be conducted to improve the accuracy of inflow and infiltration characteristics used in the hydrologic simulation.

1.3.4 Fourth Technical Committee

The Fourth Technical Committee was appointed July 1998 and held the first workshop in September 1998 and reviewed WYs 1990 through 1995. The Fourth Technical Committee was gratified by the improvement achieved in the accounting procedures, particularly in the quality of the AVM records. Some of the recommendations and findings made by the Fourth Technical Committee are summarized as follows:

1. The draft quality assurance plan (October 1988) has not been updated as recommended by the Third Technical Committee. The draft quality-assurance plan (October 1988) should be updated and finalized based on the present status of Lake Michigan diversion computational procedures and measurements (1999 conditions).

2. Before implementing lakefront accounting, a manual of procedures for lakefront accounting should be written.

3. The Lake Michigan accounting procedures should be modified to begin with an initial set of template files rather than begin with the previous year's files, which are copied and modified to represent the current year's data.

4. Results from statistical analyses of the six years of record considered in this review indicate that Budgets 9, 10, 11, and 13 may contain significant long-term biases.

5. The regression analysis used to develop backup equations to estimate flows when the Romeoville AVM is not functioning properly should be repeated to develop new backup equations for periods when the turbine AVMs are the reported flows at Lockport.

6. Potential bias error in the annual mean discharge from the Romeoville AVM for the six years reviewed in this report is ±93 cfs.

7. The USGS is continuing to revise and update the instrumentation, rating, and backup equations for the AVM on the Calumet River at O'Brien Lock and Dam. The record from this station, through WY 1998, has not been published and is still considered 'Provisional' and subject to revision. The AVM velocities show significant noise and variation among paths. The accuracy of the mean annual discharge at this site, cannot be determined by the current records.

8. The USGS is continuing to revise and update the instrumentation, rating, and backup equations for the AVM on the Chicago River at Columbus Drive. The record from this station, through WY 1998, has not been published and is still considered 'Provisional' and subject to revision. The AVM velocities show significant noise and variation among paths. The accuracy of the annual mean discharge at this site, based on current records, is approximately ±190 cfs. The committee anticipates that the accuracy of the calculated discharges at this site should be improved from this value as a result of the continuing efforts to improve the instrumentation and discharge-calculation procedures

9. The USGS is currently installing an AVM on the North Shore Channel at Wilmette, Illinois. This site may experience many of the difficulties encountered at Columbus Drive and O'Brien Lock and Dam.

10. Consecutive discharge measurements for a fixed flow condition should be grouped and averaged for rating analysis. Statistical tests for serial correlation should be a standard part of the regression analysis.

11. Backup equations should be developed to estimate flow for periods of missing AVM record based on the position of the sluice gate and the lake and channel stages. Measurements to develop this equation should be done with an ADCP. The lake and channel stage and gate-opening measurements should be verified as part of these measurements.

12. For Lakefront Accounting, the long-term average runoff from the diverted Lake Michigan watershed has been fixed at 800 cfs through the year 2020 as part of the mediation agreement. This runoff number was established as part of the mediation and has its basis from long-term simulation and streamflow separation of historical records. In order to re-evaluate this value in 2020, the capability to accurately simulate the hydrology of the watershed needs to be maintained.

13. For Lakefront Accounting the long-term consumptive use of water pumped from Lake Michigan has been fixed at 168 cfs through the year 2010 as part of the mediation agreement. Based on a review of the available data, the Committee concluded that consumptive use cannot practically be determined directly. The Committee, therefore, concluded that an indirect determination of consumptive use from a water budget analysis based on water-supply pumpage and treatment plant flow records and simulation results is consistent with best current engineering practice.

14. Water-supply pumpage accounts for about 80 percent of the measured components of Lake Michigan Diversion under the proposed Lakefront Accounting System. The USACE has initiated quality-assurance reviews of three of the water-supply facilities. These reviews were done to provide a protocol and format for subsequent review of the remainder of the water-treatment facilities and pumping stations. The reviews from the three prototype studies do not adequately document the accuracy of the pumpage records from these plants.

15. The Fourth Technical Committee was concerned regarding the data viability during the initial part of the three-water-year transition period. The USGS is using state-of-the-art technology to measure the velocities and develop the ratings at these sites. The Fourth Technical Committee believed the accuracy for the record currently available for these sites does not reflect the potential of the current technology to measure flows at these sites.

1.3.5 Fifth Technical Committee

The Fifth Technical Committee was appointed by the USACE in December 2002 to conduct the court mandated assessment of the accounting procedures and methodology used to quantify diversion. The assessment performed by the committee focused on the following primary topics: The accounting of annual diversions for WYs 1996, 1997, 1998, and 1999. Measurement methods implemented at primary flow-monitoring locations. Procedures used to calculate and verify flows that are not directly measured such as the Hydrologic and Hydraulic (H&H) models. Comparison of the anticipated relative accuracy or uncertainty in the estimates of diversion calculated using the Romeoville and Lakefront Accounting Systems, and evaluation of approaches that might be used to quantify consumptive use. The following is a summary of the Fifth Technical Committee Recommendations and Findings.

1. In general, the Fifth Technical Committee has determined, based on our review that the Lake Michigan Diversion Accounting is in compliance with the 1980 Modified Decree, with respect to the “best current engineering practices and scientific knowledge.”

2. This Fifth Technical Committee is in general agreement with the findings and recommendations made by the Fourth Technical Committee. In most instances, actions have been taken to comply with the recommendations, and progress has been made since the Fourth Technical Committee recommendations were made.

3. The technology that has evolved with respect to acoustical flow measurements has not only met the standard of "best current engineering practice and scientific knowledge," but the USACE and the USGS are establishing a higher, "state of the art" standard. The USGS leadership in this technical area is to be commended.

4. The annual diversion determinations for WYs 1996, 1997, 1998, and 1999 are satisfactory.

5. Precipitation records collected by MWRDGC between 1990 and 2002 from an independently maintained monitoring network of 12 rain gages were reviewed and compared by the MWRDGC (Lanyon and Yourell, 2003) with the records from nearby Illinois State Water Survey (ISWS) gages. Preliminary findings indicate that although the values measured by the MWRDGC were consistently less than the values measured by the ISWS, there was no apparent change over time in the relation between the two sets of data. The MWRDGC evaluation documents the availability of a backup network of precipitation gages and historic data that may be useful in future diversion analyses.

6. For Lakefront Accounting, the long-term average consumptive use of water pumped from Lake Michigan has been fixed at 168 cfs through the year 2010 as part of the mediation agreement, which represents approximately 5 percent of the diversion. The Fifth Technical Committee concluded that the determination of consumptive use from a water budget analysis based on water-supply pumpage, treatment plant flow records and simulation results is consistent with "best current engineering practice."

7. Leakage at the CRCW has been substantially reduced because of repairs to the lock and turning basin walls (completed Summer 2000), combined with recent lower Lake Michigan water levels.

8. AVM and ADCP measurements at the O'Brien Lock and Dam AVM gage suggest that there is considerable (100 cfs or more) leakage through the structure. Such leakage will likely increase as lake levels rise. Continuous gaging of flows at this station together with synoptic ADCP measurements during low flow and verification of gate opening indicators will help to better quantify the apparent leakage at this lakefront location.

9. Implementation of new ADCP current profiler technology should improve the accuracy of flow measurements in shallow channels such as the North Shore Channel at Wilmette and channels above and below the control structure at O'Brien Lock and Dam.

10. The relocation of the Romeoville AVM gage because of the proposed electric fish barrier resulted in the evaluation of three alternative sites by the USGS. The Fifth Technical Committee reviewed the three alternative sites evaluated by the USGS. The Fifth Technical Committee recommended the site on MWRDGC property 5.9 miles upstream from the present Romeoville AVM site and is pleased that the site (Lemont) has been secured.

11. The Fifth Technical Committee encourages concurrent operation of existing and proposed AVM systems on the CSSC near Romeoville and Lemont, respectively, for as long as possible to establish rating and flow correlation.

12. A Quality Assurance Plan (QAP) should be developed for the new AVM system near Romeoville as soon as the gage installation is completed. QAPs for the other AVM gages including the existing Romeoville gage should be updated to reflect current conditions.

13. It is recommended that the index-velocity rating at the Romeoville AVM gage be re-evaluated. A substantial number of additional ADCP measurements have been made since the existing rating was developed, and a new AVM system with a re-configured transducer path was installed in October 2001 and made operational in April 2002.

14. The USGS should develop some national standards or guidance regarding the development of index-velocity ratings, particularly in regards to when zero and non-zero intercepts are appropriate and when to use grouped or ungrouped data. Site-specific characteristics such as channel stability, range and variability of stage, and range and variability of AVM index velocity should be considered. The Fifth Technical Committee recommends that the USGS further evaluate the upper limits for random and systematic ADCP-measurement error and to characterize the sensitivity of uncertainty in the annual flow to measurement error bias by evaluating some other assumed (perhaps 2 percent) bias in the uncertainty analysis of WY 1997- 1999 AVM records.

15. For the AVM/ADCP stream-gaging stations, the record reported for the Romeoville station during WY's 1997 – 1999 is the most accurate (approximately 4 percent coefficient of variation), followed by Columbus Drive (18 percent), O'Brien Lock and Dam (24 percent) and Wilmette Pump Station (47 percent). Although the USGS uncertainty analysis documents large relative uncertainty in the Lakefront AVM system flow records compared to other records such as the flow at the Romeoville AVM gage (2 percent) and USACE-determined domestic pumpage (3 percent), the Fifth Technical Committee's analysis indicates that the combined uncertainty in the direct diversion flow record is only double the uncertainties associated with measurements of consumptive use and domestic pumpage.

16. The comparison of the Lakefront Accounting concept using the model error and the Romeoville Accounting shows that the Romeoville Accounting System has slightly less uncertainty (about 10 percent smaller total Coefficient of Variation, COV) than the Lakefront Accounting System because of the low uncertainty of the Romeoville AVM.

17. An independent backup flow-measurement method must be maintained for each AVM gage. This is of critical importance to stations such as the Romeoville AVM gage where the uncertainty in gage record comprises a relatively large portion of the overall uncertainty in the reported diversion.

18. Several actions are recommended as quality assurance practices in support of the LMO-6 reporting for the various controlling works and the analysis of independent flow methods suggested previously. Check measurements of gate-opening indicators at the controlling works should be made annually in addition to the periodic inspection of stage sensors maintained by the MWRDGC and USACE. A field survey should be performed to verify the elevations of reference points and/or staff gages located on the upstream and downstream sides of controlling works in the vicinity of the primary stage sensors. A reference point, or staff gage, should be established on the upstream side of the O'Brien Lock and Dam. Check measurements of stage should be made at the outside gage or reference point and compared with concurrent readings of the primary stage sensor to verify the sensor calibration.

19. The Fifth Technical Committee concurs with and reiterates the recommendations of the Fourth Technical Committee and the contractor who evaluated the pumping stations and water treatment plants that the venturi meters (a) should be calibrated to establish if manufacturers' rating curves are correct and (b) should be physically removed so that inlet

and throat dimensions can be measured and inspected for physical deterioration. This might be done by partitioning the facilities into three groups based on annual pumping and then randomly sampling 5 to 10 percent of the meters associated with the pumping reported within each group.

20. The Fifth Technical Committee's review of water withdrawal and delivery data indicates that a 10 percent consumptive use factor is substantially smaller than the losses from the withdrawal point to households. Thus, if consumptive use increases in future modeling, infiltration must increase to maintain a good flow balance during dry weather flow at the WRPs.

21. The comparisons of simulated and measured flows at the WRPs are not sufficiently precise to evaluate the accuracy of the rainfall-runoff simulation. Wastewater flow comprises more than 80 percent of the WRP flows. With a revision to the consumptive use the percentage may drop below 80 but wastewater still will dominate the WRP flows. Thus, substantial errors in the rainfall-runoff simulation could be hidden in a 5 percent difference in simulated and measured WRP flows. Thus, three new checks of rainfall-runoff simulation are recommended.

    A. The comparison of simulated and measured flows for the Midlothian Creek and Tinley Creek at Palos Park gages in the "ungaged" Calumet watershed would greatly increase confidence that the HSPF model parameters are valid for the watersheds to which they are applied in the diversion accounting.

    B. The difference in flow between the Touhy Avenue and Albany Avenue gages on the North Branch Chicago River, a 13 mi^2 of drainage area, could be compared to simulated inflows to the reach between the gages.

    C. A comparison should be made for annual flows at the North Branch, Racine Avenue, and 125th Street Pump Stations of the MWRDGC.

22. The performance of the WY 1997 modifications to land use should be monitored as additional years of diversion calculations are completed. If the CSO flows still seem to be overestimated, the DuPage County (1993) values for medium and low density residential development should be applied for the H&H modeling in the diversion accounting.

23. The comparisons at the UDPPS and for the lower Des Plaines River watershed by area ratio indicate potential underestimation of Des Plaines River watershed runoff. This requires further evaluation. If Romeoville Accounting is to be used in the future, gaging at the UDPPS must be improved so that meaningful comparisons can be made at this station and the Des Plaines River watershed flows can be properly tested and adjusted.

24. The quality of the stage agreement during Unsteady Network (UNET) model calibration for the Grand Calumet River often is very poor and the USACE original evaluation indicates too much flow may be directed East in the model resulting in an underestimate of the Indiana Water Supply pumpage deduction. The UNET model should be revised using more recent data and accounting for changes in roughness during the growing season for aquatic vegetation.

25. In the application of the Tunnel Network (TNET) model for diversion accounting, the measured stage at the TARP pumping stations should be used as the downstream boundary

condition and the outflow, i.e. pumpage, should be computed. If the computed outflow exceeds the actual pumpage, decrease TARP inflow and increase CSOs. Conversely, if the computed outflow is less than the actual pumpage, increase TARP inflow and decrease CSOs.

26. The streamflow separation in the period of record runoff analysis should be revised to more correctly adjust earlier runoff for 1990 land use conditions using the double mass curve method proposed by Riggins and Yen (1995).

1.3.6 Sixth Technical Committee

The Sixth Technical Committee was appointed by the USACE in December 2007 to conduct the court mandated assessment of the accounting procedures and methodology used to quantify diversion. The assessment performed by the committee focused on the following primary topics: The accounting of annual diversions for WYs 2000, 2001, 2002, 2003, 2004, and 2005. Procedures used to calculate and verify flows that are not directly measured such as the H&H models. Measurement methods implemented at primary flow-monitoring locations and, the status of recommendations offered by previous technical committees. The following is a summary of the Sixth Technical Committee Recommendations and Findings.

1. In general, the Sixth Technical Committee has determined, based on our review that the Lake Michigan Diversion Accounting for WYs 2000, 2001, 2002, 2003, 2004, and 2005, is in compliance with the 1980 Modified Decree, with respect to the "best current engineering practices and scientific knowledge."

2. This Sixth Technical Committee is in general agreement with the findings and recommendations made by the Fifth Technical Committee. Progress has been made to comply with most of the recommendations, and progress has been made since the Fifth Technical Committee (2004).

3. From the technology standpoint of "best current engineering practice and scientific knowledge," the progress of Lake Michigan Diversion accounting has been significant and is reflected in a number of specific engineering/scientific areas: 1) basic diverted watershed system data and understanding; 2) hydrologic modeling; and 3) flow measurements.

4. The technology that has evolved with respect to acoustical flow measurements has not only met the standard of "best current engineering practice and scientific knowledge," but the USACE and the USGS are establishing a higher, "state of the art" standard. The USGS leadership in this technical area is to be commended.

5. The Sixth Technical Committee agreed with the recommendation of the Fifth Technical Committee that since the Romeoville gage had to be abandoned due to the construction of an electric fish barrier at the Romeoville site that would affect the acoustical records at the gage, an extended period of overlapping AVM record at Romeoville and Lemont was needed and that the Romeoville AVM should be operated as long as possible. The overlapping period of record of the two gages, (October 2004 – June 2005), was unfortunately relatively limited. This partial period of record, was further limited by inconsistencies in the equipment. Unfortunately, in developing the flow rating at the Lemont gage, the extensive analysis, refinement and review of the Romeoville AVM record has been lost.

6. Now that the Romeoville/Lemont diversion accounting procedure has been selected and the models have been recalibrated, the diversion accounting manual of procedures should be completed.

7. For the Grand Calumet River the position and movement of the flow divide has been confirmed by the UNET and Hydrologic Engineering Center-River Analysis System (HEC-RAS) models that have been developed by the USACE (see Section 4.5.4 of Espey et al., 2009). However, to the Committee's knowledge the assumptions of the flow divide position on the Little Calumet River has not been checked since the early days of the accounting system. As such, the committee recommends that the Corps initiate a project to evaluate the position of the flow divide on the Little Calumet River.

1.3.6.1 Hydrologic and Hydraulic Modeling

1. The regional Hydrological Simulation Program-Fortran (HSPF) parameter approach and original calibration of HSPF meet the Supreme Court requirement of using the "best current engineering practice and scientific knowledge." However, the Fifth Technical Committee (Espey et al., 2004) recommended that "because of a lack of documentation on the transfer, additional checks of simulated flow are needed to confirm the accuracy of the HSPF model applied to the diversion accounting."

    A. The USACE had CTE (2003a-c) recalibrate the dry weather flow in SCALP and five grassland and one impervious area parameters in HSPF for WYs 2000 and 2001. The recalibration of the dry weather flows in the Special Contributing Area Loading Program (SCALP) led to compensating adjustments in the HSPF runoff model parameters. The recalibration of SCALP and grassland and impervious area HSPF parameters meets the standard of the best current engineering practice and scientific knowledge.

    B. Because the recalibration was for a two year period, the WY 2000 and 2001 Diversion Accounting Reports (USACE, 2004b, p. 51) recommended the following in the "Areas for Improvement":

    > "A longer term calibration period (10 or more years) should be looked at in the future. This long term calibration would be used to set the hydrologic parameters until a trend of over- or under-prediction becomes evident or changes in the physical system occur."

    C. Beginning with the WY 2000 Diversion Accounting Report (USACE, 2004b) the following recommendation regarding the wastewater flow adjustment has been included in the "Areas for Improvement" for the diversion accounting:

    > "The actual model change was performed by indiscriminately increasing or decreasing all Population Equivalent (PE) parameters for a particular service area in order to approximate the average change in wastewater loading. In reality, the wastewater loading is a product of the PE and the per capita usage factor for each sub area. To more accurately model the actual wastewater loadings present, both the PE and per capita usage should be reassessed. Census populations and NIPC manufacturing numbers should be considered when developing revised PE and per capita usage estimates."

Such a re-evaluation may be worthwhile, however, it is more important to determine the revised consumptive use estimates for the various WRP drainage areas. The percentage of return flow and consumptive use corresponding to the adjusted wastewater flows should be determined and compared to the findings of the Fifth Technical Committee (Espey et al., 2004).

D. The Fifth Technical Committee (Espey et al., 2004) recommended that the Midlothian Creek watershed at Oak Forest, Ill. (12.6 mi^2) and the Tinley Creek watershed at Palos Park, Ill. (11.2 mi^2) that drain to the Calumet-Sag Channel be used as test points for the calibrated HSPF watershed.

2. The Fifth Technical Committee (Espey et al., 2004) found that flow comparisons (1) at the UDPPS and (2) for the lower Des Plaines River watershed by area ratio indicate potential undersimulation of Des Plaines River watershed runoff. In order to understand the difference in results between Tinley Creek and Midlothian Creek, the USGS did a comparison of the land cover composition of the two watersheds. The Committee recommends that the recalibrated forest HSPF parameters be used in future diversion accounting calculations because the recalibrated forest parameter values 1) were derived for a 12 year calibration period, 2) yielded good results for Midlothian Creek and Tinley Creek (which is 24% forest), 3) may solve possible undersimulation problems in the lower Des Plaines River watershed, and 4) yielded parameter values that were generally in agreement with the ranges of parameter values obtained in the original calibration on nearby watersheds.

3. In the "Areas of Improvement" section in the Annual Diversion Accounting Reports for WYs 2000 to 2003 (USACE, 2004b, 2007a,b) the following recommendation was made:

i. "There appears to be a significant difference in simulated and observed flows during periods of significant snowfall. The snow melt and accumulation routines should be examined over a long period to identify possible parameter adjustments."

2. The Committee feels that if the HSPF snowmelt parameters are to be changed a larger system-wide study should be done, but the Committee feels that this recalibration will have a limited effect on the diversion computations and should not be a high priority.

4. In the Annual Diversion Accounting reports it has been long recommended in the "Areas for Improvement" that "Installation of better flow measurement equipment at the (Upper Des Plaines) pump station and measurement of bypass flows at the facility would allow for better model calibration."

5. Beginning in May 2005 the USGS began installing sewer flow gauges at 17 locations throughout the MWRDGC service area. Five of these are currently collecting continuous flow data. Sontek Argonaut SW flow meters are used at these locations. The Argonauts are superior to the area-velocity flow meters used by Waite et al. (2002). If household water meter data are available for the drainage areas of these locations, only household consumptive use would need to be approximated. Thus, infiltration during low flow periods could be more accurately determined and compared to simulation results, and the HSPF and SCALP models adjusted accordingly. The Committee suggests that re-evaluation of consumptive use and sewer infiltration should be a low priority for the improvement of Diversion Accounting procedures.

6. The Fifth Technical Committee (Espey et al., 2004) found that the quality of the stage agreement during UNET calibration for the Grand Calumet River often is very poor and the USACE original evaluation indicates too much flow may be directed East in the model resulting in an underestimate of the Indiana Water Supply pumpage deduction (Column 5 in the Diversion Accounting Table). The Fifth Technical Committee recommended that the UNET model should be revised using more recent data and accounting for changes in roughness during the growing season for aquatic vegetation.

7. The Fifth Technical Committee (Espey et al., 2004) recommended the use of the measured stage at the TARP pumping stations as the downstream boundary condition for TNET simulation and computation of the outflow. If the computed outflow exceeds the actual pumpage, decrease TARP inflow and increase CSOs.

   The Committee agrees to a compromise between the fifth Technical Committee recommendation and the USACE modifications as follows. TNET should be modified to yield computed water-surface elevations at the locations of the MWRDGC's sensors. The computed water-surface elevation should be compared with the measured values and the model computations adjusted on the basis of this comparison.

8. A substantial change was made to the groundwater inflow to the Mainstream and Des Plaines TARP systems. The Committee concludes that this change in the groundwater inflow to the Mainstream and Des Plaines TARP tunnels is completely justified.

9. The Illinois Transient Model (ITM) represents an advance in computational efficiency, economy in terms of memory requirements, and improved accuracy relative to commonly used Method of Characteristics approaches. The ITM represents a substantial advance over TNET.

1.3.6.2 Flow Measurement

The Sixth Technical Committee considers that the best current engineering practice and scientific knowledge are being used to measure various flow components involved in the LMDA.

1. Validity of the regression is periodically checked, MWRDGC (LMO-6). It is, therefore, recommended that the appropriateness of each estimating equation be documented through a more formal comparative analysis of AVM and LMO-6 records to identify any trends in differences between the records that would suggest one method or the other is providing potentially inaccurate record.

2. The Committee concludes that a thorough process of assessment and implementation should be considered to address the problem of monitoring at gaging stations during unsteady flows. The following primary recommendations are made in order to identify and correct the effect of flow unsteadiness:

   A. Assessment of the implications of the presence of unsteady flow regimes on the rating curve uncertainties at the Lemont gaging station

   B. Design and conduct of specific high temporal resolution, simultaneous measurements of stage, velocity, and discharge capable of capturing the flow unsteadiness and its effect on the discharge recordings.

C. Evaluation of the existing monitoring infrastructure and design appropriate means to capture the effect of flow unsteadiness on the rating curves. Formulate a quality control plan for conducting measurements in the Chicago Area Waterway System (CAWS) environment, including the transient flow conditions.

3. Given that the area of acoustic instruments is evolving in many aspects (design optimization, extension of measurement and processing capabilities) and new instruments are continuously developed several general recommendations in this respect would be to:

   A. Evaluate the sources of uncertainties in the discharge measured with the AVM.

   B. Given that the Acoustic Doppler Velocity Meters (ADVMs) are potentially superior compared to AVMs, testing the ADVM performance for estimating discharges using several strategies is suggested.

   C. Because of the importance of the ADCP synoptic measurement and given that the available technical guidance and protocols for acquiring discharge measurements are still evolving, it is suggested to gradually include measurement checks that allow inferences on particular aspects of the measurements.

4. At the most general level, given that the LMDA involves a suite of flow measurements provided by a variety of instruments and coupled with numerical analysis the need for a comprehensive, robust and sound uncertainty methodology is apparent. It is recommended to take advantage of the uncertainty analysis components developed for the Fifth Technical Committee (see Chapter V in Espey et al., 2004) and extend the analysis to other flow measurement instruments and procedures.

1.3.7 Seventh Technical Committee's Findings

1.3.7.1 Overview

1. The Seventh Technical Committee has determined, based on review of the LMDA for WYs 2006, 2007, 2008, and 2009, that the LMDA is in compliance with the 1980 Modified Decree, with respect to the "best current engineering practices and scientific knowledge".
2. The Seventh Technical Committee is in general agreement with the findings and recommendations made by the Sixth Technical Committee. The acoustical flow measurements have not only met the standard of "best current engineering practice and scientific knowledge", but the USACE and the USGS have established an even higher standard.
3. The LMDA Procedure manual has been completed (9/30/2013). Continual revisions should be made to keep this manual up to date. For example, the manual does not discuss use of data from Lockport Dam and Controlling Works in diversion accounting as a substitute for the Lemont Gage.
4. The summary reports of the Fifth and Sixth Technical Committees include numerous examples and citations of previous applications and use of regional parameters sets. The Seventh concurs that the "regional" calibration of HSPF parameter sets and their application to nearby hydrologically similar watersheds is consistent with the "best current engineering practice and scientific knowledge."
5. Even though watersheds are not necessarily broken out in the accounting process, it would be useful to document inflows to and outflow from each watershed, as an intermediate product. A diagram for each watershed would be useful. These should identify the source of the input

data. This would provide an important tool for future Technical Committee review. Maps and GIS shape files should be developed that clearly delineate each watershed or sewershed that contributes to the diversion accounting. These should include Flow Diagrams that indicate the division of water at key locations. These diagrams should also include key features such as canals, rain gages, treatment plants, tunnels, etc.

6. The water supply input to simulation models should be more thoroughly documented, particularly per capita water use.
7. The USACE - Chicago District should explore the possibility of including the Lake Michigan Diversion Accounting (Col 11-13) referred to as the "Verification Method" with the current accounting method to provide a better estimate of Lake Michigan Diversions.

1.3.7.2 Hydrologic and Hydraulic Modeling

1. The versions of HSPF, SCALP and TNET currently used in LMDA are DOS-based; and these may have future hardware and computer operating system issues. The Committee reviewed the models used in the LMDA processes, primarily HSPF, SCALP, and TNET, and concludes that the models and modeling strategy are adequate for the purpose of diversion accounting and meeting the standard of "best current engineering practice and scientific knowledge." The numerical processes employed by the H&H models are still current and appropriate. There are numerous newer models currently available that have similar capabilities as the LMDA models currently in use. These newer models were developed for more modern computer technology, while the older models are written in FORTRAN, which is increasingly difficult to support. Potential model replacements could be selected that are similar, but the development of model input and the calibration would require significant effort in order to match or exceed the performance of the existing model system. The Corps should consider developing a plan for the eventual replacement of these models.
2. HEC-Hydrologic Modeling System (HEC-HMS) is used in the Des Plaines River spillover simulation to compute a portion of the hydrologic inputs for HEC-RAS. This model fully meets "best current engineering practice and scientific knowledge" criteria.
3. HEC-RAS is used in spillover simulation and to indirectly estimate Indiana water supply flowing to CSSC via Grand Calumet River. This model fully meets "best current engineering practice and scientific knowledge" criteria.
4. Regarding validity of model parameter transfer, the "regional" calibration of HSPF parameter sets and their application to nearby hydrologically similar watersheds is consistent with the "best current engineering practice and scientific knowledge."
5. The original HSPF model was suitably calibrated for the purposes of the diversion accounting through WY 1999. Several recalibration studies have been performed over the past 15 years. The recalibration of the forest land parameters (used in WY2006 and forward) and grassland parameters (ongoing study) have expanded in scope, and have included a higher level of detail regarding land use. This is appropriate, and this improved methodology should be adopted as the standard. The most recent recalibration studies, once reviewed and approved, should be utilized to update the HSPF parameters.
6. Regarding hydrologic similarity, the regional HSPF parameter approach and original calibration of HSPF meet the Supreme Court requirement of using the "best current engineering practice and scientific knowledge." However, because of a lack of documentation on the transfer, additional checks of simulated flow are needed to confirm the accuracy of the HSPF model applied to the diversion accounting. The additional checks include the assumed values for consumptive use and monitoring of the replacement of combined sewers with separate sewer systems.

7. Methods employed by the USGS in recent recalibration studies meet the “best current engineering practice and scientific knowledge” standard.
8. Snowmelt – Considering the reevaluation of snowmelt parameters (2008) by the USGS, revision of snowmelt parameters is not appropriate. Recalibration attempts produced results that were generally inconclusive and would have been difficult to regionalize for use in HSPF. The snowmelt algorithm in HSPF meets “best current engineering practice and scientific knowledge” standard.
9. Simulation of runoff from Des Plaines Basin – Improved flow measurement at the UDPPS, which has only been used in the WY2011 LMDA reporting period, should be used to the extent possible. Pending further analysis with additional years of data these data could be useful for evaluation of simulation parameters.
10. Calumet TARP System Simulated to Recorded (S/R) ratios have improved due to a combination of revised groundwater inflow values and revised dropshaft gate closure simulation parameters. These are notable improvements and should be periodically reviewed. If additional TARP SCA (drainage area) data are available via the University of Illinois (U of I) study team, the data should be reviewed and used to update Calumet models as appropriate.
11. Indiana Water Supply through Grand Calumet River – After dredging is complete, the HEC-RAS model should be updated and recalibrated. Regression equations used for LMDA should be reviewed and revised as appropriate. Findings should be included in future LMDA reports.
12. TNET Model Application – Tunnel water surface elevation data (from the MWRDGC) may be of use to improve simulations, primarily to confirm dropshaft gate operation and pumping schemes employed by the MRWRDGC. Improvements to the simulation of dropshaft gate opening and pumping are critical to accurate simulation of tunnel flows, and ultimately the applicable S/R ratios.
13. Illinois Transient Model – The ITM is generally superior to TNET in its capability to simulate transients, but is not well-suited for continuous period simulations and/or use with LMDA modeling scheme. Data management is also a potential issue.

1.3.7.3 Flow Measurement

1. Uncertainty Analysis – Once standard uncertainty procedures are developed, measurement uncertainty should be estimated for the ADCP measurements. These should then be used to estimate the uncertainty of the Annual Lake Michigan Diversion estimated from AVM and ADVM measurement sites.
2. Cross Sectional Area – A periodic check on the cross sectional area at AVM and ADVM sites should be part of the USGS Quality Assurance Plan.
3. ADVM Measurement Uncertainty analysis should be performed on the ADVM measurement site.
4. Frequency of Calibration -- The frequency of index-velocity re-calibration should be included in the USGS Quality Assurance plan.
5. Flow Unsteadiness – The USGS should continue to attempt to collect ADCP measurements during the rising limb of the hydrograph.
6. Velocity Distribution over the Vertical – The USGS should continue use of the up-looking ADCP to evaluate the velocity distribution over the vertical at the Lemont Gage, and its influence on the uncertainty of diversion accounting.
7. Rating Curve Improvement – During ADCP calibration events, the USGS should experiment with using individual transects in the calibration, resulting in multiple values for a single calibration point. This might identify whether or not reflection waves are influencing the calibration of the index-velocity method.

8. Summit Conduit – The USGS should evaluate the possibility of locating the Summit Conduit measurement station at the downstream end of the conduit, and perhaps placing a small weir there to increase flow depths during low flow periods.
9. Reliability of Lemont Gauging Station Measurements –Back-up power should be considered for the Lemont Gaging Station.
10. AVM System – The AVM should be maintained as long as maintenance costs are reasonable. If the system needs replacement or the cable is cut again, the USGS should consider changing to a system that does not require a cable.
11. Lockport Powerhouse and Controlling Works – Although not a high priority, the USGS should continue to explore improved calibrations of discharge measurements at the Lockport Powerhouse and Controlling Works.

2.0 Technical Committee's Activities, Lake Michigan Diversion Accounting Water Years 2010-2015 and Annual Reports 2016-2018

Both measured and estimated flows are used to determine the annual diversion of water from Lake Michigan that is accountable to the State of Illinois pursuant to provisions of the U.S. Supreme Court Decree in Wisconsin, et al. vs. Illinois, et al. 388 U.S. 426, 87 S.Ct. 1774 (1967) as modified in 449 U.S. 48, 101 S.Ct. 557 (1980), hereinafter referred to as the 1980 Modified Decree. Continuous flow monitoring is performed whenever possible to directly measure components of the diversion budget. Hydrologic and Hydraulic (H&H) computer models use meteorological data to simulate flows for those components of the diversion budget that cannot be directly measured. When possible, continuous flow monitoring is performed to test the validity of the computer models.

The 1980 Modified Decree prescribes that the measurements and computations required by the Decree shall be made using "best current engineering practice and scientific knowledge." Furthermore, the USACE shall periodically convene a Technical Committee to review and report to the USACE "on the method of accounting and the operation of the accounting procedure." The Eighth Technical Committee was appointed by the USACE in May 2018 to conduct the court-mandated assessment of the accounting procedures and methodology used to quantify diversion. The assessment performed by the Committee focused on the following primary topics:

1. The accounting of annual diversions for WYs 2010, 2011, 2012, 2013, 2014, and 2015 (Section 2.1),
2. Procedures used to calculate and verify flows that are not directly measured such as the H&H models (Chapter 4),
3. Measurement methods implemented at primary flow-monitoring locations (Chapter 5),
4. The summary of recommendations offered by previous technical committees (Section 1.3),

The Committee addressed its goal by means of meetings with key participants in the accounting process, reviewing technical reports, and inspecting site conditions. These activities are more specifically summarized as follows:

2.1 Summary of Eighth Technical Committee Activities (2018-2019)

The following is a summary of the Eighth Technical Committee activities, technical workshops, and field trips.

Water data and interpretive reports were reviewed including:

1. Lake Michigan Diversion accounting reports for WYs 2010 through 2015, and Annual Reports 2016, 2017, and 2018.
2. USGS WYs 2010 through 2015 discharge computation records/reports and associated error analysis, and
3. A variety of supporting technical documents related to hydrologic modeling, acoustic metering, and quality assurance.

The three workshops were as follows:

Workshop 1:

1. Summary of the LMDA program, including data collection and modeling requirements

2. Briefing on the current status of the LMDA program (USACE perspective)

3. Briefing by the USGS on progress and current status of uncertainty analysis for the Lemont gage and HSPF model (note: these have been two separate efforts)

4. Presentation by Lake County Stormwater Management Commission (SMC) on a proposal to divert Des Plaines River flows into Lake Michigan

5. Field visit to the following sites:

a) Wilmette Pump Station

b) Chicago Harbor Lock and Chicago River Controlling Works

c) Upper Des Plaines Pump Station

d) Lockport Lock and Dam

e) CSSC at Lemont gage

Workshop 2:

1. Treated as an open forum discussion

2. Highlights of the workshop included discussion on the perceived under-reporting of the ISWS rain gages based on a NEXRAD dataset; continued discussion of the Q-Trak system; and a brief discussion regarding the increasing time taken to publish LMDA reports (note: Specific information of the comparison of the rain gage and NEXRAD data was not provided to the Committee, so this issue is not discussed further in this report.)

3. No field visits during this workshop

Workshop 3:

1. Continued discussion of the Q-Trak systems and proposed measurement methodologies

2. Field visits to the following sites:

a) confluence of the Grand Calumet River and Indiana Harbor Canal

b) several intermediate points along the Grand Calumet River, illustrating the bi-directional flow within the canal

c) Grand Calumet at Hohman Avenue Gage and at Columbia Avenue Gage

2.2 Technical Committee's Activities 1981-2014

Presented in Table 2.1. is a summary of chronological events regarding the Technical Committee's activities and Lake Michigan Diversion events for the period 1981-2014.

Table 2.1. Chronological Summary of Technical Committees and Lake Michigan Diversion Events (note: NIPC = Northeastern Illinois Planning Commission)

First Technical Committee Convened June 1981, Final Report – October 1981 (Espey et al., 1981) Reviewed Status of Diversion Computation as Stipulated by the 1980, Modified Decree of the U.S. Supreme Court		
Annual Report	*Water Year Diversion Results*	*Remarks*
		• Lockport flow components are deficit in practically every respect. • Master Plan be developed for the Management of the Lake Michigan Diversion Program. • Development of an "Operational Procedure Manual". • Study to evaluate alternatives to the Lockport facilities for measurement of diversion flow. • Improvement to flow measurements practices at Lockport facilities.
Second Technical Committee Convened July 1986, Final Report – November 1987 (Espey et al., 1987) Reviewed Status of Diversion Computation as Stipulated by the 1980, Modified Decree of the U.S. Supreme Court		
Annual Report	**Water Year Diversion Results**	**Remarks**
1981, 1982 Annual Report 11/1983 – Released	1981/1982	• Lockport Measurement Site – First Committee Report (Espey et al., October 1981) • Harza report proposed new diversion accounting program (Harza Engineering, 1981) • WY 81-82 Diversion certified despite Technical Committee (1981) concerns regarding Lockport rating.
1983, 1984, 1985 Annual Report 2/1986 – Released	1983	• New Accounting System (Northeastern Illinois Planning Commission, NIPC, 1985), Used hydrologic computer models. • WES Report (Hart and McGee, 1985) Powerhouse and Controlling Works sluice gate – new rating resulted in a reduced diversion (180 cfs) for WY 1983. • Romeoville AVM installation (March 18-23, 1984), AVM data suggest Lockport Turbine low flows are consistently low. • 1983 diversion certified despite concerns on Lockport rating (Technical Committee, 1981) findings. • Second Committee convenes (July 1986)
1986 Annual Report 3/1987 – Released	No diversion results	• Mainstream and Calumet Tunnel and Reservoir Plan (TARP) tunnels become operational – Began new accounting system, development of a computerized water budget, HEC analysis of Hydrologic Simulation Procedures. • Second Committee Report (Espey et al., November 1987)

Continued Table 2.1. Chronological Summary of Technical Committees and Lake Michigan Diversion Events

Third Technical Committee Convened February 1993, Final Report – July 1994 (Espey et al., 1994) Reviewed Status of Diversion Computation as Stipulated by the 1980, Modified Decree of the U.S. Supreme Court		
Annual Report	**Water Year Diversion Results**	**Remarks**
1987 Annual Report 9/1988 – Released	No diversion results	• The Water Resource Development Act of 1986 gave USACE responsibility for the computation of diversion flow (effective October 1987)
1988 Annual Report 3/1989 – Released	No diversion results	• Continuing problems with AVM; new AVM system to be installed. • Diversion Accounting certification suspended in WY 1988 pending revision of hydrologic modeling parameters as per Second Technical Committee's suggestion. • Second Technical Committee Final Report (November 1987)
1989 Annual Report 11/1993 – Released	1984-1985	• November 1988 – ORE, Inc. AVM installed • First Annual Report that USACE assumes responsibility for the computation of diversion • Diversion Accounting report developed by NIPC, reviewed and updated by USACE • USACE updated hydrologic model parameters and revised 1984-1985 flows based on AVM records
1990-92 Annual Report 1/1994 - Released	1986-1987 1988 - 1989	• New regression equations (USGS, Melching and Oberg, 1993) (WYs 1986, 1987, 1988, and 1989) • Modeling update – Mainstream and Camulet TARP • USACE Lakefront measurements • New 25-gage precipitation gage network – installed (October 1989) • Grand Calumet River West Branch gage established (October 1991) • Diversion results indicated State of Illinois exceeded allowable diversion – 1988 • 1986 problem with AVM • 1987 AVM – little missing record • 1988-89 Solar Radiation Correction

Continued Table 2.1. Chronological Summary of Technical Committees and Lake Michigan Diversion Events

Fourth Technical Committee Convened September 1998, Final Report, May 2001 (Espey et al., 2001) Reviewed Status of Diversion Computation as Stipulated by the 1980, Modified Decree of the U.S. Supreme Court		
Annual Report	**Water Year Diversion Results**	**Remarks**
1993 Annual Report 9/1994 – Released	1990	• Modification to the hydrologic runoff models and hydraulic sewer routing models to incorporate the 25-gage precipitation network into the WY 90 diversion accounting. This includes revision to map delineation for combined sewer contributing areas, delineation of area assigned for the 25-gage network, revision and update of land-use/land-cover delineations. • Third Technical Committee – convened February 1993 • Third Technical Committee final report (Espey et al., 1994)
1994 Annual Report 10/1995 – Released	1991 1992	• During WY 1994 and continuing into WY 1995 the hydrologic runoff and hydraulic sewer models were modified in order to utilize the Data Storage System (DSS) database of the USACE as the sole database in all diversion accounting computations. The modified models were used for WY 1991 and WY 1992 accounting.
1995 Annual Report 3/1997 – Released	1993 1994	• Beginning in June 1993 the southern and middle portions of the Des Plaines TARP system became operational. These tunnels were added to the modeling of the TARP system of WY 1993. • The estimate of the Grand Calumet River portion of the water supply pumpage from Indiana that reaches the Chicago Sanitary and Ship Channel (CSSC) was revised to better account for the unique hydraulics of the river. • Prior to WY 1993 there existed a double accounting of a portion of the runoff from the ungaged Calumet watershed. The flow that was double accounted was the infiltration into the separate sanitary sewers within the ungaged Calumet watershed. This revision only impacts Column 12, the diverted runoff from the Lake Michigan watershed, which is used as a component verification of the overall diversion contained in Column 10.
1996 Annual Report 10/1998 – Released	1995	• The USACE supported the Great Lakes Mediation Committee with respect to various special studies: 1) runoff and 2) consumptive use.

Continued Table 2.1. Chronological Summary of Technical Committees and Lake Michigan Diversion Events

Fifth Technical Committee Convened January 2003, Final Report, July 2004 (Espey et al., 2004) Reviewed Status of Diversion Computation as Stipulated by the 1980, Modified Decree of the U.S. Supreme Court		
Annual Report	**Water Year Diversion Results**	**Remarks**
1997 Annual Report	1996	• Work began on changing the TNET files for the Calumet TARP tunnel. • Christopher Burke Engineering, Ltd. hired to review the model to ensure consistency with as-built plans and update the TNET model to account for new Calumet tunnel legs. • Started changing over from computing solar radiation data using O'Hare meteorologic data to using the measured solar radiation data collected at Argonne National Labs. • The efforts relating to the changes to the Calumet modeling and the computation of the solar radiation were carried over into the FY 1998 and FY 1999 and were a primary reason for the delay in the release of the WY 1996 accounting report.
1998 Annual Report 7/2001 - Released	1997	• USGS AVM gages at Columbus Drive and O'Brien Lock and Dam established in December and October 1996, respectively. • The efforts relating to the changes to the Calumet modeling and the computation of the solar radiation were carried over from FY 1996 and were the primary reason for the delay in the release of the WY 1997 accounting report. • Percentages of pervious and impervious areas adjusted in the hydrologic modeling to correct for suspected overestimate of combined sewer overflow discharges. • Contracting efforts occurred related to the establishment of the Fourth Technical Committee. The first workshop of the Fourth Technical Committee was in September 1998.
1999 Annual Report 5/2004 - Released	1998-1999	• USGS installation of an AVM gage at Wilmette (September 1999). • Contract initiated for work on a detailed QA/QC of ten primary water supply diverters in Chicago and five in the northern Chicago suburbs. (work completed in 2003). • USACE completed a hydraulic analysis of various alternatives for Navigation Makeup Reduction.

Continued Table 2.1. Chronological Summary of Technical Committees and Lake Michigan Diversion Events

Sixth Technical Committee Convened January 2008, Draft Report (July 2009), Final Report (Sept. 2009) Reviewed Status of Diversion Computation as Stipulated by the 1980, Modified Decree of the U.S. Supreme Court		
Annual Report	**Water Year Diversion Results**	**Remarks**
2000 Annual Report 8/2004 Released	2000 2001	• Two new budgets (14A and 14B) were added to help determine the accuracy of the TARP CSO simulations at the North Branch and Racine Avenue Pumping Stations, respectively, and for their potential future use as calibration points for the heretofore uncalibrated CSO overflows. • Backflows from the CRCW, O'Brien Lock and Dam and Wilmette Locks were removed from the accounting, as it was noted that backflows were already accounted for in the Lakefront AVM measurements. • The HSPF SCALP/TNET models were calibrated using flow data at the Water Reclamation Plants for WY00 and WY01.
2001 Annual Report 3/2007 - Released	Lakefront Diversion Accounting Results (1997-2003)	• The State of Illinois completed the construction of the Chicago Inner Harbor Basin Cutoff Wall during 2001. The wall was constructed across the turning basin, and serves to greatly reduce the leakage of Lake Michigan water through the basin walls and into the canal system. In addition to the new watertight cutoff wall, the facilities also include a pump station and four 10-foot by 10-foot sluice gates. • The Chicago District completed an uncertainty comparison of the accounting methods that can be used to determine the diversion of Lake Michigan waters by the State of Illinois. • The comparison of uncertainties in Lockport accounting versus Lakefront accounting from both a theoretical and measurement basis, has been determined to be more accurate. Using Lockport accounting the average annual diversion for WY97-03 for the existing system is 2,812 cfs, with an uncertainty of 2.3%; while the average annual diversion for the same period from a Lakefront accounting system with fixed values of runoff and consumptive use would be 2,765 cfs, with an uncertainty of 7.9%.
2002 Annual Report 3/2007 - Released	2002	• During July 30, 2001 through January 29, 2003, the Salt Creek Interceptor was taken out of service for repair. • During the above time interval, combined and separate sewer flows from the service area into the Des Plaines Watershed were diverted to the Des Plaines Tunnel, and combined sewer flows from a portion of the Lake Michigan Watershed were diverted to the mainstream Tunnel.
2003 Annual Report 3/2007 - Released	2003	• During July 30, 2001 through January 29, 2003 the Salt Creek Interceptor was taken out of service for repair. • During the above time interval, combined and separate sewer flows from the service area into the Des Plaines Watershed were diverted to the Des Plaines Tunnel, and combined sewer flows from a portion of the Lake Michigan Watershed were diverted to the mainstream Tunnel. • Modifications to the normal computation procedure were applied to the 4-month interval between October 1, 2002 and January 29, 2003.
2004 Annual Report 7/2008 - Released	2004	• Beginning WY04, the Torrence Ave Tunnel in the Calumet System went online and was included in the TNET modeling. • Changes to Budget 14 were also made. Runoff for an ungaged area of the Little Calumet River Watershed (approximately 84.2 mi^2) was historically computed from raingage data. • Two stream gages operated by the USGS exist for two tributaries within the Basin (Midlothian and Tinley Creeks) and flows from these subareas were included in Budget 14 computations rather than using simulated runoff based on rainfall data.
2005 Annual Report	2005	No procedural changes were made in WY05 diversion computations.
7/2008 – Released		

Continued Table 2.1. Chronological Summary of Technical Committees and Lake Michigan Diversion Events

Seventh Technical Committee Convened May 2013, Draft Report (January 2014) Reviewed Status of Diversion Computation as Stipulated by the 1980, Modified Decree of the U.S. Supreme Court		
Annual Report	**Water Year Diversion Results**	**Remarks**
2006 Annual Report 2/2011 Released	2006	• The AVM on the CSSC at Romeoville was removed in May, 2006 when the construction of dispersal barrier. • USGS to perform a hydrological study of Midlothian and Tinley Creek Watersheds based on the parameter sets used in diversion accounting modeling before and after WY 2000. • MWRDGC agreed to install an additional flow meter in the incoming intercepting sewer upstream of both the pumping station and the new TARP diversion structure. • The Corps published the lakefront accounting report for WY 1997 through WY 2003 (USACE, 2006.).
2007 Annual Report 2/2011 Released	2007	• Two real time stage gages at the Chicago Lock were installed in 2007 to monitor water levels and water temperature in the Chicago River and Lake Michigan. • A multi-sensor weather station was also installed at the Chicago Lock. • The ISWS noticed that the raingage at Chicago Heights in the precipitation data collection network consistently registered low. After testing the suspected raingage with a trusted gage, the ISWS replaced the equipment and revised the hourly precipitation records at Chicago Heights for WY 2005 and WY 2006
2008 Annual Report 11/2012 Released	2008	• The AVM at Lemont was out of service from January 7, 2008 to May 20, 2008 due to severed cross-channel cables that had to be repaired by divers. During this period, the co-located horizontal acoustic Doppler current profiler (H-ADCP), the backup gage at Lemont, continued to collect velocity data for discharge computations. • On September 15, 2008, the USGS measured a flood discharge (15,780 cfs) on the CSSC at Lemont that helped enhance the accuracy of the rehabilitation of the Upper Des Plaines Pumping Station including installation of a velocity profiler (flow meter) in the intercepting sewer delivering the combined sewer flow from the Upper Des Plaines River drainage basin to the pumping station.
2009 Annual Report 11/2012 Released	2009	• The AVM at Lemont was out of service from September 7, 2009 to December 15, 2009 due to an equipment failure and unavailability of replacement parts. During this period, the co-located H-ADCP continued to collect velocity data for discharge computations. • The 6th Technical Committee commenced the second phase of review. They completed the review and published the finding report in September 2009 (USACE, 2009). The Committee was very disappointed that the period of concurrent data collection on the CSSC at Romeoville and Lemont was relatively short (October 2004 through June 2005).

2.3 Summary of Lake Michigan Diversion Accounting Reports for Water Years 2010-2015 and Annual Reports 2016, 2017, and 2018

The following is a brief summary of the Annual Reports for 2010-2015 and Annual Report 2016, 2017, and 2018 Activities.

2.3.1 Water Year 2010, Annual Report 2010

The activities in Fiscal Year (FY) 2010 included data collection for WY 2010, continuing modeling of diversion accounting for WY 2006 and WY 2007. Analyses of flow measurement data at Lemont and assessment of accounting changes resulting from relocating the AVM from Romeoville to Lemont were performed. Incorporating the 6th Technical Committee's recommendations the USACE requested that the USGS document the history of flow measurement for LMDA, the flow measurement instrument currently deployed at Lemont, and detailed analyses of flow measurement data collected at Lemont versus Romeoville. In 2010 the Corps contracted the ISWS to upgrade the field raingage equipment with new data loggers, cellular telemetry, and power supply. This upgrade allowed the raingage network operators to remotely monitor the raingage performance, and plan for special trips to the gaging sites if any operation problems were detected. In 2010 the Corps also requested the USGS to install an acoustic velocity meter in the Summit Conduit to measure the runoff from a 5.4 mi^2 Des Plaines River watershed to the CSSC. This flow is deductible from the flow measured at Lemont, and has been estimated by hydrologic simulation. The deployment of this flow meter would significantly improve the accuracy of this flow component for diversion computations. The State of Illinois completed repairs near the north basin wall of the CRCW to reduce leakage. The MWRDGC's project for rehabilitation of the UDPPS was delayed. The 60-day acceptance test began in December 2010, and reliable data collection in the sewer would be expected by February 2011.

2.3.2 Water Year 2011, Annual Report 2011

The activities in FY 2011 included data collection for WY 2011, and completion of Lemont accounting computations for WY 2006 and WY 2007. The Lemont accounting computations for WY 2008 and WY 2009 were also begun at this time. The Corps installed new lock gates at the Chicago Lock that would help reduce leakage. In August 2011 the Corps met with model developers from the University of Illinois to discuss the current progress made on several hydrologic and hydraulic models. It is being evaluated that several of these models – in particular the Illinois Transient Model (ITM) and Illinois Conveyance Analysis Program (ICAP) – may take the place of the current TNET models.

2.3.3 Water Year 2012, Annual Report 2012

The activities in FY 2012 included data collection for WY 2012, and completion of Lemont accounting computations for WY 2008 and WY 2009. The Lemont accounting computations for WY 2010 and WY 2011 were also begun at this time. Revisions to the Diversion Accounting manual were incorporated into the electronic document as the document was brought up-to-date. The USGS published the report on "Comparison of Index Velocity Measurements Made with a Horizontal Acoustic Doppler Current Profiler and a Three-Path Acoustic Velocity Meter for Computation of Discharge in the Chicago Sanitary and Ship Canal near Lemont, Illinois." This report provides a detailed analysis of the flow structure and index velocity measurements in the CSSC near Lemont, Illinois, to ensure that decisions regarding the future of this streamgage will be made with the best possible understanding of the site and the characteristics of the flow. The USGS published the report on "Monitoring of Stage and Velocity, for Computation of Discharge

in the Summit Conduit near Summit, Illinois, 2010-2012". This report provides a detailed analysis of the index-velocity method used to establish a rated discharge for the nonstandard site conditions present in the Summit Conduit. The USGS published a report on the "Role of the U.S. Geological Survey in Lake Michigan Diversion Accounting in Illinois, 1984-2010". This report provides a summary of the role the USGS has played in the LMDA from 1984 to 2010 including the responses to the comments from the Technical Review Committees. The USGS completed the discharge rating of the sluice gates at Lockport Controlling Works. This study was based on flow measurements in the CSSC and Des Plaines River, rather than physical model testing performed by the University of Illinois in 1960s or the USACE Waterways Experiment Station (WES) in 1980s. A pilot study on the consumptive use was initiated using water supply and sewer flow measurement data in a northwestern suburban community of Chicago (Elk Grove Village). Under a research grant the University of Illinois is modifying their TARP modeling software to include the data Input/Output (I/O) interface with the HEC-Data Storage System (HEC-DSS) and accept user specified inflow hydrographs at the drop shaft locations. These modifications allow the Corps to evaluate the tunnel hydraulic computations using the runoff and sanitary inflows simulated by HSPF and SCALP.

2.3.4 Water Year 2013, Annual Report 2013

The activities for FY 2013 included data collection for WY 2013, and completing the Lemont accounting computations for WY 2010 and WY 2011. Revisions to the Diversion Accounting manual included the introduction of a section describing the incorporation and execution of the Lower Des Plaines River Bypass models. Three service contracts for the 7th Technical Committee were established in May 2013. During this FY, Committee members attended workshops and meetings to listen to the briefings on various activities and technical procedures related to the LMDA. The USACE invited the stakeholders from various Great Lakes states and the Province of Ontario, and conducted the first workshop in July 2013. The USGS hosted the second workshop that included a two-day meeting at Urbana in September 2013. The USGS published the report "Evaluation of the Potential for Hysteresis in IndexVelocity Ratings for the Chicago Sanitary and Ship Canal near Lemont, Illinois". This report was generated in response to a concern expressed by the 6th Technical Committee that the index-velocity rating of the Lemont gage may be subject to hysteresis because of the unique, unsteady hydraulics of the canal. Based on the study, the USGS concluded that there was no conclusive evidence for the existence of hysteresis in the index-velocity rating at the USGS streamgage on the CSSC near Lemont, Illinois. The USGS installed a vertical Acoustic Doppler Velocity Meter in the CSSC at Lemont in July 2013. This instrument will collect continuous velocity data in the water column and verify if the velocity distribution during the rising and falling phase of the discharge hydrograph will be different and that may affect the index velocity rating. The University of Iowa is analyzing the flow measurement data for the Lemont gaging station for several rain events in 2010 and 2012 to evaluate the index velocity rating for different flow regimes in the CSSC.

2.3.5 Water Year 2014, Annual Report 2014 – Activities

During FY 2014, the annual and diversion accounting reports for WY 2010 and 2011 were finalized, reviewed, and published. A study on the inventory of green infrastructure and their potential impact on the runoff from the diversion watershed for LMDA was initiated. The third workshop for the 7th Technical Review Committee was held in October 2013. The Technical Committee completed their review and published their findings report in April 2014. Updates to the water control manual for the Chicago Harbor Lock began in April 2014 and continued through the end of the fiscal year.

2.3.6 Water Year 2015, Annual Report 2015 – Activities

The final column computations for WY 2012 were completed in May 2015, while the review of the WY 2012 report was completed in September 2015. The final column computations for WY 2013 were completed in September 2015. The USGS published the report "Analysis of Regional Rainfall-Runoff Parameters for the Lake Michigan Diversion Hydrological Modeling". This report provides a summary of the analysis undertaken by the USGS and USACE - Chicago District to assess the predictive accuracies of selected parameter sets. Recalibration of the parameters based on updated inputs was completed on two representative watersheds. The Agency Technical Review (ATR) for the Chicago Harbor Lock's water control manual was completed in February 2015.

2.3.7 Annual Report 2016 – Activities

Data collection for WY 2014 and 2015 continued through to the end of the fiscal year. The review of the WY 2013 report was completed in August 2016, while publication and distribution of the WY 2013 report was completed in September 2016. The USGS continued its analysis of the uncertainty within the HSPF modeling approach used by the LMDA program. The USGS continued the first phase of a study entitled, "Uncertainty Analysis of an Index Velocity Meter and Discharge Computations at the Chicago Sanitary and Ship Canal near Lemont, Illinois". The USGS completed its "Analysis of Long-term Trends in Streamflow, Precipitation, and Runoff Coefficients in Northeastern Illinois". This study provides a summary of the assessment of the changes in precipitation and streamflow at long-term streamgages in northeastern Illinois, and changes in the runoff coefficients (Q/P). The USGS initiated a study comparing gaged and ungaged areas of the diverted watershed to evaluate their hydrologic similarity using current digital soil mapping and GIS.

2.3.8 Annual Report 2017 – Activities

Data collection for WY 2014 and WY 2015 was substantially completed by January 2017, although the required groundwater data were not available as of the end of the fiscal year. Since the required meteorological data had been collected, the computations for WY 2014 and WY 2015 began in October 2016 with the TNET modeling beginning in November 2016. Instabilities in the simulations and poor agreement between the modeled and observed data resulted in a prolonged period before nominally acceptable results could be achieved. Once TNET modeling was completed in July 2017, the remaining modeling and budget computations were undertaken. The USGS continued its analysis of the uncertainty within the HSPF modeling approach used by the LMDA program, specifically within the runoff volumes due to imprecision in precipitation input data. The USGS continued the first phase of the study entitled, "Uncertainty Analysis of an Index Velocity Meter and Discharge Computations at the Chicago Sanitary and Ship Canal near Lemont, Illinois". This effort is in response to a 7th Technical Committee recommendation to characterize the uncertainty in the LMDA process. This study was completed in FY18. The USGS continued its "Analysis of Long-term Trends in Streamflow, Precipitation, and Runoff Coefficients in Northeastern Illinois".

2.3.9 Annual Report 2018 – Activities

Data collection for WY 2014 and WY 2015 was substantially completed in FY17, although the required groundwater data continue to be unavailable as of the end of the fiscal year. Budget computations were substantially completed in August 2017. The USGS continued its "Analysis of Long-term Trends in Streamflow, Precipitation, and Runoff Coefficients in Northeastern

Illinois". This study provides a summary of the assessment of the changes in precipitation and streamflow at long-term streamgages in northeastern Illinois, and changes in the runoff coefficients (Q/P). The 8th Technical Review Committee for the Lake Michigan Diversion Accounting Program was convened on June 1, 2018.

3.0 Review Lake Michigan Diversion Accounting System

3.1 Overview

The general methodology used for LMDA includes both measured and estimated flows of the water cycle passing through the Chicago watershed (Table 3.1). The vast majority of the measured data is used as input for the hydrologic and hydraulic computer models that simulate the unmeasured part of the accounting protocol as described in the modeling section of this report (Chapter 4). Along with the diversion calculation, a number of water budgets (Table 3.2) verify simulated flows and estimate the reliability of the computed diversion. The majority of the diverted Lake Michigan flow, and some non-Lake Michigan flow, pass through the Lemont gaging station located close to the Chicago watershed area. The flow passing through this station represents more than 90% of the total annual diversion, hence the quality and reliability of the data monitored at this station is paramount for the entire study.

The Lake Michigan diversion accountable to the State of Illinois is calculated by using measured flows at Lemont and deducting flows not accountable to Lake Michigan diversion (USACE 2018). Additions are made to the Lemont record for diversions that are not discharged to the CSSC upstream from the Lemont station. The measured values at Lemont, combined with deductions and additions, are used to determine the net accountable diversion of water from Lake Michigan. Deductible flows, not attributable to Lake Michigan diversion, which are discharged to the CSSC above Lemont, include the following:

- Runoff from 217 square miles of the Des Plaines River watershed
- Groundwater supply effluent and seepage into the Tunnel and Reservoir Plan (TARP) tunnels
- Indiana's Lake Michigan water supply from the Calumet River system flowing into the Calumet-Sag Channel
- Water Supply pumpage from Lake Michigan used for Federal facilities
- Bypass flow from the Des Plaines River into the CSSC

Additions for diversion flows that do no pass Lemont include flows diverted from the canal upstream of the AVM and Lake Michigan water supply pumpage whose effluent is not discharged to the canal. The latter component, which is the primary component of the additions, is obtained directly through pumping records of the communities involved and accounts for approximately 8% of the diversion (USACE, 2018).

The annual accounting of Lake Michigan diversion for the State of Illinois follows a series of procedures including data collection and compilation, running hydrologic and hydraulic computer models, computing water budgets, performing statistical analyses, and interpreting the results. Once measured data and simulated values are calculated for the reference period, water budgets are used to independently compute components of the diversion and to assess how well model results compare with the measured counterparts. Historically, the diversion has included 14 water budgets (Table 3.2) with well-defined spatial locations (USACE, 2018). Budgets 1 and 2 are the compilation of water supply pumpage from Lake Michigan and groundwater, respectively. Once each of the budgets is completed, a statistical analysis of the budget components is performed to determine how the simulated values compare to the recorded values. The presentation of the diversion accounting is made through a series of spreadsheet columns derived from observed and simulated data compiled in Budgets 3 through 14. The synthetic table itemizing the diversion

components contains 13 columns (USACE, 2018). The "budgets" are mechanisms by which runoff is divided among the "columnar" diversion accounting. Each of Budgets 3 through 14 has a physical location where flow rate components of the CSSC drainage basin are measured (Espey et al., 2014). The budgets and columnar diversion accounting are described in Tables 3.1 and 3.2 and Figure 3.1.

A large amount of data is needed to perform the LMDA and verify the results. The raw data needed to perform the LMDA comes from a number of different agencies and is provided in a wide variety of formats. Besides the flow monitoring at the Lemont station, the measured data within diversion accounting include flows used directly in the accounting procedure or indirectly as checks on the simulation and to quantify the various diversion components. The measured data collected for each diversion accounting year primarily includes the following:

- Precipitation
- Meteorological parameters
- channel flows
- Direct diversions at CRCW, Wilmette Pump Station, and O'Brien Lock and Dam
- Lake Michigan water supply
- Industrial withdrawals and discharges
- Water Reclamation Plant flows
- Groundwater pumpage

A synthetic summary of the measurements used for the diversion accounting was compiled by the 7th Technical Committee and it is replicated herein for completeness (Table 3.3). In an attempt to better visualize the components of the mass balance in the watersheds, Figure 3.1 provides a spatial distribution of the inflows and outflows of fresh and used waters along with their method of estimation (i.e., measurements or simulations) and Figure 3.2 presents the interaction between diversion columns (Table 3.1) and budgets (Table 3.2).

Table 3.1. Description of the Diversion Accounting Columns

Column	Description
1	Chicago Sanitary and Ship Canal (CSSC) at Lemont AVM Gage Record
2	Diversion from the CSSC above the Lemont AVM Gage
3	Total Flow Through the CSSC
4	Groundwater Pumpage Discharged into the CSSC and Adjoining Channels
5	Water Supply Pumpage from Indiana Reaching the CSSC
6	Runoff from the Des Plaines River Watershed which Reaches the CSSC
7	Lake Michigan Pumpage by Federal Facilities which Discharge to the CSSC and Adjoining Channels
8	Total Deduction from the CSSC Lemont AVM Gage Record
9	Lake Michigan Pumpage Which is not Discharged into the CSSC
10	Total Diversion Accountable to the State of Illinois
11	Pumpage from Lake Michigan Which is Accountable to the State of Illinois
12	Runoff from the Diverted Lake Michigan Watershed
13	Direct Diversions Through Lakefront Control Structures Accountable to the State of Illinois

Table 3.2. Description of the Diversion Accounting Computational Budgets

Budget Number	Title	Description
1	Diverted Lake Michigan Pumpage	This budget sums the Lake Michigan water diverted by the State of Illinois in the form of Industrial and Municipal water supply. The results of this budget are used in Column 11.
2	Groundwater Discharged to the CSSC	This budget sums groundwater pumpages that are discharged to the CSSC. The results of this budget are used in Column 4.
3	North Branch Chicago River at Niles, IL	This budget performs a simple separation of stream flow into sanitary and runoff portions. The results of this budget are used in Budget 14 and Column 12.
4	Little Calumet River at the IL-IN State Line	This budget performs a simple separation of stream flow into sanitary and runoff portions. The results of this budget are used in Budget 14 and Column 12.
5	Thorn Creek at Thornton, IL	This budget performs a simple separation of stream flow into sanitary and runoff portions. The results of this budget are used in Budget 14 and Column 12.
6	Little Calumet River at South Holland, IL	This budget performs a simple separation of stream flow into sanitary and runoff portions. The results of this budget are used in Budget 14 and Column 12.
7	MWRDGC O'Brien Water Reclamation Plant	This budget performs hydrologic and hydraulic simulations of the service basin tributary to the MWRDGC O'Brien Water Reclamation Facility. The simulations estimate the runoff from portions of the Lake Michigan and Des Plaines River watersheds within the O'Brien service basin that is diverted to the CSSC in the form of inflow-infiltration. The budget provides an internal verification of the accounting procedures. The results of this budget are used in Budget 14 and Columns 6 and 12.
8	Upper Des Plaines Pumping Station	This budget performs hydrologic and hydraulic simulations of the MWRDGC Upper Des Plaines Pumping Station. This budget provides a calibration point to verify models of the Des Plaines River watershed.
9	MWRDGC Mainstream TARP Pumping Station	This budget performs hydrologic and hydraulic simulations of the MWRDGC Mainstream TARP Pumping Station. The results of this simulation are used in Budgets 10 and 14 and Columns 6 and 12. The budget also provides internal verification of the accounting procedures.
10	MWRDGC Stickney Water Reclamation Facility	This budget performs hydrologic and hydraulic simulations of the service basin tributary to the MWRDGC Stickney Water Reclamation Facility. The simulations estimate the runoff from portions of the Lake Michigan and Des Plaines River watersheds within the Stickney service basin that is diverted to the CSSC in the form of inflow-infiltration. The budget provides an internal verification of the accounting procedures. The results of this budget are used in Budget 14 and Columns 6 and 12.
11	MWRDGC Calumet TARP Pumping Station	This budget performs hydrologic and hydraulic simulations of the MWRDGC Calumet TARP Pumping Station. The results of this simulation are used in Budgets 12 and 14 and Columns 6 and 12. The budget also provides internal verification of the accounting procedures.
12	MWRDGC Calumet Water Reclamation Facility	This budget performs hydrologic and hydraulic simulations of the service basin tributary to the MWRDGC Calumet Water Reclamation Facility. The simulations estimate the runoff from portions of the Lake Michigan and Des Plaines River watersheds within the Calumet service basin that is diverted to the CSSC in the form of inflow-infiltration. The budget provides an internal verification of the accounting procedures. The results of this budget are used in Budget 14 and Columns 6 and 12.
13	MWRDGC Lemont Water Reclamation Facility	This budget performs hydrologic and hydraulic simulations of the service basin tributary to the MWRDGC Lemont Water Reclamation Facility. The simulations estimate the runoff from portions of the Des Plaines River watershed within the Lemont service basin that is diverted to the CSSC in the form of inflow-infiltration. The budget provides an internal verification of the accounting procedures.
14	Chicago Canal System	This budget performs a water balance of the Chicago Canal System which includes the CSSC and adjoining channels. This budget provides a verification point for the accounting procedures.

Table 3.3. Measured data used for annual diversion accounting (Espey et al., 2014)*

Type of Data	No. of Locations	Source of Data
Discharge of the Chicago Sanitary and Ship Canal	2	USGS and MWRDGC (1 each)
Streamflow	9	USGS
Direct diversion flows	3	MWRDGC
Lake Michigan water-supply withdrawals	30	Illinois DNR (25), Indiana DNR (2), and several municipal and federal (3)
Industrial withdrawals or discharges	5	IEPA (2) and individual industries
Groundwater withdrawals	Not noted	ISWS
Water Reclamation Plant Flows	21	MWRDGC (10), IDEM (4), CIW (3), and other utilities (4)
Meteorological data	5	NOAA (3), ANL (1), ISWS (1)
Precipitation data	25	ISWS
Lake Level Storage Data	1	NOAA (1)

* The acronyms in the table denote the following data sources: USGS (U.S. Geological Survey), MWRDGC (Metropolitan Water Reclamation District of Greater Chicago), IEPA (Illinois Environmental Protection Agency), IDEM (Indiana Department of Environmental Management), CIW (Consumers Illinois Water Company), ISWS (Illinois State Water Survey), Illinois and Indiana Departments of Natural Resources (DNR), NOAA (National Oceanic and Atmospheric Administration), and ANL (Argonne National Laboratory).

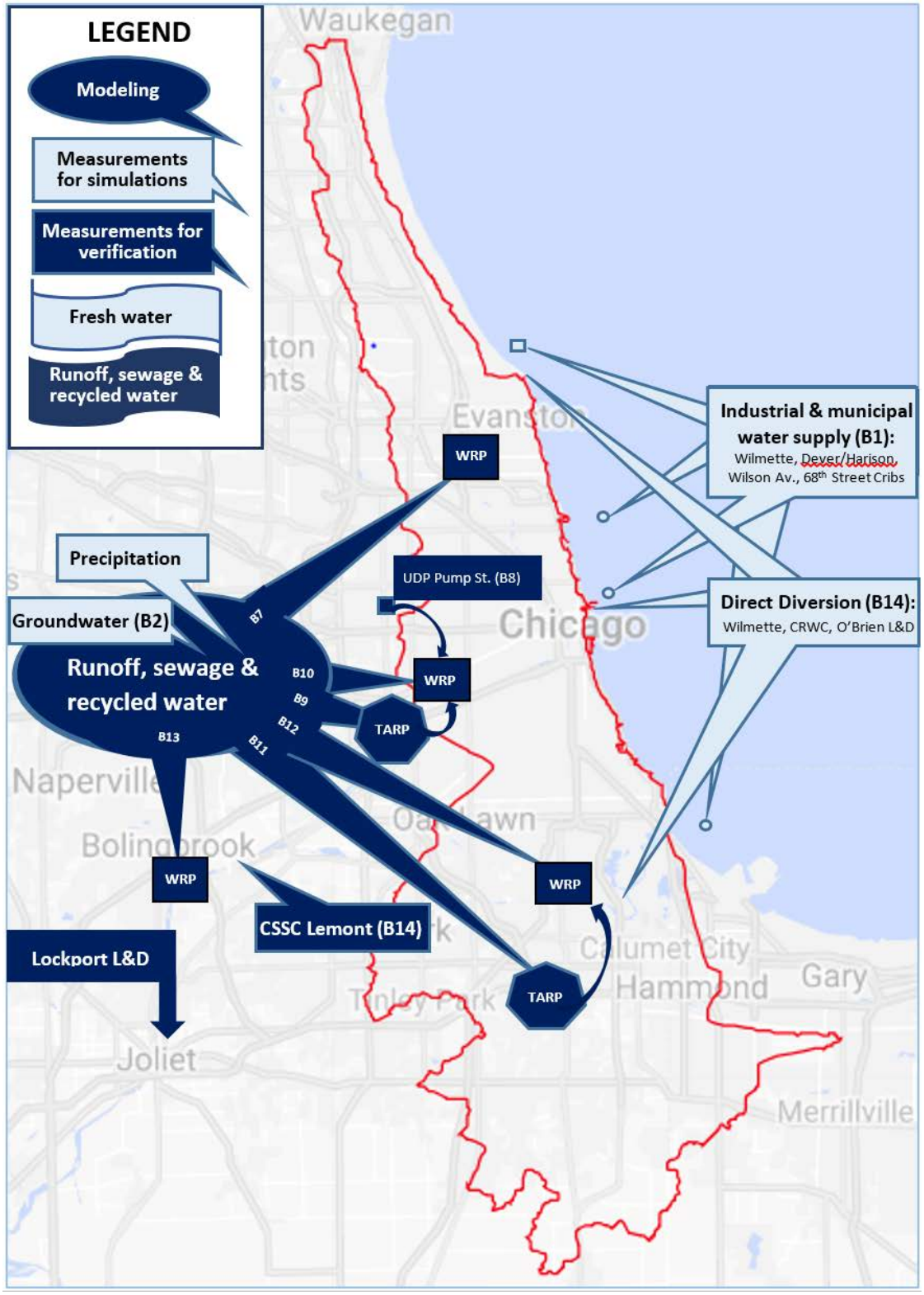

Figure 3.1. Lake Michigan Diversion Accounting budget (B) flow chart (see also Table 3.2). Most of the diversion accounting budgets are used to compare simulated flows to recorded flows to assess the accuracy of the diversion accounting.

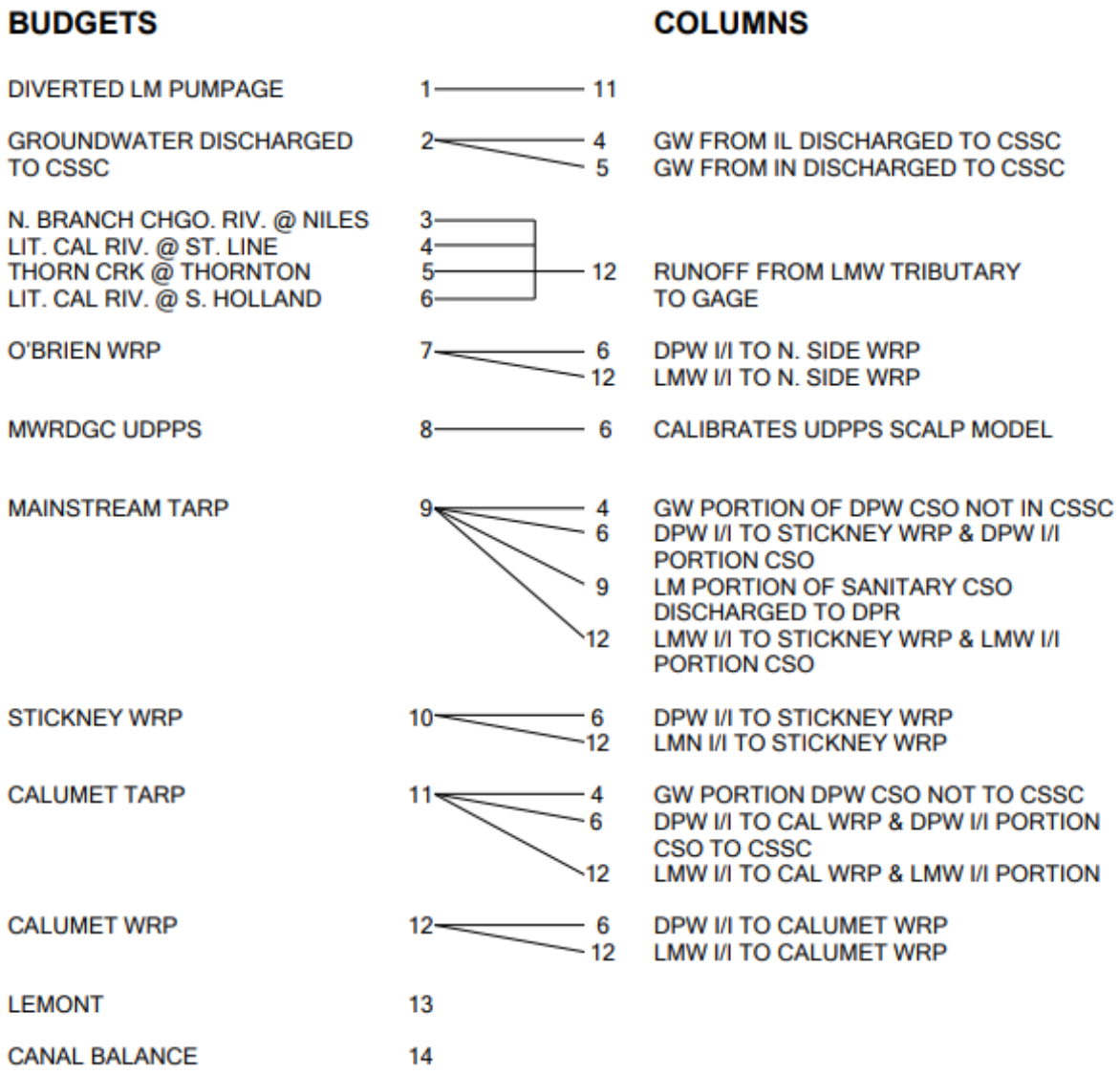

Figure 3.2. Budget and Column Interactions

3.2 Lake Michigan Cumulative Diversion Deficit (Through WY 2015)

Summarized in Table 3.4 is a comparison of various Lake Michigan diversion components: 1) certified diversion (Column 2); and, 2) running average (Column 3) and 3) cumulative deviation (Column 4) as defined by the 1980 Modified Supreme Court Decree. Based on the data provided by the USGS and the USACE the cumulative deviation has decreased dramatically since 1994-95. The cumulative deviation of Lake Michigan diversion Table 3.4 and Figure 3.3 had increased from 1983 until 1994-95, when the trend reversed. The Lake Michigan Diversion is shown through WY 2015. This reduction in Lake Michigan Diversion can be attributed to the levels of Lake Michigan and the reduction in leakage at the CRCW as a result of the repairs made to the lock gates and completion of the new turning basin wall by the summer of 2000 and significant

reduction in Lake Michigan pumpage. The USACE presents the long-term record (1918 to 2019) of Lake Michigan-Huron lake levels (Figure 3.3a, 3.3b). Lake levels for Lake Michigan/Huron during recent years have been high compared to the historical average (Figure 3.3a, 3.3b), hence lockage and leakage are expected to be high The continued reduction in Lake Michigan pumpage (Table 3.5, Figures 3.4 and 3.5) since the early 1990s reflect an aggressive campaign by the City of Chicago to repair leaky water mains to reduce water pumpage. This water supply reduction also has contributed to the reduction in the cumulative deviation from allowed diversion flows. Presented in Table 3.6 are Lake Michigan Levels and Figure 3.6 Components of Lake Michigan Diversion, total diversion, and cumulative diversion for the period 1981 – 2015. Table 3.7 lists the WY2015 Lake Michigan Accounting Diversion Flows.

Accounting Year (WY)	Certified (cfs)		Running Average (cfs)	Cumulative Deviation (cfs-yrs)
1981	3106		3106	94
1982	3087		3097	207
1983	3613		3269	-206
1984	3432		3310	-438
1985	3472		3342	-710
1986	3751		3410	-1261
1987	3774		3462	-1835
1988	3376		3451	-2011
1989	3378		3443	-2189
1990	3531		3452	-2520
1991	3555		3461	-2875
1992	3409		3457	-3084
1993	3841		3487	-3725
1994	3064		3456	-3589
1995	3197		3439	-3586
1996	3108		3418	-3494
1997	3114		3400	-3408
1998	3060		3382	-3268
1999	2909		3357	-2977
2000	2584		3318	-2361
2001	2698		3289	-1859
2002	2919		3272	-1578
2003	2398		3234	-776
2004	2757		3214	-333
2005	2771		3196	96
2006	2628		3174	668
2007	3094		3171	774
2008	3002		3165	972
2009	3135		3164	1037
2010	2874		3155	1363
2011	2791		3143	1772
2012	2267		3115	2705
2013	2431		3095	3474
2014	2785		3086	3889
2015	2390		3066	4699

Table 3.4. Status of the State of Illinois Diversion under the 1980 Modified U.S. Supreme Court (note: Lockport Gage (81-86) green highlighted area, Lemont Gage (06-15) pink highlighted area)

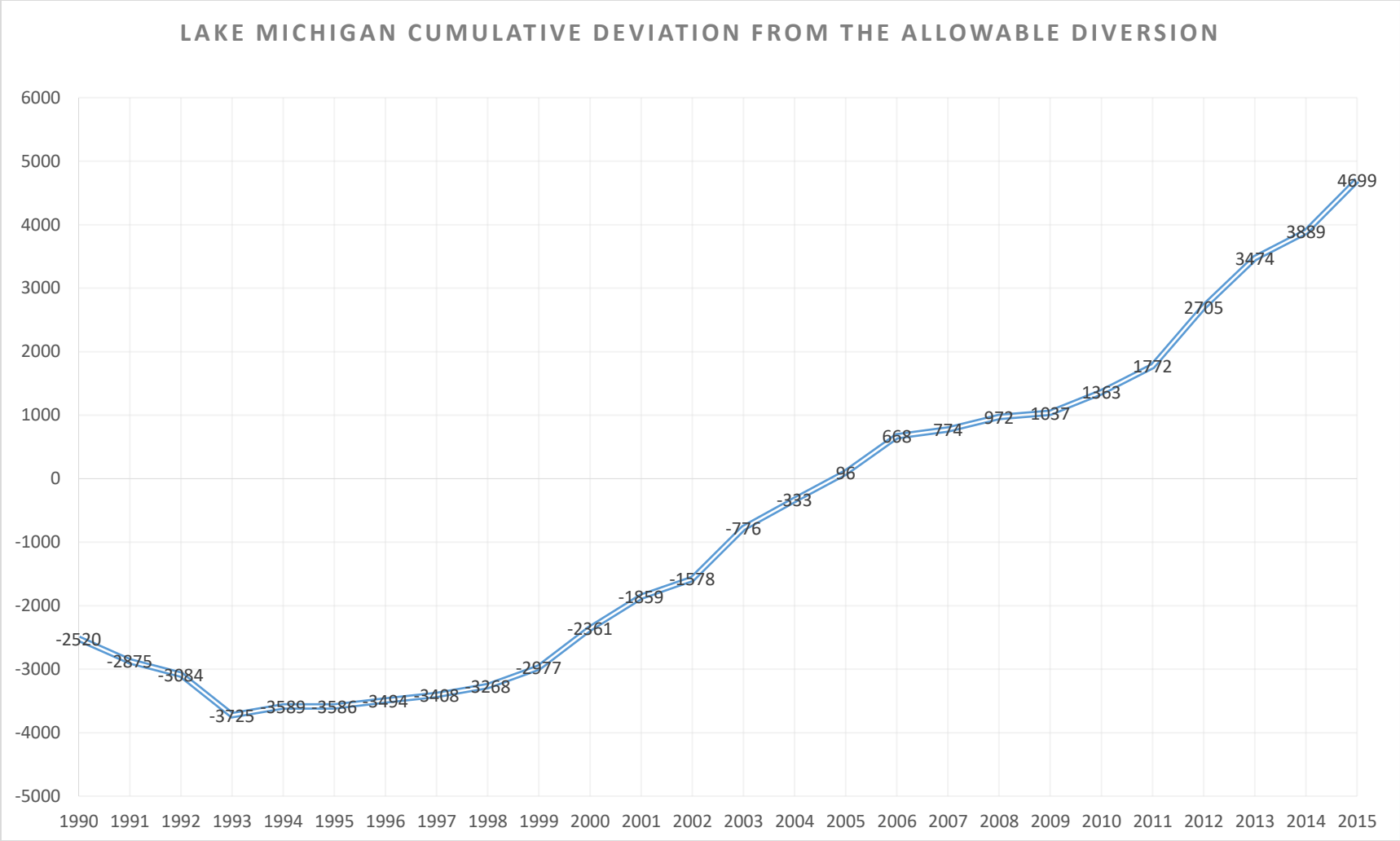

Figure 3.3. Lake Michigan Cumulative Deviation from the Allowable Diversion for 1990-2015.

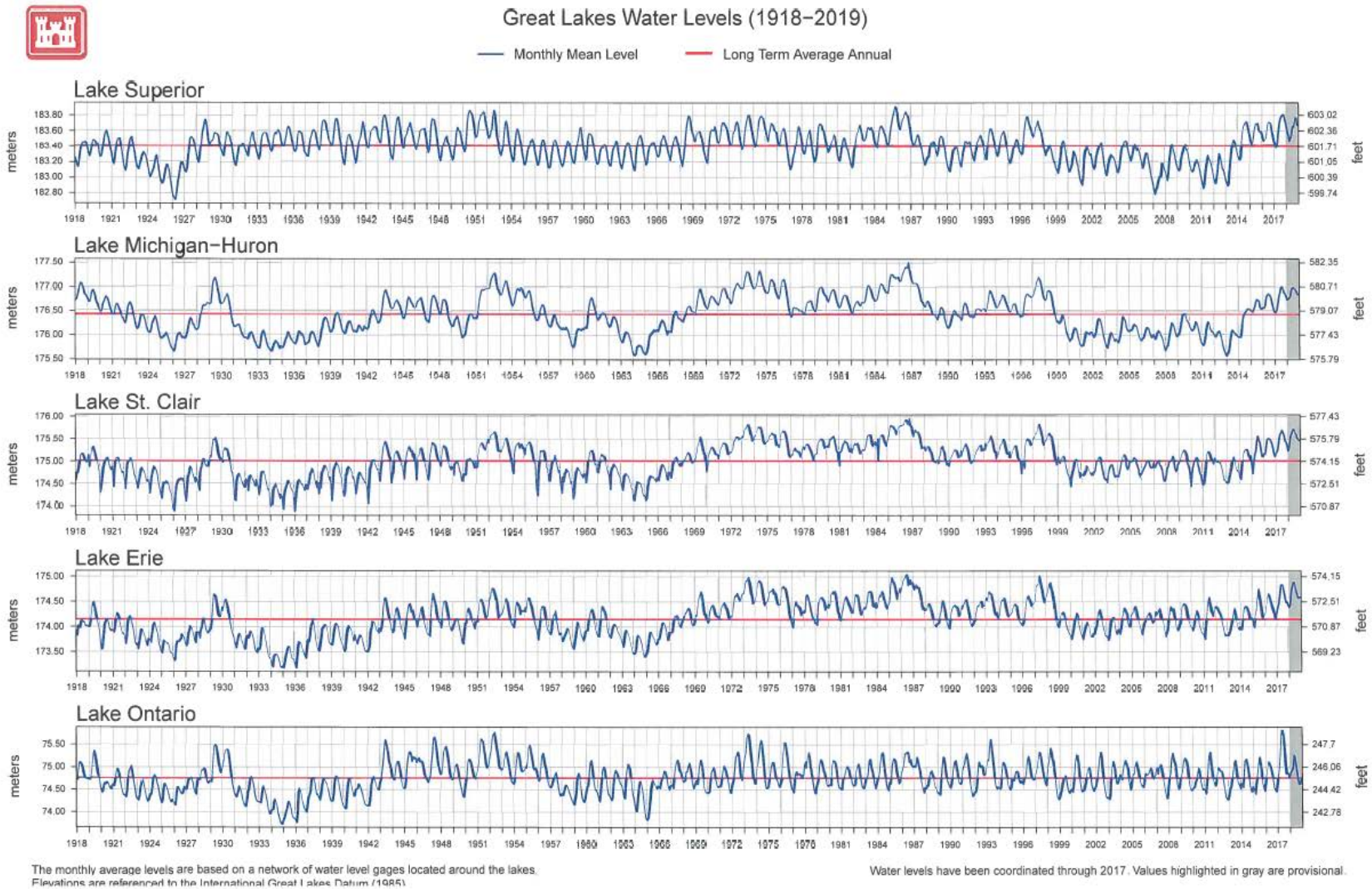

Figure 3.3a. Great Lakes Water Levels 1918-2019

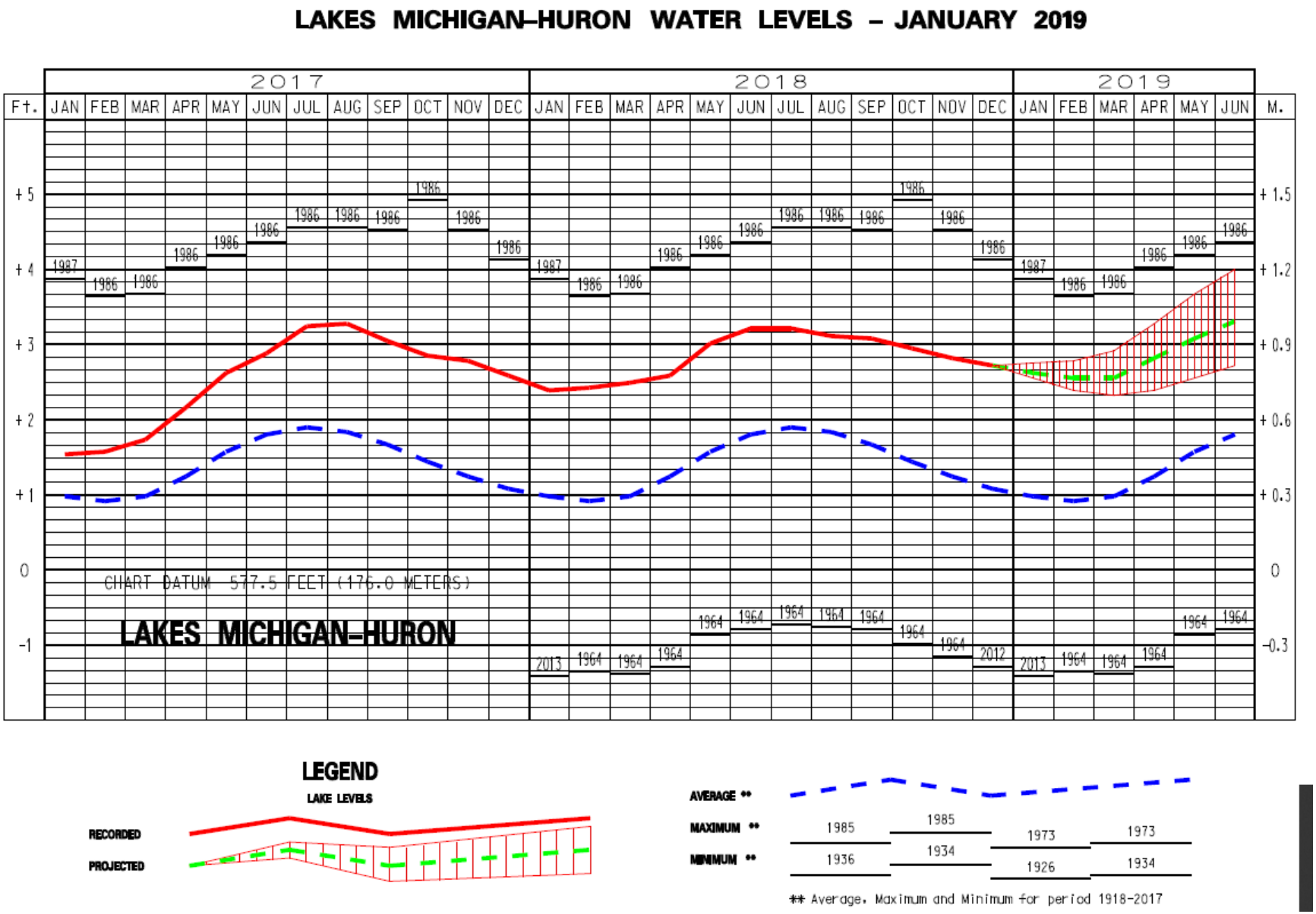

Figure 3.3b. Lake Michigan-Huron Water Levels January 2017-2019

Pumpage from Lake Michigan Accountable to the State of Illinois

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Oct	1,377.9	1,366.7	1,373.4	1,258.7	1,335.2	1,248.1	1,193.3	1,212.2	1,201.7	1,197.7	1,159.0	1,131.4
Nov	1,306.6	1,301.7	1,278.8	1,222.5	1,234.0	1,185.9	1,134.2	1,133.2	1,153.4	1,136.3	1,106.7	1,115.1
Dec	1,303.2	1,314.4	1,314.2	1,233.5	1,246.3	1,256.1	1,151.2	1,178.6	1,142.8	1,126.3	1,143.4	1,099.8
Jan	1,326.4	1,330.0	1,309.4	1,226.9	1,270.2	1,298.4	1,174.1	1,181.9	1,153.1	1,169.1	1,231.3	1,159.6
Feb	1,357.7	1,312.3	1,271.5	1,352.3	1,295.7	1,289.3	1,161.2	1,201.3	1,146.8	1,174.7	1,262.4	1,159.8
Mar	1,306.0	1,302.8	1,260.2	1,302.9	1,256.7	1,232.1	1,148.0	1,142.9	1,136.9	1,149.7	1,228.2	1,155.1
Apr	1,338.1	1,331.0	1,285.8	1,268.3	1,249.4	1,207.8	1,160.9	1,113.1	1,147.8	1,139.8	1,176.1	1,120.3
May	1,383.7	1,426.1	1,358.9	1,425.9	1,300.0	1,287.4	1,248.8	1,198.3	1,291.2	1,219.1	1,218.4	1,157.3
Jun	1,494.6	1,848.3	1,536.9	1,616.8	1,426.3	1,353.9	1,276.5	1,295.0	1,616.6	1,252.5	1,286.1	1,195.6
Jul	1,609.7	1,947.0	1,646.1	1,643.2	1,567.1	1,432.3	1,478.8	1,570.4	1,684.6	1,429.2	1,298.7	1,267.0
Aug	1,567.0	1,802.3	1,600.5	1,521.8	1,530.6	1,485.4	1,441.4	1,397.9	1,457.3	1,443.3	1,311.2	1,318.7
Sep	1,597.3	1,662.8	1,348.8	1,497.3	1,380.8	1,403.9	1,290.5	1,309.5	1,323.8	1,318.2	1,221.9	1,225.6
	1,414.1	*1,496.5*	*1,383.2*	*1,380.9*	*1,341.5*	*1,307.1*	*1,239.1*	*1,245.2*	*1,288.9*	*1,230.2*	*1,220.2*	*1175.7*

Pumpage by the City of Chicago

2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
1,357.0	*1,431.9*	*1,337.3*	*1,334.5*	*1,286.6*	*1,254.9*	*1,197.2*	*1,195.2*	*1,229.3*	*1,175.1*	*1,168.4*	*1,125.6*

Total Diversions Accountable to the State of Illinois

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Oct	2,023.2	2,054.9	2,106.6	3,200.2	2,189.0	2,683.4	3270.7	1971.7	2241.9	1855.4	2106.8	2357.5
Nov	3,118.3	2,488.3	1,768.6	2,214.7	1,727.3	1,546.6	2110.8	1765.5	2240.4	1466.9	2065.9	1655.9
Dec	2,050.1	2,643.2	1,589.5	3,194.9	1,980.7	3,232.3	2538.4	1693.1	2211.9	1691.3	1698.5	1538.1
Jan	1,703.9	3,512.1	2,133.7	2,635.7	2,807.7	2,258.7	2018.8	1819.2	2061.8	1899.2	2180.3	1763.7
Feb	1,916.1	3,104.5	1,806.2	2,038.2	2,870.6	3,205.8	1623.2	2661.3	1883.4	2092.0	2263.2	1473.5
Mar	2,854.6	2,237.9	2,314.0	3,373.3	2,780.5	4,103.7	2572.0	2687.9	2134.2	2597.9	3154.5	2236.5
Apr	2,098.4	2,321.2	2,710.3	3,295.2	2,863.1	3,826.7	2588.0	3435.6	1791.1	4129.6	2622.3	2286.7
May	3,440.0	2,330.9	2,697.2	2,479.0	2,783.9	3,484.4	3292.4	3480.1	2429.9	2872.6	3457.5	2677.6
Jun	3,925.8	2,734.3	3,048.8	3,030.9	3,064.3	4,106.4	4311.7	3914.3	2323.7	3356.2	3455.8	3958.6
Jul	3,714.7	2,891.0	3,348.5	3,289.1	3,315.3	3,025.9	3626.6	3686.5	2785.3	2487.8	4125.9	2685.9
Aug	3,644.8	3,185.6	3,904.7	5,210.5	3,686.6	3,421.6	3682.0	3601.8	2706.3	2392.3	3463.1	2725.7
Sep	2,562.9	3,786.1	4,066.9	3,039.6	6,001.4	2,723.2	2735.0	2781.9	2362.6	2351.8	2773.8	3287.4
Avg.	*2,757.1*	*2,770.8*	*2,628.3*	*3,094.1*	*3,002.1*	*3,135.2*	*2873.5*	*2790.6*	*2267.4*	*2431.2*	*2785.4*	*2390.3*

Table 3.5. Pumpage – State of Illinois, Chicago and Total Diversion Illinois

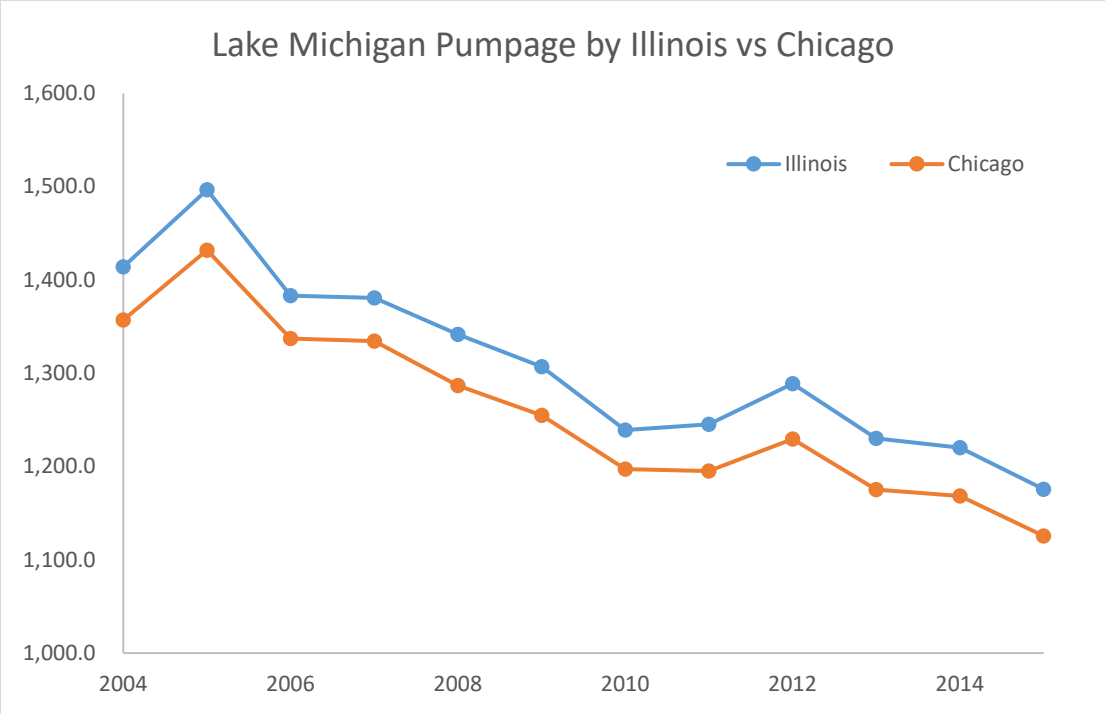

Figure 3.4. Lake Michigan by Illinois and Chicago

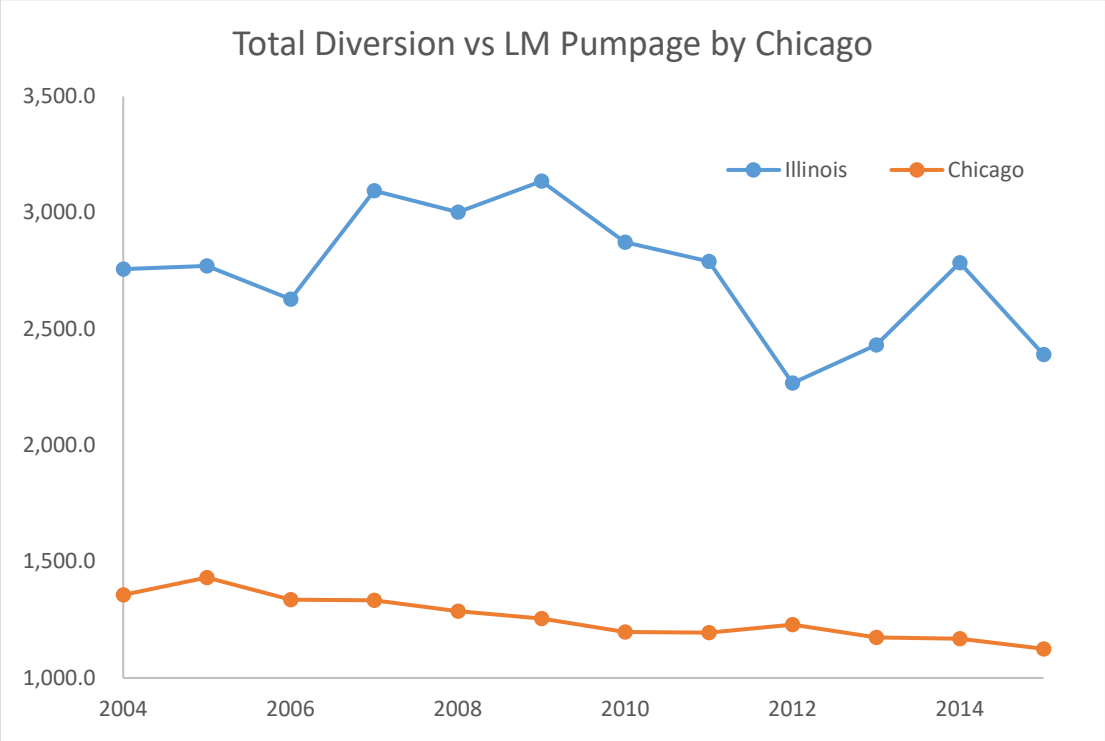

Figure 3.5. Total Diversion vs. Lake Michigan Pumpage by Chicago

Year	Romeoville (cfs)	Diverted Watershed Runoff (Column 12) (cfs)	*Lake Michigan Pumpage (Column 11) (cfs)	Direct Diversion (Column 13) (cfs)	Lake Michigan / Huron Levels (ft MLS)	Total Diversion (cfs)	Cumulative Deviation (cfs-yr)
1981	3347	829.0	1593	684.0	579.7	3106.0	94.0
1982	3309	928.0	1610	549.0	579.4	3087.0	207.0
1983	3991	940.8	1613.7	574.2	580.2	3613.0	-206.0
1984	3791	829.0	1652	601.3	580.4	3432.0	-438.0
1985	3789	785.5	1662.5	630.1	581.1	3472.0	-710.0
1986	4113	876.5	1723.8	665.8	581.7	3751.0	1261.0
1987	4028	811.7	1804.9	665.4	580.6	3774.0	-1835.0
1988	3537	519.6	1906.4	560.4	579.3	3376.0	-2011.0
1989	3515	706.8	1797.9	430.7	578.7	3378.0	-2189.0
1990	3749	872.9	1579.2	449.6	578.6	3531.2	-2520.0
1991	3790	1041.1	1638.5	472.3	579.0	3560.5	-2875.0
1992	3860	847.9	1607.1	451.7	579.0	3408.9	-3084.0
1993	4074	1504.7	1618.7	519.0	579.7	3840.8	-3725.0
1994	3088	681.1	1698.1	497.3	579.7	3057.6	3589.0
1995	3235	797.6	1645.1	480.1	579.2	3196.7	-3586.0
1996	3162	882.0	1603.8	378.8	579.6	3107.5	-3494.0
1997	3231	776.6	1596.6	439.7	580.6	3114.2	-3408.0
1998	3120	773.6	1620.6	633.1	579.8	3059.4	-3268.0
1999	2945	759.3	1605.3	408.0	578.2	2909.3	-2977.0
2000	2563	718.2	1531.0	292	577.4	2584.0	-2361.0
2001	2710	871.5	1545.6	350.1	577.3	2698.5	-1859.0
2002	2919	970.6	1514.4	270.7	577.8	2919.0	-1578.0
2003	2342	608.7	1446.2	285.3	577.1	2398.0	-776.0
2004	2771	832.6	1414.1	338.2	577.8	2757.1	-333.0
2005	2725	693.2	1496.5	311.6	577.7	2770.8	96.0
2006	2615	807.3	1383.2	355.7	577.5	2628.0	668.0
2007	3096	1194.8	1380.9	361.6	577.2	3094.0	774.0
2008	3002	1145.3	1341.5	364.6	577.4	3002.7	972.0
2009	3267	1215.9	1307.1	381.6	578.3	3135.0	1037.0
2010	3006	1189.8	1253.3	382.2	577.8	2874.0	1363.0
2011	2887	1146.0	1245.2	352.1	577.6	2791.0	1772.0
2012	2237	623.3	1288.5	317.4	577.2	2267.0	2705.0
2013	2479	946.9	1230.3	342.4	577.1	2431.2	3474.0
2014	2905	1127.7	1220.2	421.2	578.4	2785.4	3889
2015	2439	859.9	1175.7	348.5	579.4	2390.3	4699

Lockport Gage (81-86) Lemont Gage (06-15)

Table 3.6. Lake Michigan Lake Levels, Components of the Lake Michigan Diversion, and Cumulative Deviation from the Allowable Diversion

*Historical value 1981-1989 are adjusted by 0.9 to be consistent.

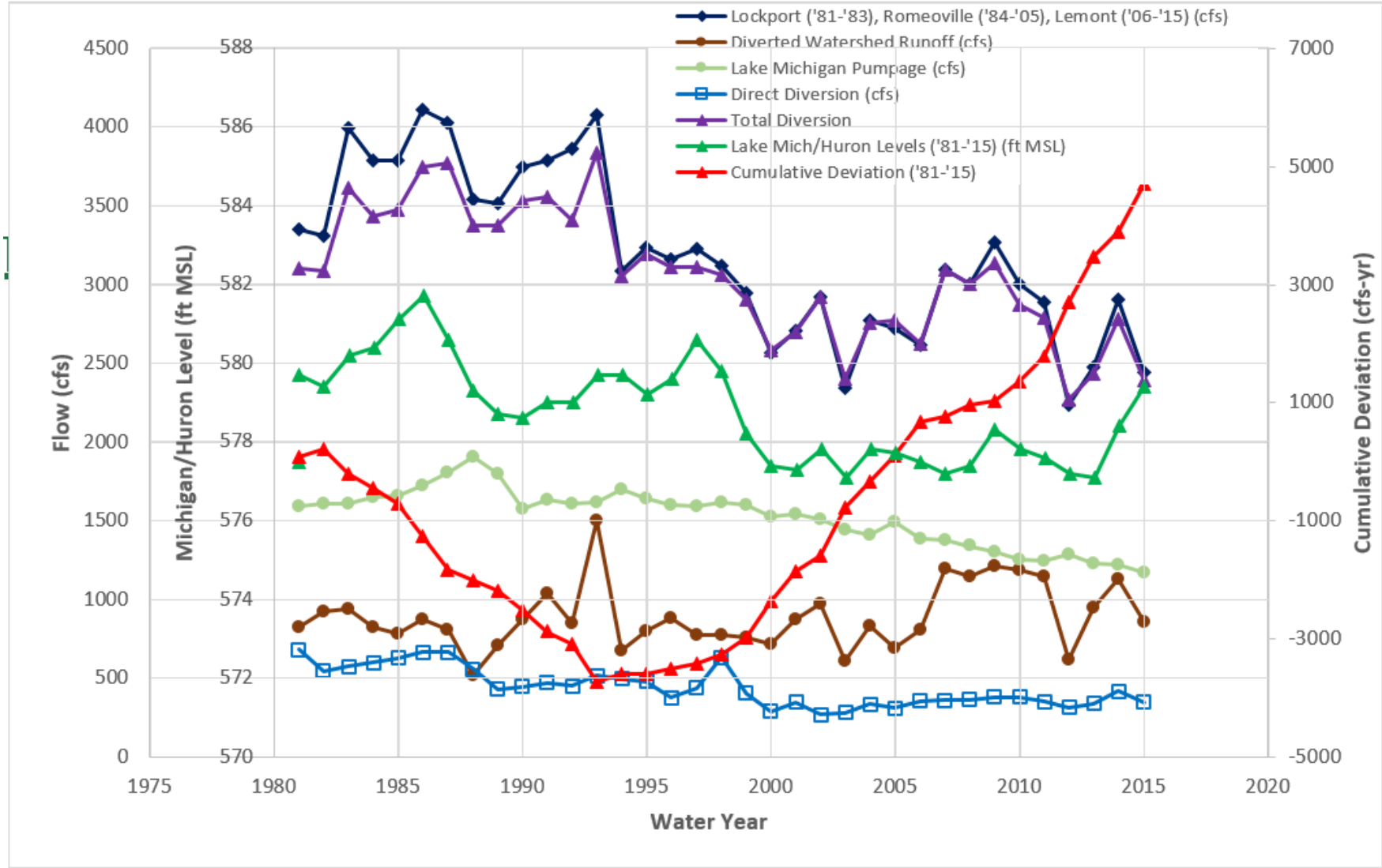

Figure 3.6. Lake Michigan Cumulative Deviation from the Allowable Diversion, Annual Lake Michigan Pumpage, Diverted Watershed Runoff, Direct Diversion and Lockport/Romeoville/Lemont/ Annual Flows, and Lake Michigan/ Huron Levels for 1981-2011.

Lake Michigan Diversion Accounting – WY2015
Summary of Diversion Flows (All in cfs)

LAKE MICHIGAN DIVERSION ACCOUNTING WY 2015	LEMONT AVM GAGE RECORD	DIVERSIONS ABOVE THE GAGE	TOTAL FLOW THROUGH THE CANAL	GROUNDWATER PUMPAGE DISCHARGED INTO THE CANAL	WATER SUPPLY PUMPAGE FROM INDIANA REACHING THE CANAL	RUNOFF FROM THE DES PLAINES RIVER WATERSHED REACHING THE CANAL	LAKE MICHIGAN PUMPAGE BY FEDERAL FACILITIES DISCHARGED TO THE CANAL	TOTAL DEDUCTION FROM THE LEMONT GAGE RECORD	LAKE MICHIGAN PUMPAGE NOT DISCHARGED TO THE CANAL	**TOTAL DIVERSION ACCOUNTABLE TO THE STATE OF ILLINOIS**	PUMPAGE FROM LAKE MICHIGAN ACCOUNTABLE TO THE STATE OF ILLINOIS	RUNOFF FROM THE DIVERTED LAKE MICHIGAN WATERSHED	DIRECT DIVERSION ACCOUNTABLE TO THE STATE OF ILLINOIS
DATE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Oct-14	2498.6	-	2498.6	71.9	6.7	260.1	0.5	339.2	198.1	2357.5	1131.4	962.8	401.1
Nov-14	1614.9	-	1614.9	48.1	6.6	95.0	0.5	150.1	191.1	1655.9	1115.1	446.6	70.5
Dec-14	1501.3	-	1501.3	46.3	6.7	102.1	0.4	155.5	192.3	1538.1	1099.8	399.5	85.3
Jan-15	1776.1	-	1776.1	58.9	7.4	146.7	0.4	213.5	201.0	1763.7	1159.6	515.1	72.5
Feb-15	1546.4	-	1546.4	74.4	6.6	195.3	0.5	276.9	204.0	1473.5	1159.8	639.4	35.0
Mar-15	2227.4	-	2227.4	52.8	6.4	132.0	0.4	191.5	200.6	2236.5	1155.1	737.6	124.8
Apr-15	2365.3	-	2365.3	68.6	6.5	201.9	0.4	277.5	198.9	2286.7	1120.3	997.4	87.5
May-15	2742.6	-	2742.6	71.6	7.4	198.1	0.5	277.5	212.6	2677.6	1157.3	967.0	352.4
Jun-15	4220.0	-	4220.0	71.8	7.9	403.8	0.5	484.0	222.6	3958.6	1195.6	2011.4	584.9
Jul-15	2670.3	-	2670.3	57.3	9.1	153.1	0.5	220.0	235.6	2685.9	1267.0	673.0	679.8
Aug-15	2685.8	-	2685.8	68.0	12.1	136.7	0.6	217.4	257.3	2725.7	1318.7	710.7	762.0
Sep-15	3395.7	-	3395.7	70.3	9.5	264.7	0.5	345.0	236.7	3287.4	1225.6	1274.4	904.2
Averages	2439.3	-	2439.3	63.2	7.8	190.2	0.5	261.7	212.6	2390.3	1175.7	859.5	348.5

Computations:

1. Column 3 equals the sum of Columns 1 and 2.
2. Column 8 equals the sum of Columns 4 through 7.
3. Column 10 = Column 3 - Column 8 + Column 9.

Note: The averages presented in the final row are calculated from the daily values contained in Appendix B.

Deductions from the Lemont Gage Record

Additions to the Lemont Gage Record

Table 3.7. Lake Michigan Diversion Accounting WY2015. Summary of Diversion Flows (All in cfs)

4.0 Hydrologic and Hydraulic Models Applied to Diversion Accounting

In Lake Michigan Diversion Accounting (LMDA), the hydrologic and hydraulic (H&H) models are directly used to compute the runoff from the Des Plaines River watershed reaching the Chicago Sanitary and Ship Canal (CSSC) that must be deducted from the measured flow at Lemont (Column 6 of the Diversion Accounting Table). The H&H models also are directly used to compute the groundwater infiltration into the TARP tunnels that must be deducted from the measured flow at Lemont (part of Column 4 of the Diversion Accounting Table). Beginning in WY 1993, a hydraulic model was used to determine the relation between the Lake Michigan water level and Indiana water supply pumpage from Lake Michigan reaching Illinois through the Grand Calumet River (part of Column 5 of the Diversion Accounting Table). Finally, the H&H models are used to compute runoff from the diverted Lake Michigan watershed (Column 12 of the Diversion Accounting Table) and from the "ungaged" Calumet Watershed, lower Des Plaines River Watershed, and combined sewer overflows reaching the CSSC (Budget 14) as checks of the overall Lemont Accounting procedure.

The average values of simulated Des Plaines River watershed runoff (from 1983-2015) and TARP groundwater inflow (from 1986-2015) are 194.9 and 52.2 cfs, respectively, which together compose 8.1 percent of the total diversion of 3,065 cfs or 7.7 percent of the total flow measured at Lemont/Romeoville of 3,220 cfs (both averages for 1983-2015). At first glance, this might seem to be a fairly small portion of the diversion accounting. However, it should be noted that the combined 2000 water supply withdrawals of Arlington Heights, Bedford Park, Des Plaines, Evanston, Glenview, Naperville, Schaumburg, Skokie, and Waukegan was less than the average annual Des Plaines River watershed runoff (142.7 cfs vs. 194.9 cfs), and that the 2000 water supply withdrawal for Evanston was 14.9 cfs. Thus, errors in the H&H models easily could be of the magnitude of the water supply for a city of 70,000 people. Thus, the model-estimated portion of the Lemont Accounting may be relatively small, but it still is important.

The fifth and sixth Technical Committees for Review of the Diversion Flow Measurements and Accounting Procedures (hereafter, 5th and 6th TCs) presented detailed summaries of the models applied in the LMDA, and the 7th TC presented an abbreviated summary based on those of the 5th and 6th TCs (Espey et al., 2004, 2009, 2014). In the 5th and 6th TC reports (Espey et al., 2005, 2009) the basic features of the modeling were described, whether the models were state of the art and properly applied were evaluated, suggestions were made for improved application of the models, and issues needing further study were identified. The 7th TC report (Espey et al., 2014) evaluated whether the models were state of the art and properly applied, made suggestions for the improved application of the models, and identified issues needing further study (see Chapter 4 and Section 6.2 of Espey et al. (2014)).

Three models primarily are applied in the main LMDA computations. The Hydrological Simulation Program-Fortran (HSPF) is used to compute the runoff from the diverted Lake Michigan watershed and the Des Plaines River watershed. The Special Contributing Area Loading Program (SCALP) is used to route surface runoff (inflow) and subsurface runoff (infiltration) computed using HSPF through the major interceptor, combined sewer system together with monthly, daily, and hourly representations of the wastewater yielded from each Special Contributing Area (SCA). Finally, the Tunnel Network (TNET) model is used to determine the fraction of the combined sewer flows that reaches the drop shafts to the Tunnel and Reservoir Plan (TARP) tunnels and subsequently the deep tunnels (and eventually reservoirs)

and the amount of flow discharged to the Chicago Area Waterway System (CAWS[1]) as combined sewer overflows (CSOs). TNET makes this determination by simulating the flow through and pump out of the deep tunnel systems and applying approximations to the operational rules for the deep tunnel systems that indicate maximum water levels allowed in the system and pumping operations. Among the three models—HSPF, SCALP, and TNET—the accuracy of the HSPF model is much more important to the diversion computations than the other two models. HSPF determines the amount of total runoff resulting from rainfall, whereas SCALP and TNET determine the amount of this total runoff and sewage flow that directly reach the CAWS or the Des Plaines River as CSOs. Since overflows to the CAWS are measured at Lemont the only components of the diversion computation affected by SCALP and TNET are the amount of CSOs from the Des Plaines River watershed draining to the CAWS, and the distribution of interceptor versus CSO flows in the Des Plaines River watershed draining to the water reclamation plants (WRPs) in the CAWS drainage area. TNET computations also determine the groundwater infiltration to the TARP tunnels.

The H&H modeling evaluations carried out by the 5th, 6th, and 7th TCs concluded the following with respect to the performance of these models as applied in the LMDA (Espey et al., 2004, 2009, 2014):

a) Proper application of HSPF in the diversion accounting would meet the Supreme Court's requirement that the diversion accounting be done according to the **"best current engineering practice and scientific knowledge".**
b) Even though SCALP is not a "state-of-the art" model of sewer system hydraulics, it is adequate for the purpose of diversion accounting.
c) Even though TNET is not "state-of-the art" and it has computational difficulties during rapidly varied flow, it is sufficient for its current use in the diversion accounting.
d) If the models used to compute aspects of the diversion accounting are properly applied to the Lake Michigan and Des Plaines River watersheds, they fulfill the Supreme Court's requirement that the diversion accounting is done according to the **"best current engineering practice and scientific knowledge".**

While the foregoing conclusions generally indicate that the LMDA models meet the standard of **"best current engineering practice and scientific knowledge"** set forth by the U.S. Supreme Court for the LMDA, there are some caveats about the "proper application" of these models being a requirement to meet the standard. Each of the 5th, 6th, and 7th TCs made several suggestions to improve and/or evaluate the application of these models. Over the past 15 years, the U.S. Army Corps of Engineers (USACE) and the U.S. Geological Survey (USGS) have done numerous studies to improve the application of these models for the LMDA to achieve the standard of **"best current engineering practice and scientific knowledge"**. The following sections of this chapter summarize the findings of the various studies to evaluate and improve the LMDA models in response to the suggestions of the 5th, 6th, and 7th TCs and in the USACE's internal evaluation of the models. The following sections briefly describe aspects of the models that were evaluated, why they were evaluated, and the evaluation outcomes.

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[1] The Chicago Area Waterway System is the combination of streams and canals draining to and including the CSSC whose flow is measured at Lemont, Ill., during the period under review by the 8th TC.

4.1 Evaluation of the Hydrological Simulation Program-Fortran (HSPF) Application to Diversion Accounting

The HSPF model (Bicknell et al., 1997) is supported by the U.S. Environmental Protection Agency (USEPA) and the USGS. It has been applied for solving many hydrologic and water-quality problems across the U.S. including urban stormwater and floodplain management. Many of these applications are cited in the subsequent discussions of the HSPF performance. The "state-of-the-art" status of the HSPF model for the continuous simulation of the rainfall-runoff process is evidenced by its support by two Federal agencies and its many applications nationwide. **As noted earlier, proper application of HSPF in the diversion accounting would meet the Supreme Court's requirement that the diversion accounting be done according to the "best current engineering practice and scientific knowledge."**

4.1.1 HSPF Model Parameters

HSPF is a conceptual model that approximates the land-surface portion of the hydrologic cycle by a series of interconnected water storages: an upper zone, a lower zone, and a ground-water zone. The amounts of water in these storages and the flux of water between the storages and the stream or atmosphere are simulated on a continuous basis for a subarea of a given land cover and meteorological input (precipitation, potential evapotranspiration, temperature, solar radiation, cloud cover, wind speed, and dew point). The fluxes of water between storages and to the stream or atmosphere are controlled by model parameters. The model parameters have physical meaning conceptually, some are physically measurable, but most must be determined through calibration. The model parameters include threshold values, partition coefficients, and linear reservoir-release coefficients. The conceptual storages, their interactions, and the model parameters that affect the storages and their outflows are shown schematically in Figure 4.1. The definitions of the key rainfall-runoff and snowmelt parameters are listed in Tables 4.1 and 4.2, respectively.

A distinction should be clearly drawn between the model parameters listed in Tables 4.1 and 4.2 and watershed characteristics such as drainage area and percentages of the various land covers (directly connected impervious surfaces, grassland, and forest land in the diversion accounting H&H models). Several reports related to diversion accounting specify that the adjustment or correction of the watershed characteristics has been referred to as "calibration." Calibration normally is defined as the process of systematically adjusting the model parameters (Tables 4.1 and 4.2) within physically reasonable ranges (if available) to reduce the difference between calculated and measured discharge. As described in Sections 4.1.3 and 4.1.6 a number of different measures are commonly used to characterize the difference between calculated and measured discharge when HSPF is calibrated. However, rainfall-runoff and snowmelt parameters were not adjusted or changed at all through a "calibration" process in these earlier reports.

The HSPF model parameters HAVE NEVER BEEN CALIBRATED FOR THE AREAS TO WHICH HSPF IS APPLIED FOR DIVERSION ACCOUNTING. Emphasis is added to the foregoing statement because many reviewers of the diversion accounting procedures assume the models have been calibrated for the areas to which HSPF is applied for diversion accounting. This is substantiated by the comments of the State of Illinois, State of New York, and the Hydrologic Engineering Center on the Lake Michigan Diversion Accounting Lakefront Accounting Technical Analysis (see USACE, 1996). There are two reasons why HSPF has never been calibrated for the watersheds whose flows are simulated for diversion accounting. First, many of the areas simulated with HSPF for the diversion accounting are ungaged or poorly gaged, such as the "ungaged" Calumet River watershed, the Des Plaines River watershed, and

combined sewer overflows in the Lake Michigan watershed. Calibration cannot be done without gaged flows. Second, whereas gaged flows are available for the drainage basins for the WRPs, uncertainties in the flow source make calibration difficult. Thus, the recalibration of HSPF and SCALP done by CTE (2003a-c) that focused on matching WRP flows still does not achieve the normal standard for a good calibration because of limitations in the measured data as described in the following discussion.

Table 4.1. Hydrological Simulation Program-Fortran (HSPF) parameters used to simulate hydrology for pervious land segments (PERLND) and impervious land segments (IMPLND).

Parameter	Explanation	Function
LZETP	Lower zone evaporation. An index value (ranging from 0 to 0.99) representing the density of deep rooted vegetation that can remove water from the lower zone.	PERLND
INFILT	Infiltration capacity. An index to the infiltration capacity of soils. This parameter also affects percolation to the ground-water zone.	PERLND
INFEXP	Exponent for the infiltration equation. Controls the rate of infiltration decrease as a function of increasing soil moisture. Default value of 2 used.	PERLND
INFILD	Ratio of maximum to mean infiltration rate. Default value of 2 used.	PERLND
INTFW	Interflow index. An index that controls the amount of infiltrated water that flows as shallow subsurface runoff.	PERLND
IRC	Interflow recession coefficient. An index for the rate of shallow subsurface flow.	PERLND
CEPSC	Interception storage capacity	PERLND
RETSC	Retention storage capacity	IMPLND
LZSN	Lower zone nominal storage. The lower zone storage level at which half of the incoming infiltration enters the lower zone and half moves to groundwater. The lower zone may be viewed as the entire soil from just below the surface down to the capillary fringe above the water table. In practice the focus is on the transient portion of this storage, i.e. the volume which is emptied by evapotranspiration and refilled by infiltration. Thus, values of LZSN do not necessarily reflect the total moisture storage capacity of the lower zone.	PERLND
UZSN	Upper zone nominal storage. An index to the amount of surface storage in depressions and the upper few inches of soil.	PERLND
BASETP	Fraction of available potential-evapotranspiration demand that can be met from ground-water outflow. Simulates evapotranspiration from riparian vegetation. Added in the 1980s to simulate the effects of phreatophytes on the water balance. Default value of 0 used.	PERLND
AGWETP	Fraction of available potential-evapotranspiration demand that can be met from stored groundwater.	PERLND
AGWRC	Ground-water recession parameter. An index of the rate at which groundwater drains from the land.	PERLND
KVARY	Ground-water outflow modifier. An index of how much effect recent recharge has on ground-water outflow.	PERLND
DEEPFR	Fraction of groundwater that does not discharge to the surface water bodies within the boundaries of the modeled area.	PERLND
LSUR	Average length of the overland flow plane	PERLND/ IMPLND
SLSUR	Average slope of the overland flow plane	PERLND/ IMPLND
NSUR	Average roughness of the overland flow plane	PERLND/ IMPLND

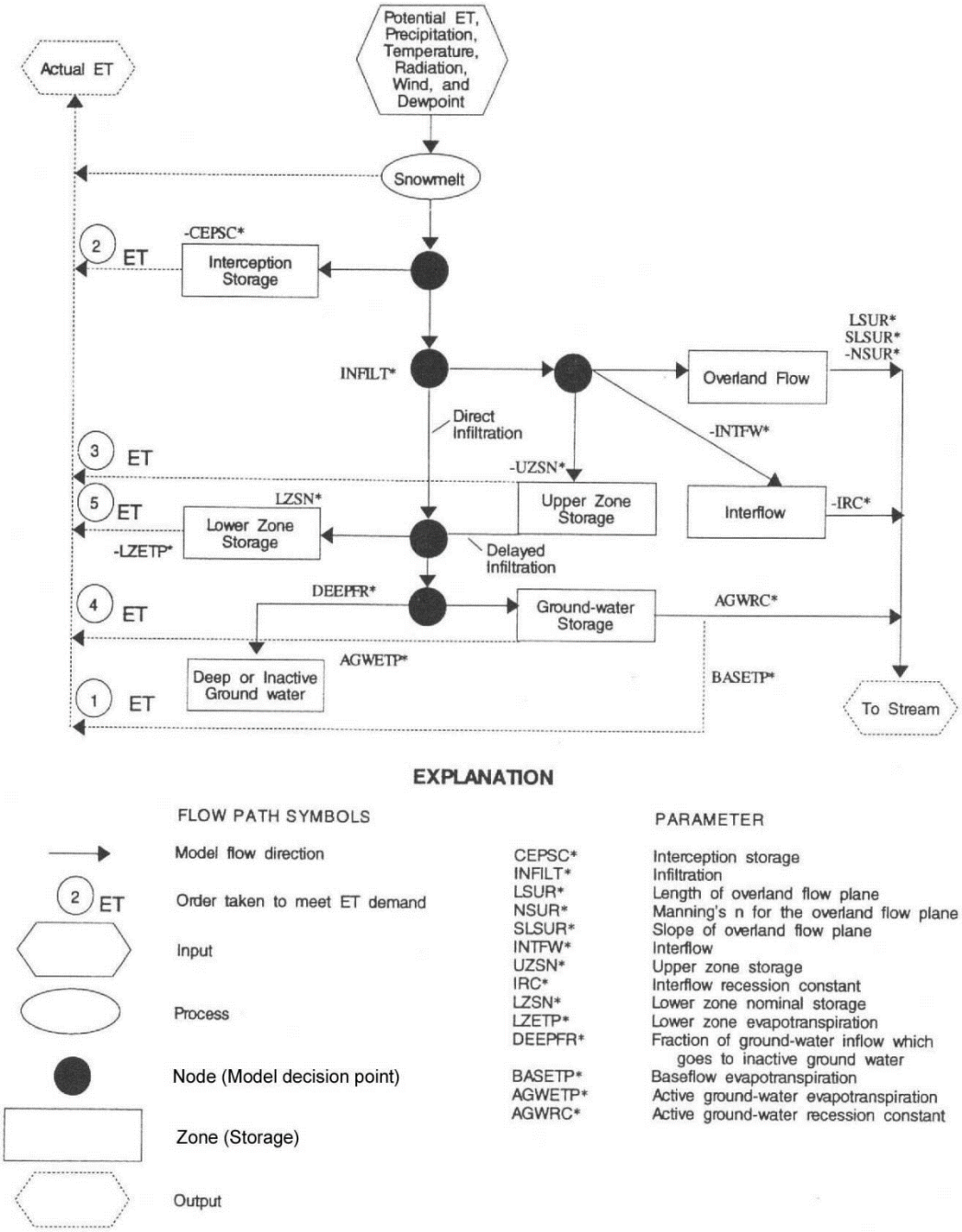


Figure 4.1. Schematic diagram of the Hydrological Simulation Program—Fortran model.

Table 4.2. Hydrological Simulation Program-Fortran (HSPF) parameters used to simulate snowmelt.

Parameter	Description
CCFACT	A parameter that adapts the snow condensation/convection melt equation to field conditions.
SNOWCF	The factor by which the input precipitation data will be multiplied, if the simulation indicates it is snowfall, to account for the poor catch efficiency of the gage under snow conditions.
RDCSN	The density of cold, new snow relative to water. This value applies to snow falling at air temperatures lower than or equal to 0° F. At higher temperatures the density of snow is adjusted.
SHADE	The fraction of the pervious or impervious land segment that is shaded from solar radiation, e.g., by trees.
MGMELT	The maximum rate of snowmelt by ground heat, in depth of water per day. This is the value that applies when the pack temperature is at the freezing point.
MWATER	The maximum content of the snow pack, in depth of water per depth of water.
COVIND	The maximum snowpack (water equivalent) at which the pervious or impervious land segment will be covered with snow.
SNOEVP	A parameter that adapts the snow evaporation (sublimation) equation to field conditions.
TSNOW	The air temperature below which precipitation will be snow under saturated conditions. Under non-saturated conditions the temperature is adjusted slightly.

In their review of the original diversion accounting models, the USACE Hydrologic Engineering Center (1986, p. 5-1) stated the following with regard to the Stickney WRP:

> "approximately 80 percent of the influent to the plant is sanitary flow. The component of flow at the plant that is derived from storm runoff cannot be determined accurately because the sanitary portion of the flow is not precisely known, but must be based on assumptions regarding the proportion of water supply that is returned as wastewater. Hence, the basis for calibration, the "measured" storm runoff, is itself subject to substantial uncertainty. For these reasons, the LANDS parameters for the contributing drainage areas at treatment plants are based primarily on adopting values that were previously calibrated for the stream gages in the North Branch and Little Calumet basins."
>
> Note 1: LANDS is the Hydrocomp Simulation Program (HSP) [a forerunner of HSPF] equivalent to PERLNDs in HSPF.
>
> Note 2: the above statement is also valid for the other WRPs.

The 2nd TC (Espey et al., 1987) described this issue even more clearly (statement in italics added):

> "Since more than 80 percent of the total simulated flow to the treatment plants is sanitary flow, the estimation of influent is highly sensitive to return flow *(consumptive use)* assumptions and relatively insensitive to the infiltration and inflow parameters."

The return flow/consumptive use assumption was that 90 percent of the water supply for the WRP drainage basin returns to the WRP as wastewater flow. This flow then was divided by the population of the drainage basin to determine the per capita wastewater flow used in SCALP. This return flow/consumptive use assumption was revised in the recalibration of HSPF and SCALP (CTE, 2003a-c) which has remained in effect for the SCALP wastewater flow values.

Since, in general, the HSPF model parameters need to be calibrated before HSPF can be effectively used three questions must be answered.

1. Is transfer of HSPF model parameters from nearby calibrated, hydrologically similar watersheds consistent with the "best current engineering practice and scientific knowledge"?
2. Was HSPF accurately calibrated to the nearby, hydrologically similar watersheds?
3. If the answers to the previous questions is yes, then has the transfer been properly done?

These questions are addressed in the following subsections.

4.1.2 Validity of Model Parameter Transfer

In order to develop a method to apply the Stanford Watershed Model (a predecessor of HSPF) to ungaged watersheds several early studies with the Kentucky version of the Stanford Watershed Model attempted to relate model parameters to soil properties. These studies attained mixed results with some model parameters (e.g., the Lower Zone Nominal Storage) strongly related to soil properties and others weakly related to soil properties (e.g., Infiltration Capacity Index). James (1972) presented graphical relations between lower-zone nominal storage and available moisture capacity, and the infiltration index and soil permeability. Magette et al. (1976) developed linear-regression relations between model parameters and watershed and soil characteristics.

Because past research found that relations between measurable soil properties and HSPF parameters are difficult to develop and apply, an alternative approach for simulation of runoff for ungaged watersheds was sought. The concept that has been used successfully in many places is that of regional parameter sets. Regional parameter sets are obtained by calibrating and verifying HSPF rainfall-runoff parameters to runoff data in a given region (e.g., a county). These parameters are then assumed to apply for all similar pervious land segments (PERLNDs), which are defined by the land cover/soil type combination, in all hydrologically similar watersheds within that region. For countywide stormwater management, Lumb and James (1976) first proposed this approach for DeKalb County, Georgia. Lumb and James (1976) jointly calibrated the Stanford Watershed Model for rainfall and runoff data for 4 watersheds in or near DeKalb County, and reasoned that these parameters could be applied to any watershed in the county with similar soil types. The optimal parameters for the primary soil type in DeKalb County represented by these four watersheds then were slightly adjusted to account for higher and lower permeability soils.

The use of regional parameter sets for stormwater management has about a 40-year history. The transferability of regional HSPF parameter sets to other watersheds in a region has been successfully tested in numerous regions around the country including: Dupage County, Ill. (Price, 1994; Duncker and Melching, 1998); Lake County, Ill. (Duncker et al., 1995); Jefferson County, Ky. (Jarrett et al., 1998); Heron Lake Basin, Minn. (Jones and Winterstein, 2000); the Walt Disney World property in Florida (Wicklein and Schiffer, 2002), and the watersheds in the vicinity of the proposed Crandon Mine in northern Wisconsin (Chruscicki et al., 2003). Regional parameter sets also have been developed for southeastern Wisconsin by the Southeastern Wisconsin Regional Planning Commission (SEWRPC) and are frequently used for hydrologic simulation on ungaged watersheds.

The 7th TC (Espey et al., 2014) offered the following comment on the need to use parameter transfer:

> "The report of the Sixth Committee (Espey et al., 2009) includes a statement regarding previous studies that attempted to relate model parameters to soil properties. The

> conclusion was that relations between measurable soil properties and HSPF parameters are difficult to develop and apply. The Committee understands the reasoning for this statement, but wonders if this statement is as applicable today as it was previously. Digital soil mapping and GIS tools enable modelers to develop summary statistics of a variety of soil properties much easier and quicker than previously. It is possible that this type of assessment could be used to assist with the evaluation of the hydrologic similarity of the gaged and ungaged watersheds, if not used for the derivation of model input parameters."

Thus, it is worthwhile to discuss the earlier studies in more detail to clarify why the transfer of regional parameter sets has become the "best current engineering practice" with respect to applications of HSPF.

To better understand the problems with the attempts to relate HSPF model parameters with measureable watershed characteristics, the study of Magette et al. (1976) is reviewed in more detail. Magette et al. (1976) calibrated the Kentucky version of the Stanford Watershed Model for twenty-one watersheds located in Virginia, North Carolina, South Carolina, and Tennessee and ranging in size from 9.4 to 3054 acres. Five of these watersheds were randomly selected and reserved to form an independent set of watersheds by which to test the predictive equations. They sought to relate the parameters in the Kentucky version of the Stanford Watershed Model to which simulated runoff was most sensitive to easily determined watershed characteristics including the following:

> Area, Watershed Perimeter, Compactness coefficient (ratio of the watershed perimeter to that of a circle of equal area), Drainage density, Form factor (ratio of the average width to the axial length of the basin, where the axial length is measured from the outlet along the main path of flow to the most remote point in the watershed), average slope of the main channel, Maximum relief, Average watershed slope, Relief ratio, Percent of wooded area, Axial length, Depth to impervious layer, Overland flow surface slope, Average permeability of the A soil horizon (i.e. the upper layer of the soil profile), and Total length of channels.

Considering the foregoing list, as the 7th TC suggests, modern digital soil mapping, Digital Elevation Models (DEMs), and Geographical Information System (GIS) tools are well suited to quickly and efficiently determine these characteristics. However, the difficulty in using the regression equations derived by Magette et al. (1976) was not related to determining the watershed characteristics, but rather by concerns regarding the reliability and utility of the multiple linear regression equations derived. Table 4.3 lists the coefficient of determination (R^2) for the various key model parameters (with the equivalent HSPF parameters given in parentheses). Some of the multiple R^2 values given in the table appear to be reasonable and reliable. However, to achieve these results it was necessary to use two model parameters (LZC and BMIR) in the multiple regression equations as indicated in the table. In practical applications, inaccurate estimation for BMIR values yields estimates of LZC and BUZC that are less accurate than indicated by the R^2 values. Furthermore, use of inaccurate estimates for LZC value will yield estimates of ETLF and SIAC that are substantially less reliable than indicated by the R^2 values.

Table 4.3. Quality and limitations of equations used to estimate parameters of the Kentucky version of the Stanford Watershed Model (after Magette et al., 1976)

Parameter	Parameter description	R^2	Additional parameter needed
BUZC (UZSN)	Index of watershed depression storage	0.8181	BMIR
SUZC	Index of seasonal variation in depression storage	0.8820	
LZC (LZSN)	Index of watershed soil moisture storage capacity	0.9484	BMIR
ETLF (LZETP)	Index of soil moisture loss rate through evaporation	0.9331	LZC
SIAC	Index of seasonal variation in the infiltration rate	0.7999	LZC
BMIR (INFILT)	Index of water infiltration rate	0.9250	

This compounding of errors in the application of the multiple regression models is why the simulated flows for the five verification watersheds in Magette et al. (1976) yielded poorer agreement with measured flows than obtained using the regional parameter sets in the studies cited previously in this section. The better simulation results obtained results using "regional parameter sets" have led to this approach being the "best current engineering practice".

In summary, "regional" calibration of HSPF parameter sets and their application to nearby hydrologically similar watersheds is consistent with the "best current engineering practice and scientific knowledge." To evaluate whether this approach has been appropriately applied for the Diversion Accounting H&H Models three questions must be considered:

- Was the original calibration done adequately resulting in accurate models?
- Are the watersheds (diversion accounting watersheds) to which the regionally determined parameters are applied hydrologically similar to the original calibration watersheds?
- Was the parameter transfer done properly?

These questions are evaluated in the following sections.

4.1.3 Quality of the Original Calibration

The 5th and 6th TC reports (Espey et al., 2004, 2009) provide complete details on the original calibration of the HSPF to watersheds in the hydrologic region of the LMDA diversion basin. In this section, some key highlights of the quality of the original calibration are provided for comparison with the latest evaluation of the calibration of the HSPF model and the transfer of calibrated parameters to hydrologically similar watersheds in the Chicago area, which are detailed in the sections on Parameter Transfer (Section 4.1.5) and the "best" HSPF parameters (Section 4.1.6).

The source areas for the calibrated model parameters applied in the diversion accounting H&H models include the North Branch Chicago River watershed upstream of Touhy Avenue in Niles, Ill. (Hydrocomp, 1977d) and the Little Calumet River watershed upstream of Cottage Grove Avenue in South Holland, Ill. (Hydrocomp, 1977c). Hydrocomp (1979) also stated that parameters for the ungaged Calumet and lower Des Plaines River watersheds were in part based on the hydrologic calibration for the Hickory Creek watershed (Hydrocomp, 1977b). Finally, whereas the calibration experience on the Des Plaines River watershed (Hydrocomp, 1977a) is not specifically mentioned as a source for the HSPF parameters applied in the diversion accounting, it is part of the "regional experience" with HSPF and is included in the discussion here. For nearly all of these watersheds the calibration period was WYs 1965-1969 and the verification period was WYs 1970-1974. Among these 4 watersheds, the calibration and verification were checked at the following 14 sites:

- Des Plaines River at Gurnee (230 mi^2)
- Des Plaines River at Des Plaines (359 mi^2)
- Des Plaines River at Riverside (635 mi^2)
- Buffalo Creek (19.4 mi^2) – Des Plaines River Basin
- McDonald Creek (7.52 mi^2) – Des Plaines River Basin
- Long Run (20.8 mi^2) – Des Plaines River Basin
- Hickory Creek at Joliet (107 mi^2)
- Thorn Creek at Thornton (104 mi^2) – Little Calumet River Basin
- Little Calumet River at South Holland (208 mi^2)
- West Fork North Branch Chicago River at Northbrook (11.5 mi^2)
- Skokie River at Lake Forest (13.0 mi^2) – North Branch Chicago River Basin
- Skokie River near Highland Park (21.1 mi^2) – North Branch Chicago River Basin
- North Branch Chicago River at Niles (100 mi^2)
- North Branch Chicago River at Deerfield (19.7 mi^2)

For all the watersheds the total simulation error was less than 10 percent indicating a very good calibration. Nine of 14 total simulation errors were less than 5 percent, the largest total simulation error was 6.1 percent, and the model resulted in oversimulations for 7 watersheds and undersimulations for 7 watersheds.

For the 14 watersheds a total of 127 years of flow was simulated. Among these 58 percent of the years had simulation errors less than 10 percent indicating a very good calibration, 13 percent had simulation errors between 10 and 15 percent indicating a good calibration, and 23 percent had simulation errors between 15 and 25 percent indicating a fair fit. Only 7 of the 127 years had simulation errors greater than 25 percent. Further, 67 of the years were undersimulated and 60 of the years were oversimulated. The average annual error was 2.0 percent and the average absolute annual error was 10.6 percent. **These results clearly show that the HSPF model was well calibrated to these watersheds on annual and overall bases, which is very important for diversion accounting purposes. The original calibration also reliably estimated high flows, indicating that estimated CSO volumes might be accurately estimated** (see Espey et al., 2004)**. Thus, the original model was suitably calibrated for the purposes of the diversion accounting.**

4.1.4 Hydrologic Similarity of Watersheds

A key assumption of the transfer of calibrated HSPF parameters to "ungaged" watersheds is that the "ungaged" watersheds are hydrologically similar to the "calibration" watersheds. This assumption is reasonable for the transfer of the calibrated model parameters to the ungaged lower Des Plaines River and "ungaged" Calumet watersheds. However, it is questionable for the drainage basins of the WRPs.

Subsurface Drainage in Combined Sewer vs. Separate Sewer Areas

The WRP drainage basins are substantially more impervious than the "calibration" watersheds, but this can be reasonably accounted for by varying the proportions of pervious and impervious areas (discussed in detail later in this subsection). The bigger issue is the proportion of areas drained by combined sewers in the WRP drainage basins relative to the calibration watersheds. Hydrocomp (1979) reported that the percentages of the WRP drainage areas with combined sewers were 62, 73, and 29 percent for the O'Brien (formerly North Side), Stickney, and Calumet

WRPs, respectively. Whereas areas drained by combined sewers make up 6 percent of the North Branch Chicago River at Niles and 3 percent of the Little Calumet River at South Holland (the "calibration") watersheds (this issue remains relevant even if new watersheds are selected as the "calibration" watersheds as discussed in Section 4.1.6). The primary issue is that the combined sewers create a much more efficient drainage network than a natural river system such as found in the Little Calumet River watershed upstream of the South Holland gage and the North Branch Chicago River watershed upstream of the Niles gage. This issue has been recognized, but not emphasized since the early development of the diversion accounting models. Hydrocomp (1979, p. 29) noted (italics added):

> "In the Chicago area, the combined sewer system forms a dense network of underground pipes. The system is old and some sections are constructed of brick. Infiltration of groundwater into this system is considerable. Therefore, it was assumed that 100 percent of the subsurface flow computed by LANDS *(the pervious land portion of HSP)* eventually entered the system."

Initially this 100 percent of subsurface flow was only for SCAs drained by combined sewers, but later Burke (1990) expanded this to 100 percent of pervious areas in separately sewered areas. Later the 3rd TC (Espey et al., 1994, p. 60) more directly addressed this issue:

> "The subsurface component of HSPF was designed to simulate the flow of water from soil storage into stream channels—thus creating baseflow. This concept is similar but different from the infiltration into the sewers."

This difference may need to be emphasized in future modeling. Through WY 1999 the procedure for computing infiltration into the sewer system was added to 90 percent of the water supply (return/wastewater flow) in the WRP drainage basin to yield a reasonable estimate of dry weather flows to the WRPs. However, review of water withdrawal and delivery data in Section 4.6 of the 5th TC report (Espey et al., 2004) indicates that a 10 percent consumptive use factor is substantially smaller than the losses from the withdrawal point to households. Thus, if consumptive use increases in future modeling, infiltration may need to increase to maintain a good flow balance during dry weather flow. Thus, the ground-water flow and interflow portions of HSPF may need to be adjusted in future modeling. The porous nature of the sewer systems and the efficiency and density of the drainage networks make such an increase in sewer system infiltration reasonable. However, a recent attempt to estimate consumptive use in the Chicago area using water supply records and detailed sewer flow monitoring for a subdivision in Elk Grove Village, Ill., proved inconclusive (Mills et al., 2014). Thus, it is unlikely that the 10% consumptive use assumption will change in the near future.

The update of the HSPF and SCALP models done by CTE (2003a-c) described in detail in Section 4.4.1 of the 6th TC report (Espey et al., 2009) adjusted the dry weather flow (by adjusting the population equivalent) for the various WRPs. These adjustments were made to improve the flow balances at the WRPs and were not based on a re-evaluation of return flow/consumptive use. Thus, the most recent model revisions may not reflect possible errors in the consumptive use estimate of 10% and may need more thorough evaluation in the future. **Nonetheless, the effective changes in consumptive use in the recalibration led to corresponding changes in subsurface runoff parameters in HSPF that improved the regional parameter transfer basis of HSPF (see Section 4.4.1 of Espey et al., 2009).**

Impervious Areas

Time series of surface runoff per unit area from both pervious and impervious areas and subsurface runoff per unit area from pervious areas are computed with HSPF for precipitation input from each of 25 precipitation gages operated by the Illinois State Water Survey for the LMDA (e.g., Westcott, 2014) and other associated meteorological data (potential evapotranspiration, temperature, solar radiation, cloud cover, wind speed, and dew point) for each appropriate land cover: grassland, forest land, and impervious. The total inflow to the sewer system from an SCA is equal to

$$\text{Inflow } (SCA_i) = LSRO_G \text{ x } Area_{Gi} + LSRO_F \text{ x } Area_{Fi} + IMPRO \text{ x } Area_{Ii}$$

where $LSRO_G$ is the surface runoff per unit area for grassland, $LSRO_F$ is the surface runoff per unit area for forest land, IMPRO is the surface runoff per unit area for impervious areas, $Area_{Gi}$ is the grassland area in SCA i, $Area_{Fi}$ is the forest land area in SCA i, and $Area_{Ii}$ is the impervious area in SCA i. Similarly, the total infiltration to the sewer system from an SCA is equal to

$$\text{Infiltration } (SCA_i) = SSRO_G \text{ x } Area_{Gi} + SSRO_F \text{ x } Area_{Fi}$$

where $SSRO_G$ is the subsurface runoff per unit area for grassland, and $SSRO_F$ is the subsurface runoff per unit area for forest land. The inflow and infiltration computations for an SCA may need to be further subdivided by precipitation gage if the drainage area of an SCA is represented by more than one gage. For separately sewered areas in the ungaged Calumet and lower Des Plaines River watersheds the summation of Inflow and Infiltration is the total streamflow. If the meteorological data have been accurately measured and/or estimated and the model parameters have been reliably determined through calibration and/or transfer from hydrologically similar watersheds, then proper determination of the drainage areas of the different land covers is the key to accurate simulation of flows from an SCA. A useful review the various changes in drainage area throughout the diverted Lake Michigan watershed and the Des Plaines River watershed tributary to the CAWS from the beginning of model use to 2004 is given in the 5th TC report (Espey et al., 2004).

The 5th TC recommended (Espey et al., 2004, p. 52):

> "The performance of the WY 1997 modifications to land use should be monitored as additional years of diversion calculations are completed. If the CSO flows still seem to be overestimated, the DuPage County (1993) values for medium and low density residential development should be applied for the H&H modeling in the diversion accounting."

The issue in question in this comment is the estimation of the impervious areas in the modeled watersheds. Beginning in 2004 and continuing through 2015 the USACE and the USGS did several studies to determine the best and most effective way to determine the land cover types in the modeled watersheds with an emphasis placed on the determination of the impervious areas these studies are discussed in the remainder of this section.

Espey et al. (2009) noted that the adjustments to the percentage of impervious area made for the WY 1997 diversion accounting appear to have improved the simulated CSO flows relative to the USACE conclusion that CSO flows might be overestimated (USACE, 1997b). However, it still is worthwhile to review the delineation of watersheds into impervious and pervious areas. Aerial photographs of the watersheds modeled for LMDA were delineated into subareas falling into 11

land use categories. For each of these land uses a representative percentage of impervious cover was determined by Rust Environment and Infrastructure (1993a) and division of an SCA into pervious (grassland in the Lake Michigan watershed, and grassland and forest land in the Des Plaines River watershed) and impervious areas was determined as the product of the land use in acres and the percentage impervious (Table 4.4) divided by 100. The percentages of directly connected impervious area determined by Rust for residential areas appeared to be too high relative to other information in the literature. Therefore, the USACE (2001) adjusted the impervious percentages for residential areas on the basis of information provided by the Soil Conservation Service (1986) in Technical Release 55 (also listed in Table 4.4). However, information in the literature indicates that impervious percentages could be even lower for residential areas. Also listed in Table 4.4 are percentages of impervious area used in Du Page County, Ill., for HSPF modeling in 1993[2]. Antonie (1964) found that for lots with areas between 6,000 and 15,000 ft^2 the impervious area typically comprises 40 percent of the total area. Thus, the Du Page County (1993) value for ¼ acre lots probably is too low for use for high-density residential development, but the values for medium and low density residential development may merit consideration in the watersheds whose runoff affects the diversion accounting.

Table 4.4. Percentage of impervious area for various land uses.

Land Use	Rust (1993a)	TR-55[1]	Du Page (1993)[2]
Forest	0		
Open Space/Park	5		determined case by case
Low Density Residential: (1.1 acre median lot)	19	20	10
Medium Density Residential: (1/2 acre median lot)	40	25	15
High Density Residential: (1/5 acre median lot)	56	38[3]	28[3]
Multifamily and High Rise	70	65	50
Commercial	85	85	85
Industrial	72	72	85
Highway Corridor:			
With Grassed Median	50		50
No Median	80		100
Open Water	100		100

[1]The Soil Conservation Service (1986) only listed average percentage impervious values for the land uses for which numbers are included in this table. Multifamily and high rise is taken as equivalent to the 1/8 acre or less (town houses) land use in TR-55.
[2]The Du Page County (1993) guidelines included percentages for hydraulically connected and non-hydraulically connected residential lots, the percentages for hydraulically connected lots are considered more representative of the watersheds simulated in diversion accounting and are included here.
[3]For both TR-55 and Du Page (1993) values for ¼ acre lots are entered here.

The Du Page County Department of Environmental Concerns substantially lowered the percentage of directly connected impervious area for residential areas used in HSPF modeling in a March 11, 1994, memorandum by Jon Steffen, Principal Engineer, on "Hydrologic and Hydraulic Methods used for Flood Plain Mapping of Du Page County Watersheds". The 5th and 6th TCs felt these percentages were too low for use in the watersheds whose runoff affects the diversion accounting.As part of an evaluation of HSPF simulation accuracy for Tinley Creek and Midlothian Creek done by the USGS for the USACE, the use of the Rust, TR-55, and Du Page County values in Table 4.4 to estimate imperviousness were evaluated against detailed aerial photo interpretation and simulation results (however, in the consideration of the Du Page County values, the TR-55 value for ¼ acre lots was used by the USGS). It was found that the TR-55 based approach yielded the best simulation results in comparison to those for the imperviousness resulting from detailed photo interpretation (Soong et al., 2007; Soong and Su, 2008). **Thus, the pervious and impervious percentages by land use category used since WY 1997 meet the standard of the best current engineering practice.** Additional details on the USGS comparison are given in Section 4.4.5 of the 6th TC report (Espey et al., 2009).

The most recent evaluation of the land cover in the LMDA diversion basin was done by the USGS in 2015 (Sharpe and Soong, 2015). In this study, the 2006 National Land Cover Dataset (NLCD) was used as raw data in conjunction with an in-house developed automated process for determining the area of the three land cover types. The automated processes allow faster updating of the land use for future models and for evaluating land cover changes by use of historical NLCD datasets. The 7th TC (Espey et al., 2014, p. iv) concurred with the approach proposed by Sharpe and Soong (2015) stating:

> "This approach is consistent with the "best current engineering practices and scientific knowledge", and is well-suited for objective model parameter development. This method

lends itself well to updating the imperviousness parameters as updated land use data becomes available."

Acreages for the three land covers determined by using the NLCD and the conversion weights determined by Sharpe and Soong (2015) compared favorably for gaged and ungaged basins of the diverted Lake Michigan watershed with the land covers and conversion weights previously developed by Rust Environment and Infrastructure (1993a) and the USACE (2001). Sharpe and Soong (2015) also found that for the entire LMDA diversion basin the impervious area slightly changed from 39.4% in 1992 to 41.5% in 2011. **Thus, the continued use of the land cover percentages in use since 1997 is reasonable and meets the standard of the best current engineering practice.**

4.1.5 Regional Parameters and Their Transfer

Table 4.5 lists the HSPF rainfall-runoff parameters for grassland determined by the original calibrations on the North Branch Chicago River, Little Calumet River, Des Plaines River, and Hickory Creek watersheds. For some watersheds, slightly different values of a parameter may have been used for the different raingage inputs resulting in the ranges in parameter values rather than a single parameter value for some watersheds listed in Table 4.5. Also listed in Table 4.5 are the HSPF parameter values used in the original HSPF model of the watersheds draining to the CSSC (Hydrocomp, 1979). It is clear that the original CSSC model directly applied the parameter transfer concept. Table 4.5 also lists the parameter values applied to 10 of 13 raingages used in the WY 1989 diversion accounting (Rust Environment and Infrastructure, 1993b) and the re-calibrated parameter values determined by CTE (2003a-c) that have been used in the LMDA since WY 2000. It is assumed that the WY 1989 parameter values are those originally used by NIPC in the first diversion accounting models because none of the diversion accounting reports for WYs 1984-1989 mention any adjustment of the HSPF model parameters. For grassland the HSPF parameters used through WY 1999 are identical to those used in WY 1989 (NIPC), and the CTE (2003a-c) recalibration resulted in changes in 5 of the model parameters. A detailed discussion of the CTE (2003a-c) recalibration is given in Section 4.4.1 of the 6th TC report (Espey et al., 2009).

Table 4.6 lists the HSPF rainfall-runoff parameters for forest land determined by the original calibrations on the North Branch Chicago River, Little Calumet River, Des Plaines River, and Hickory Creek watersheds. For some watersheds slightly different values of a parameter may have been used for the different raingage inputs resulting in the ranges in parameter values for some watersheds in Table 4.6. Table 4.6 also lists the parameter values applied in the WY 1989 diversion accounting (Rust Environment and Infrastructure, 1993b) and the recalibrated values determined by the USGS which have been used in the LMDA since WY 2006. The forest land HSPF parameters used through WY 2005 are identical to those used in WY 1989 (NIPC) except for LZSN which decreased from 10 to 9.5 and LSUR which increased from 300 to 400 ft.

The rainfall-runoff parameters for impervious areas and the snowmelt parameters also have changed slightly from the original calibration to the current application. They are summarized in Appendix B.

Table 4.5. Rainfall-runoff parameters for grassland in the Hydrological Simulation Program-Fortran model used in the diversion accounting through Water Year 1999 (1999), found by calibration in neighboring watersheds, applied in the original model of the Chicago Sanitary and Ship Canal (CSSC), applied for 10 of 13 raingages in the diversion accounting models developed by the Northeastern Illinois Planning Commission (NIPC) for Water Year 1989, and determined in re-calibration done by CTE (2003a-c).

Parameter	North Branch	Little Calumet	Des Plaines	Hickory Creek	CSSC	NIPC	1999	CTE
CEPSC	0.12	0.1-0.2	0.12-0.15	0.15	0.1-0.12	0.25	**0.25**	0.1
UZSN	1.1	0.75-0.8	0.75-2.2	1.5	0.75-1.1	1.8	1.8	**0.5**
LZSN	7.5	8.5	7.5-8.0	8.0	7.5-8.5	9.5	**9.5**	8.5
LZETP	0.25	0.1-0.25	0.25-0.35	0.25	0.1-0.25	0.38	**0.38**	**0.38**
AGWETP	0.08	0.02-0.05	0.05-0.30	0.05	0.00-0.08	0.05	0.05	0.05
INFILT	0.015	0.02-0.022	0.015-0.045	0.02-0.03	0.015-0.02	0.015	0.015	**0.1**
DEEPFR	0.08	0.05-0.10	0.05-0.30	0.05	0.00-0.08	0.05	0.05	0.05
INTFW	3.5	2.7-3.2	2.5-5.0	3.5	3.2-3.5	15.0	**15.0**	**10.0**
LSUR	250	400	250-500	400	250-400	50	**50**	**50**
SLSUR	0.01	0.002	0.01-0.05	0.05	0.002-0.01	0.01	0.01	0.01
NSUR	0.25	0.35	0.2-0.35	0.35	0.25-0.35	0.2	0.2	0.2
IRC	0.5	0.5	0.5-0.6	0.5	0.5	0.5	0.5	0.5
KVARY	1.0	1.5	1.0-1.5	1	1.0-1.5	1.7	**1.7**	**1.7**
AGWRC	0.98	0.99	0.97-0.99	0.97	0.98-0.99	0.98	0.98	0.98

References: North Branch = Hydrocomp (1977d)
Little Calumet = Hydrocomp (1977c)
Des Plaines = Hydrocomp (1977a)
Hickory Creek = Hydrocomp (1977b)
CSSC = Hydrocomp (1979)
NIPC = Rust Environment and Infrastructure (1993b)

As indicated by the use of bold numbers in Table 4.5, the values of CEPSC, LZSN, LZETP, INTFW, LSUR, and KVARY for grassland used through WY 1999 were outside of the range of calibrated values used on nearby watersheds. The recalibration done by CTE (2003a-c) resulted in CEPSC and LZSN moving inside and UZSN and INFILT moving outside the range of calibrated values used on nearby watersheds. Table 4.6 shows that the values of UZSN, LZSN, INTFW, and KVARY used through WY 2005 for forest land are outside of the range of calibrated values obtained on nearby watersheds. The recalibration done by the USGS for Midlothian and Tinley creeks resulted in LZSN and KVARY moving inside and LZETP and AGWRC moving outside the range of calibrated values used on nearby watersheds. Thus, HSPF parameter transfer on the basis of regional model parameters really has not been applied in the HSPF models applied since at least WY 1989, and probably throughout the entire period of using models in the diversion accounting. Further, this implies that the ±10 percent accuracy in the annual flow estimate achieved in the original calibration may not be valid for the HSPF model currently applied in the diversion accounting.

Table 4.6. Rainfall-runoff parameters for forest land in the Hydrological Simulation Program-Fortran model used in the diversion accounting through WY 2005 (2005), found by calibration in neighboring watersheds, and applied in the diversion accounting models developed by the Northeastern Illinois Planning Commission (NIPC) for Water Year 1989, and determined by calibration on Tinley Creek and Midlothian Creek by the U.S. Geological Survey (USGS).

Parameter	North Branch	Little Calumet	Des Plaines	Hickory Creek	NIPC	2005	USGS
CEPSC	0.2	0.25-0.4	0.18-0.20	0.2	0.2	0.2	.02
UZSN	6.0	6.0	5.0-6.0	6.0	3.0	**3.0**	**1.0**
LZSN	7.5	8.0	7.5-8.0	8.0	10.0	**9.5**	7.5
LZETP	0.9	0.8-0.9	0.85-0.90	0.9	0.9	0.9	**0.6**
AGWETP	0.15	0.10-0.26	0.05-0.15	0.05	0.15	0.15	0.05
INFILT	0.007	0.01-0.025	0.005-0.015	0.005	0.01	0.01	0.005
DEEPFR	0.15	0.15-0.20	0.05-0.20	0.05	0.05	0.05	0.05
INTFW	3.5	2.5-5.0	3.0-5.0	3.5	7.5	**7.5**	**5.0**
LSUR	1000	1000	100-1000	1000	300	400	400
SLSUR	0.001	0.002	0.00-0.01	0.0	0.01	0.01	0.01
NSUR	0.35	0.35	0.25-0.35	0.35	0.25	0.25	0.25
IRC	0.5	0.5	0.5-0.6	0.5	0.5	0.5	0.5
KVARY	1.0	1.5	1.0-1.5	1	1.7	**1.7**	1.5
AGWRC	0.99	0.99	0.97-0.99	0.97	0.98	0.98	**0.95**

References: North Branch = Hydrocomp (1977d)
Little Calumet = Hydrocomp (1977c)
Des Plaines = Hydrocomp (1977a)
Hickory Creek = Hydrocomp (1977b)
NIPC = Rust Environment and Infrastructure (1993b)
USGS = Presentation made to Sixth Technical Committee by Dr. David Soong, U.S. Geological Survey, November 13, 2008.

Given that the regional parameter transfer basis of the HSPF model applied in the LMDA does not meet the general level of consistency found in most regional applications of HSPF, the 5th TC (Espey et al., 2004) recommended that additional comparisons with gaged flows are needed to reduce the uncertainty with respect to the parameter transfer and demonstrate the accuracy of the HSPF model applied in LMDA. As noted earlier, the comparisons of simulated and measured flows at the WRPs are not sufficiently precise to evaluate the accuracy of the rainfall-runoff simulation. Wastewater flow comprises more than 80 percent of the WRP flows. Thus, substantial errors in the rainfall-runoff simulation could be hidden in a 5 percent difference in simulated and measured WRP flows. The 5th TC (Espey et al., 2004) recommended that the North Branch Chicago River at Albany Avenue and Grand Avenue, the North Branch Pumping Station and Racine Avenue Pumping Station, Tinley Creek, and Midlothian Creek might be suitable locations to test the "calibrated" HSPF model. Section 4.4 of the 6th TC report (Espey et al., 2009) describes in detail several studies done by the USACE and the USGS to test the HSPF results with gaged flows at these locations. It was found that only Tinley Creek and Midlothian

Creek yielded useful tests of the "calibrated" HSPF model, and the studies on these creeks led to the recalibration of the forest land parameters in HSPF done by the USGS (listed in Table 4.6) and detailed in Section 4.4.2 of the 6th TC report (Espey et al., 2009). The findings of the tests on Tinley Creek and Midlothian Creek led the USACE and USGS to study the transfer of HSPF parameters among 9 gaged watersheds in the Chicago metropolitan area to try to determine the best parameters and the accuracy of the use of regional parameter sets. This study done by Soong and Over (2015) is summarized in the following section.

4.1.6 Determination of the "best" HSPF parameters for use in the LMDA

Overview of Comprehensive Study of HSPF Parameter Transfer in the Chicago Area

Because the study of HSPF parameter transfer to the Midlothian Creek and Tinley Creek watersheds provided interesting insight on the performance of the HSPF model and on the calibration of HSPF parameters for forest land, the USACE and USGS decided a larger study which studied runoff simulation for 7 more gaged watersheds which either drained to the CAWS (Butterfield Creek, Hart Ditch, and Skokie River) or are near the diversion accounting watersheds (Flag Creek, Hickory Creek, and Long Run) (Soong and Over, 2015). The locations of these watersheds in relation to the diversion accounting watersheds are shown in Figure 4.2 (note: the full boundary of the Hickory Creek watershed is partially blocked by the figure legend). Table 4.7 lists the areas and land covers of these watersheds.

Table 4.7. Characteristics of the watersheds considered in the testing of the transfer of HSPF parameters among watersheds

Gaged Stream	Area (mi^2)	Impervious (%)	Forest (%)	Grass (%)
Flag Creek near Willow Springs, IL	16.5	37.6	2.0	60.4
Skokie River near Highland Park, IL	21.1	31.4	13.1	55.5
Butterfield Creek near Flossmoor, IL	23.5	29.9	7.4	62.7
Midlothian Creek at Oak Park, IL	13.5	36.6	10.1	53.3
Tinley Creek near Palos Park, IL	11.2	28.8	24.9	46.3
Long Run near Lemont, IL	20.9	23.3	16.9	59.8
Hickory Creek at Joliet, IL	107.0	23.2	12.8	64.0
Hart Ditch at Dyer, IN	37.6	7.7	22.4	69.9
Hart Ditch at Munster, IN	70.7	19.6	17.0	63.4

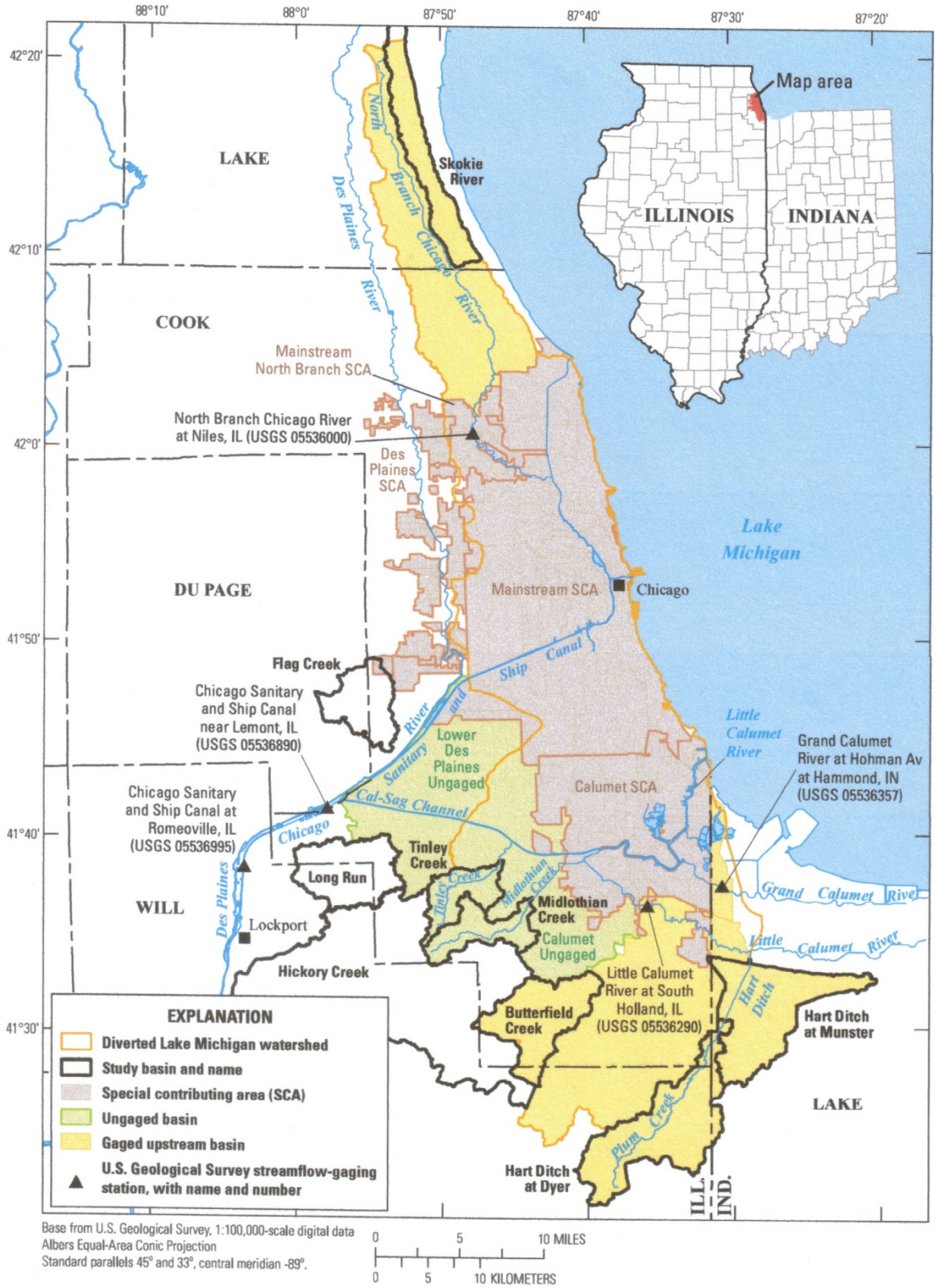


Figure 4.2. Test watersheds for the HSPF parameter transfer evaluation and their relation to the diverted Lake Michigan watershed (provided by the U.S. Geological Survey)

As noted in Section 4.1.5, the nine parameter sets comprising the North Branch, Little Calumet, Des Plaines, Hickory Creek, CSSC, NIPC, 1999, CTE (for forest lands CTE is equivalent to the 2005 parameter set in Table 4.6), and USGS have been developed at different time periods and used by the USACE. Six of the parameter sets, comprising North Branch, Hickory Creek, NIPC, 1999, CTE, and USGS, were applied to the nine gaged watersheds for evaluating their simulation accuracy from WY 1996 to 2011. The nine gaged watersheds were modeled by using the three LMDA land-cover types (grassland, forest land, and hydraulically connected impervious) based on the 2006 NLCD, and the latest meteorological and precipitation data consistent with the current LMDA modeling framework. The HSPF model parameters also were recalibrated focusing on runoff from the Tinley Creek and Long Run watersheds. The recalibrated HSPF parameter set also was applied in the evaluation of the HSPF parameter transfer.

HSPF Recalibration

Recalibration of the HSPF parameters to the updated inputs and land covers was completed on two representative watersheds (Tinley Creek and Long Run) using a manual method (HSPEXP, Lumb et al., 1994) and an automatic method (PEST, Doherty, 2005, 2013). SNOW and IMPLAND parameters were not modified in this study, and the model development did not emphasize the flow routing component of HSPF. Daily discharge was the basis of the simulation. The calibration period was from October 1, 2000, to September 30, 2009, and the validation periods were WYs 1997 to 2000 and WYs 2010 to 2011. The best performing parameter set was determined by the automatic calibration method on a two-watershed model (i.e. simultaneously calibrated on both watersheds). In the calibration 17 grassland and forest land parameters were calibrated. The objective function of PEST, phi, is the sum of squared weighted residuals between models and observations for each of the observation groups considered (Soong and Over, 2015):

- Selected storm hydrographs (Weight = 1)
- Daily streamflow (Weight = 1)
- Daily quickflow derived from daily streamflow (Weight = 1)
- Monthly runoff volume (Weight = 1)
- Annual runoff volume (Weight = 2)
- Total runoff volume of the calibration period (Weight = 2)
- Flow duration curve (Weight = 2)

The Tinley Creek and Long Run watersheds were selected as the base watersheds for recalibrating the regional parameters because they represent the primary watershed response groups identified by Soong and Over (2015). These watersheds have no known effluent discharges and have more balanced distribution of forest land, grassland, and impervious land compared to the other seven gaged watersheds in the Chicago area used to test the regional parameter sets. The Tinley Creek and Long Run watersheds also have better raingage network coverage than the alternative watersheds (Soong and Over, 2015).

Criteria for Evaluating the Quality of the HPSF Parameter Transfer Verification

The main premise for using continuous simulation models for planning and design is that accounting for water stored in the watershed throughout time more realistically considers antecedent conditions and estimates flood sequences (and CSOs) than do event-based models using assumed antecedent conditions. Annual and monthly water balances must be accurately simulated for this to be correct. Thus, HSPF calibration typically is done in a stepwise manner

using data available at streamflow gages and matching the overall water budget, the annual water budgets, the monthly and seasonal water budgets, and finally, considering storm-runoff volumes and frequencies. In evaluating the monthly and seasonal water budgets and storm-runoff volumes, the relative proportions of high flows and low flows are considered. Several criteria are utilized to determine if the quality of the fit between the simulated and observed runoff is acceptable. The 5th TC (Espey et al., 2004) discussed many of the statistics commonly used in the calibration of HSPF. However, the evaluation of the quality of HSPF performance relative to its usefulness to LMDA has focused primarily on three criteria: the overall percentage error in simulated flows (referred to as PBIAS by Soong and Over, 2015), the annual percentage error in simulated flows, and the Nash and Sutcliffe (1970) coefficient of model-fit efficiency (E). Further, Soong and Over (2015) considered the ratio of Root Mean Square Error to the standard deviation of the measured data (RSR). These criteria are used to assess the current status of the "model calibration/parameter transfer".

For the overall and annual water budgets the percent error (Percent Bias, PBIAS) typically is considered. Donigian et al. (1984, p. 114) state that for HSPF simulation the annual or monthly fit is very good when the error is less than 10 percent, good when the error is between 10 and 15 percent, and fair (or satisfactory in Soong and Over (2015)) when the fit is between 15 and 25 percent. Further, Soong and Over (2015) noted that the model fit is unsatisfactory if PBIAS is greater than 25%.

The quality of fit for monthly or daily values typically is evaluated using the Nash-Sutcliffe E calculated as

$$E = \frac{\sum_{i=1}^{N}(Q_{mi} - \overline{Q}_m)^2 - \sum_{i=1}^{N}(Q_{mi} - Q_{si})^2}{\sum_{i=1}^{N}(Q_{mi} - \overline{Q}_m)^2}$$

where Q_{mi} is the measured runoff volume for time period (day, month) i, Q_{si} is the simulated runoff volume for time period i, $\overline{Q}_m$ is the average measured runoff volume, $\overline{Q}_s$ is the average simulated runoff volume, and i = 1,..., N, where N is the number of time periods in the calibration period. The Conservation Effects Assessment Project-Watershed Assessment Study (CEAP-WAS) was a project to quantify the environmental benefits of conservation practices supported by the U.S. Department of Agriculture. One of the CEAP-WAS goals was to formulate guidelines for calibration, validation, and application of watershed models used in CEAP-WAS to simulate the effects of conservation practices. For CEAP-WAS Moriasi et al. (2007) reviewed many watershed modeling case studies and proposed statistical criteria for acceptable performance of watershed models used to estimate the effects of conservation practices. Moriasi et al. (2007) proposed the following criteria for model evaluation based on E: $E \geq 0.75$ –Very Good, $0.75 > E \geq 0.65$ – Good, and $0.65 > E \geq 0.5$ – Satisfactory. These criteria are for a monthly evaluation and Engel et al. (2007) noted typically, model simulations are poorer for shorter time steps than for longer time steps (e.g., daily versus monthly or yearly). These criteria for E commonly are used to assess the quality of watershed models for continuous simulation of streamflow, and are used here (and in Soong and Over, 2015) to assess the current status of the "model calibration/parameter transfer" for the HSPF model applied to LMDA.

The RSR is computed as follows:

$$RSR = \frac{\sum_{i=1}^{N}(x_{mi} - x_{si})^2}{\sum_{i=1}^{N}(x_{mi} - \overline{x_m})^2}$$

Soong and Over (2015) stated that RSR values between 0.0 and 0.5 indicate a very good fit, between 0.5 and 0.6 indicate a good fit, between 0.6 and 0.7 indicate a satisfactory fit, and greater than 0.7 indicate an unsatisfactory fit.

Evaluation of the Performance of the Various HSPF Parameter sets

Table 4.8 summarizes the best and worst performing among the six older HSPF parameter sets evaluated by Soong and Over (2015) by watershed on the basis of the PBIAS comparison. Whereas the USGS parameters currently used in the LMDA computations had the worst overall performance for PBIAS for 5 of the 9 test watersheds, they also had the best performance for three of the 9 test watersheds (namely the ones with the highest percentages of forest land). Further it should be noted that the USGS parameter set generated "very good" overall PBIAS for Midlothian Creek (one of the cases where it was "worst overall"), Tinley Creek, Hart Ditch at Dyer and Munster, and Long Run watersheds (also a watershed with a high percentage of forest land), and "satisfactory" results at all watersheds except Butterfield Creek.

Table 4.8. Overall performance on the basis of PBIAS for the six historic HSPF parameter sets used in the Lake Michigan Diversion Accounting and the percentage of forest in each watershed

Gaged Stream	Best Overall	Worst Overall	Forest (%)
Flag Creek near Willow Springs, IL	NIPC, 1999	CTE, USGS	2.0
Skokie River near Highland Park, IL	NIPC, 1999	CTE, USGS	13.1
Butterfield Creek near Flossmoor, IL	NIPC, 1999	CTE, USGS	7.4
Midlothian Creek at Oak Park, IL	North Branch, Hickory	CTE, USGS	10.1
Tinley Creek near Palos Park, IL	CTE, USGS	NIPC, 1999	24.9
Long Run near Lemont, IL	North Branch, Hickory	NIPC, 1999	16.9
Hickory Creek at Joliet, IL	Hickory	CTE, USGS	12.8
Hart Ditch at Dyer, IN	CTE, USGS	NIPC, 1999	22.4
Hart Ditch at Munster, IN	CTE, USGS	NIPC, 1999	17.0

Table 4.9 lists the performance of the various HSPF parameter sets (including the PEST 2 watershed calibration) measured by the Nash-Sutcliffe E for monthly flows assessed for all watersheds and years. In this case the North Branch and Hickory Creek parameter sets give the best performance, whereas the PEST 2 watershed and USGS parameters sets give the worst performance. However, the difference in performance among the 7 parameter sets is not very large given that all the parameter sets yield "very good" or "good" results for 8 of the 9 test watersheds.

Table 4.10 lists the number of very good and unsatisfactory results over all sites and years for various HSPF parameter sets (including the PEST 2 watershed calibration) measured by the RSR, PBIAS, and E. Again, in this case the North Branch and Hickory Creek parameter sets give the best performance, whereas the PEST 2 watershed and USGS parameters sets give the worst performance. However, the difference in performance among the 7 parameter sets is not very large.

Table 4.9. Nash-Sutcliffe Efficiency results for monthly flows over all sites and years

Parameter Set	Range	Average	Rating by watershed			
			Very Good	Good	Satisfactory	Unsatisfactory
North Branch	0.57-0.87	0.753	6	2	1	0
Hickory Creek	0.62-0.87	0.769	6	2	1	0
NIPC	0.63-0.87	0.760	5	2	2	0
1999	0.63-0.87	0.760	5	2	2	0
CTE	0.51-0.85	0.742	4	4	1	0
USGS	0.48-0.84	0.728	4	4	0	1
PEST 2 watershed	0.44-0.84	0.717	4	4	0	1

Table 4.10. Number of very good (VG) and unsatisfactory (US) results over all sites and years

Parameter Set	Rating by Watershed							
	PBIAS		E		RSR		Total	
	VG	US	VG	US	VG	US	VG	US
North Branch	3	1	6	0	6	0	15	1
Hickory Creek	3	1	6	0	6	0	15	1
NIPC	3	1	5	0	5	0	13	1
1999	3	1	5	0	5	0	13	1
CTE	5	1	4	0	5	0	14	1
USGS	5	1	5	1	4	1	13	3
PEST 2 watershed	5	1	4	1	4	1	13	3

Finally, Table 4.11 lists the number of monthly simulated flow over all sites and years that fall into the very good, good, fair, and unsatisfactory ranges. In this case the PEST 2 watershed HSPF parameter set performs the best with the USGS and CTE HSPF parameter sets following closely behind. However, again the difference in performance among the 7 parameter sets is not very large.

Table 4.11. Number of monthly simulated flows over all sites and years that fall into the very good, good, fair, and unsatisfactory ranges

Parameter Set	Very Good	Good	Fair	Unsatisfactory
North Branch	53	25	34	32
Hickory	52	27	35	30
NIPC	49	25	34	36
1999	49	25	34	36
CTE	56	17	31	40
USGS	57	18	29	40
PEST 2 watershed	58	16	34	36

In summary, the results of the very extensive evaluation of regional HSPF parameter sets and parameter transfer in the Chicago area done by Soong and Over (2015) considering a number of quality-of-fit statistics indicate that the various HSPF parameter sets yield fairly similar overall levels of performance. The current HSPF parameter set (derived by the USGS in 2008 by recalibrating the parameters for forest land and combining these with the CTE (2003a-c)

parameters for grassland and impervious area), generally yields the best results for watersheds with higher amounts of forest land. This is important because the ungaged lower Des Plaines River and Summit Conduit watersheds that drain to the CSSC are key components of the LMDA determined by model simulation and these watersheds are 29.6% forest land. As discussed in Section 4.6.1 the USGS parameter set used since WY 2006 appears to be giving reasonable estimates of flows from the ungaged lower Des Plaines River and Summit Conduit watersheds when compared to neighboring gages using the area ratio method. **Therefore, given the generally good performance of the 2008 USGS parameters found by Soong and Over (2015) for various gaged watersheds in the Chicago area, and, especially, the good performance in estimating flows from the ungaged lower Des Plaines River and Summit Conduit watersheds, this Committee recommends that the USACE continue to use this parameter set in the LMDA computations.**

4.2 Special Contributing Area Loading Program (SCALP)

4.2.1 Overview of the SCALP model

The SCALP model is a specialty model primarily developed for use in the Chicago area. SCALP applies the linear reservoir concept to represent storage in each of the aggregated lateral, submain, and main pipe networks of the combined (or separate sanitary) sewer system in a designated area draining to the CAWS, known as a special contributing area (SCA). A storage is defined for each of the three types of pipe, and flow is routed through each of the storages consecutively.

The sanitary flow from an SCA is computed on the basis of the population in the SCA and is distributed in time on the basis of monthly, daily (Sunday-Saturday), and hourly coefficients that were set by examination of the recorded flow to the WRPs over the year and week (Hydrocomp, 1979, USACE, 2001). Subsurface flow generated by HSPF enters the pipe system as infiltration if sufficient capacity is available. Surface flow generated by HSPF enters the pipe system as inflow if sufficient capacity is available. If sufficient capacity is not available, excess inflow and infiltration are "stored" at the entrance to the pipe (lateral, submain, or main) until capacity is available. The capacity (Q_{MAX}) for each aggregated pipe system represents the maximum outflow under surcharged conditions. SCALP keeps track of the relative percentages of sanitary, infiltration, and surface flows reaching WRPs and in CSOs, which is important for the LMDA, e.g., CSOs to the Des Plaines River may include Lake Michigan water supply pumpage return flow (wastewater).

A simple cutoff rule is used to approximate the operation of hydraulic devices used to divert flow out of a combined sewer. Any flow up to the cutoff level, SPLIT, is routed to the interceptor and WRP, while any excess over the cutoff is diverted toward the stream. Values for SPLIT were based on calibration of interceptor flows to the WRPs, particularly when matching peak flows at the WRPs (Hydrocomp, 1979; Hey et al., 1980). Whether this excess flow becomes an overflow to the CAWS depends on the operation of TARP as simulated with TNET.

From a hydraulic standpoint, SCALP is not a "state-of-the-art" model for a sewer system. Models such as Modeling of Urban Sewers (MOUSE) which is part of MIKE-Urban developed by the Danish Hydraulic Institute (http://www.mike-by-dhi.com/) can provide more accurate and detailed simulation of the combined sewer and separate sewer systems. The dynamic wave routing option in MOUSE, MOUSE HD, is founded on an implicit, finite difference numerical solution of the full dynamic wave equations (also known as the de Saint Venant equations) for momentum and flow conservation in open channels and closed conduits (approximated as open

channel flow using the Preissman slot technique). Application of dynamic wave modeling to individual pipes is far more accurate than the linear reservoir routing through aggregated pipe systems done with SCALP. MOUSE has been applied to a number of large wastewater systems in the U.S. (e.g., it has been used by the Milwaukee Metropolitan Sewerage District).

Even though SCALP is not a "state-of-the-art" model of sewer system hydraulics, it is adequate for the purpose of diversion accounting. That is, complete hydraulic modeling may be necessary to understand the operation of a sewer system, and, especially sewer failures. However, simplified models similar to SCALP frequently are used for design and planning of sewer systems and treatment plants. For example, the KOSIM model (Harms and Kenter, 1987) developed by the Institut fur Technisch-Wissenschaftliche Hydrologie in Hanover, Germany, is similar to SCALP. Dry weather flows (wastewater flows) are determined on a per capita basis and distributed in time by coefficients. Infiltration is taken as a ratio to the dry weather flow determined from field measurements. Inflow is computed by a rainfall-runoff model that routes the inflow using a cascade of three identical linear reservoirs, and the flow is then routed through the sewer system using a hydrograph translation technique. Overflows are determined using the same approach as in SCALP. The KOSIM model has frequently been applied for sewer design and management in Europe. Vanrolleghem et al. (2005) considered the use of KOSIM for the simulation of the sewer system of the Tielt, Belgium, as part of a real-time control system for the wastewater treatment plant and CSO control to meet water-quality standards in the receiving stream. They compared the results of KOSIM to those of a full hydraulic modeling of the sewer system using Hydroworks, and found that the total overflow volumes and overflow peak discharges were modeled with the same accuracy in both models. In a second example, KOSIM was applied to model the combined sewer system for Brussels, Belgium, to aid in the design of two wastewater treatment plants and the adjustment of CSOs (Demuynck and Bauwens, 1996).

4.2.2 Recalibration of the SCALP model

The USACE contracted with CTE Engineers Inc. to do the diversion accounting calculations for WYs 2000 and 2001. In addition to the diversion accounting calculations CTE was asked to evaluate the calibration for the HSPF and SCALP models using WYs 2000 and 2001 as the recalibration/testing period. For the recalibration CTE (2003a-c) focused on the return flow assumptions in SCALP for the four WRPs—O'Brien (formerly North Side), Stickney, Calumet, and Lemont—drainage areas and on five parameters for grassland and one parameter for impervious land in HSPF. Details on CTE's recalibration of HSPF are given in Section 4.4.1 of the 6th TC report (Espey et al., 2009).

In the recalibration, the population equivalent in SCALP was adjusted such that the wastewater flows changed to shift baseflows to more closely match the observed baseflows at the WRPs. The following changes in wastewater flows resulted:

- Wastewater flows were increased by 3% for the CSO service areas tributary to the O'Brien (North Side) WRP
- Wastewater flows were decreased by 20% for the CSO service areas tributary to the Stickney WRP
- Wastewater flows were decreased by 24% for the CSO service areas tributary to the Calumet WRP
- Wastewater flows were increased by 10% for the CSO service areas tributary to the Lemont WRP

These changes mean the statement in nearly every Annual Diversion Accounting report "Per capita sanitary flows are determined based on the service basin's water supply minus an assumed 10% consumptive loss." (e.g., USACE, 2004b, p. 27; USACE, 2016, p. 25) is no longer true. As noted earlier, Section 2.5 of the 5th TC report (Espey et al., 2004) speculated that consumptive loss in the Chicago area might be substantially higher than the 10% commonly assumed in the diversion accounting. The decreases in wastewater loadings for the Stickney and Calumet WRP drainage areas support the recommendations of the 5th TC.

Beginning with the WY 2000 Annual Diversion Accounting report (USACE, 2004b) and ending with the WY 2007 Annual Diversion Accounting report (USACE, 2011b) the following recommendation regarding the wastewater flow adjustment was included in the "Areas for Improvement" for the diversion accounting:

> "The actual model change was performed by indiscriminately increasing or decreasing all Population Equivalent (PE) parameters for a particular service area in order to approximate the average change in wastewater loading. In reality, the wastewater loading is a product of the PE and the per capita usage factor for each sub area. To more accurately model the actual wastewater loadings present, both the PE and per capita usage should be reassessed. Census populations and NIPC manufacturing numbers should be considered when developing revised PE and per capita usage estimates."

Such a re-evaluation may be worthwhile, however, it is more important to determine the revised consumptive use estimates for the various WRP drainage areas. Unfortunately, as noted earlier, a recent attempt to estimate consumptive use in the Chicago area using water supply records and detailed sewer flow monitoring for a subdivision in Elk Grove Village, Ill., proved inconclusive (Mills et al., 2014). Thus, it is unlikely that the 10% consumptive use assumption will change in the near future. The USACE seems to have recognized this difficulty and have dropped this issue from the "Areas for Improvement" in more recent Annual Diversion Accounting reports.

4.3 Tunnel Network (TNET) Model

4.3.1 Overview of the TNET model

The TNET model solves the full dynamic wave equations for momentum and flow conservation (also known as the de Saint Venant equations) in open channels and closed conduits (approximated as open channels using the Preissman slot technique), to simulate the movement of flow in the TARP tunnels. Because TNET solves the full dynamic equations of motion it is a sophisticated hydraulic model. The full dynamic equations of motion are based on the assumption of gradually varied flow for which use of a hydrostatic pressure distribution is valid. However, flows in the TARP tunnels are not always gradually varied. For example, water-hammer type pressure waves resulting from the rapid closure of gates or switching off pumps in the TARP system yield rapidly varied flow for which use of a hydrostatic pressure distribution is not valid. However, it should be noted that water hammer is rare because the TARP tunnels are seldom pressurized as the MWRDGC closes the drop shaft sluice gates (except the uncontrolled drop shafts) much earlier than when the tunnels reach full capacity (this is certain to change now that the TARP reservoirs have become operational). Further, the sudden influx of flow from the drop shafts also results in rapidly varied flow. This rapid influx has made it necessary to restrict the simulated drop shaft inflow to prevent the tunnel from pressurizing too rapidly such that computational instability would result (Mead and Hunt, 2002). The restriction on simulated inflows to the TARP tunnels is used to avoid computational "break downs" of the TNET model.

TNET also experiences computational instability at various times in the simulation and some of these can be solved by shortening the computational time step from 0.25 hr to 0.2, 0.1, or 0.05 hr (Mead and Hunt, 2002). These instabilities also may result from rapidly varied flow in the TARP tunnels that is more easily approximated as gradually varied flow at short time steps.

The modeling of the Des Plaines and Mainstream tunnels and the Calumet tunnels include designation of index points to control inflows to the systems (i.e. the inflow restrictions described previously), as well as controlling the pumpout cycling. During the simulation, the model compares the computed tunnel stage at each index point to the input parameters to determine if changes are necessary. The index points that control the drop shaft inflows are referred to as index drop shafts, and limit the inflow (expressed as a fraction of drop shaft capacity) relative to the computed water-surface elevation (CWSEL). The simulated pumping is controlled by the CWSEL at the downstream ends of the tunnels. The user-specified input parameters include the elevations at which the pumping starts and stops.

TNET primarily was developed for the design of the TARP reservoirs, and, thus, it has hypothetical pump operation rules coded into it. In the TNET model, the TARP pump station is modeled as a pumped diversion with 2 pumping levels from a small storage area that represents the wet shaft of the pump station (Burke, 1999). TNET cannot simulate variable head pumps, therefore, constant nominal pump capacities are incorporated in the model and all units are switched on whenever the water level in the tunnels exceeds designated levels. The simulated TARP pumpage is sometimes out of phase with the observed record. This could be the result of simulated pumpage occurring sooner and more frequently than actual pumpages in order to maintain computational stability during simulation (USACE, 2004a). Whereas hypothetical operation rules are necessary for system design, it seems that simulating the actual observed pump operation would more reliably evaluate TARP flows for determination of overflows. A suggested approach to use actual operation in simulation is discussed in detail in Section 4.5.5 of the 6th TC report (Espey et al., 2009). Such a change in approach would require major changes to TNET, thus, initially the 6th TC recommended comparing simulated and observed water-surface elevations in the TARP tunnels and adjusting inflows accordingly.

The 6th TC (Espey et al., 2009) further concluded that "**At present, whereas TNET is not "state-of-the-art" and it has computational difficulties during rapidly varied flow, it probably is sufficient for its current use in the diversion accounting…"** Over the last 10 years the USACE has made a number of improvements to TNET that have reduced the computational instabilities. The USACE also has attempted to verify the performance of TNET with available water level measurements in the TARP tunnels, but with limited success. However, the 7th TC (Espey et al., 2014) has correctly pointed out that the limited success is not just the result of limitations in TNET, but also is the result of limitations in the simulated inflows to TARP yielded by the HSPF and SCALP models. The improvements in TNET, the testing results, and comments of the 7th TC are discussed in detail in the following subsection.

4.3.2 TNET Improvements and Testing

Computational Improvements

The "Lake Michigan Diversion Accounting Manual of Procedures" (USACE, 2018) details the modifications to TNET that have been made since the 6th TC review to reduce the computational instabilities experienced in TNET simulations. These improvements are discussed in the following paragraphs.

USACE (2018, p. 48) notes that model instabilities often occur during times when there are minimal or zero flow depths in the tunnel. One way to circumvent this problem is to add a pilot channel. A pilot channel is a small rectangular channel located at the bottom of the tunnel cross section. Its purpose is to stabilize the model during low flow situations where the tunnel is likely to be in a near dry situation. Numerically, the TNET model needs to have some depth of water in the tunnel system or else the model will crash. A complimentary approach to deal with instabilities during low water periods is to change the pumping rate. Changing the pumping rate can leave more water in the tunnel, thus, providing a greater depth of water prior to the occurrence of the next storm event. The final option to deal with low water periods is to add a baseflow to the simulation. USACE (2018, p. 49) notes

> "A baseflow is included in the model for stabilization during periods of low or otherwise no-flow. Since this baseflow is artificial, it is removed at the downstream end of the TNET model. Modifying the baseflow and the initial flows in the tunnels can help stabilize the TNET models."

USACE (2018, p.47 & 50) described three other improvements to TNET to reduce computational instabilities.

- The model user can use a "warm start" for the TNET model. For a "warm start" the TNET model is started sometime in September, i.e. the month prior to the water year under analysis, in order to establish some flow in the tunnels before the true water year modeling begins. The TNET model iterates on the first time step the number specified at MAXINSTEPS. MAXINSTEPS can be varied to ensure that the simulation approaches a steady state at the start of the simulation. Although this sounds like an inconsequential change, it is often enough to stabilize the model (USACE, 2018, p. 47).
- Altering the index drop shaft's operating curves—tunnel elevation versus gate opening—can restrict or allow more overflow volume to reach the TARP system, and can help in stabilizing the TNET simulation. Another option for assisting in model stability is to provide additional index drop shafts to the TNET simulation (USACE, 2018, p. 47).
- Another method used to improve model stability is to include some additional rating curves at selected locations in the *.CS file. The rating curves are beneficial because they do not allow the TNET model to search for depths that lie below the invert of the tunnel system – resulting in a negative depth search (USACE, 2018, p. 50).

The 7th TC report (Espey et al., 2014, p. 61) also noted an important improvement to TNET to reduce computational instabilities:

> "The TNET source code was modified slightly in 2006, which generally improved the numeric stability of the model. The modification included the coding of drop shafts as small storage areas, producing a surge tower effect and mitigating some of the spurious numeric instabilities."

Finally, now that the TARP Thornton Reservoir became operational in the fall of 2015 (first taking flow on November 26, 2015) and Stage 1 of the TARP McCook Reservoir became operational on January 1, 2018 (first taking flow on February 18, 2018) the causes of flow

instabilities will be reduced. That is, Leon et al. (2009b) noted that the operation of the Thornton Reservoir will reduce the pressure transients in the Calumet system significantly.

However, it should be noted that the instabilities mitigated may not be "spurious numeric instabilities". According to Yen (1986, p. 59) three types of instability problems may be involved in obtaining numerical solutions of the de Saint-Venant equations for one-dimensional (1-D) unsteady flow in open channels and/or closed conduits. The first type is the natural phenomena of hydraulic instabilities (i.e. some flow conditions are naturally unstable) such as at transitions between (i) supercritical and subcritical flows, (ii) surcharge and open-channel flows in sewer pipes or culverts, and (iii) roll waves. The second type of instability comes from the assumptions made in deriving the differential equations to represent the physical phenomena (e.g., the de Saint-Venant equations are approximations to the exact momentum equations for 1-D unsteady flow in open channels (see Yen (1973)). The third type of instability is the numerical instability coming from numerical computations, irrespective of the other two types of instabilities, although they interact making the situation worse. Many of the instabilities encountered in the application of TNET to the TARP system are naturally unstable conditions. Yen (1986, p. 59) further noted about such natural phenomena "If the equations truly represent the flow, under certain situations the solution may become unstable, reflecting the true physical situation,". When dealing with hydraulic instabilities due to natural phenomena, the typical solution is to apply an approximation method that allows the computations to pass through the unstable conditions with the assumption that the critical condition occurs in a flow regime unaffected by the computational inaccuracies in the transition region where natural hydraulic instabilities are approximated. The previously listed approaches to reduce instability applied in TNET are examples of such approximations used to get the computations past the period of instabilities, and, thus, are important improvements to TNET.

Finally, with respect to the general performance and accuracy of TNET, USACE (2018, p. 51) notes: "Quite often, though, the comparisons simulated and recorded TARP pumpages are not acceptable after the first successful TNET run. In that event, some of the suggestions given in the Model Instability section of this manual should be implemented."

TNET Testing

As noted earlier, the 6th TC suggested an approach to use actual pump operation by changing the downstream boundary condition and to compare observed and simulated water levels in the TARP tunnels. Such a change in approach would require major changes to TNET, thus, initially the 6th TC recommended comparing simulated and observed water-surface elevations in the TARP tunnels and adjusting inflows accordingly. In response to this recommendation the USACE (2013a, p. 47) reported:

> "Although modification of the TNET model to incorporate these boundary conditions was not possible, a comparison between gage locations versus the modeled results was undertaken. After the initial attempt, the use of these points for calibration was not considered viable. Many of the monitored stations did not coincide with output locations of the existing model. Where there was overlap between observed and simulated points, it was found that the results did not compare well."

Unfortunately, the USACE did not retain any of the results of the comparison between observed and simulated water levels for this Committee to review.

With regard to the 6th TC's recommendation to compare simulated and observed water levels in the TARP tunnels, the 7th TC (Espey et al., 2014, p. 89) offered the following insightful comments:

> "While agreeing that the calibration and verification of the computed water-elevations within the tunnel are beneficial, the substantiative benefits of this comparison for LMDA purposes are more related to the hydrologic processes than the hydraulics of the tunnel system. The water surface elevation in the tunnel at any given location is a function of numerous phenomena, including:
>
> - The magnitude and intensity of the precipitation event.
> - The tunnel stage prior to the onset of the event, which is a function of the time since the most-recent pumpout.
> - The inflow to the TARP system, which is controlled by the gated dropshafts.
>
> In order for an effective calibration of the computed water-surface elevation, the simulation of these model inputs would need to be observed conditions and controls. These conditions (as simulated and observed) are often not synchronous, which limits the effectiveness of the calibration process. There is benefit however, in terms of comparison of the TNET's logic for controlling gated dropshafts and the pumping scheme. The minimization of simulation error introduced by TNET apart from the other modeling components is largely a function of the TARP operational scheme."

4.4 Current Modeling Summary

HSPF is a "state-of-the-art" model for continuous simulation of the rainfall-runoff process. SCALP is not a "state-of-the-art " model for hydraulic modeling of flow through the combined and separate sanitary sewer systems. However, SCALP is consistent with models commonly used in design and evaluation of sewer systems and treatment plants. TNET is a sophisticated hydraulic model of the TARP tunnels, but it assumes gradually varied flow, which is not always present in the tunnels leading to numerical instability and possible computational shut down although these instabilities have been reduced by modifications the USACE has made to TNET in recent years. Despite its limitations TNET is adequate for use in diversion accounting. **Thus, the models used to compute aspects of the diversion accounting meet the Supreme Court's requirement that the diversion accounting be done according to the "best current engineering practice and scientific knowledge" if these models are properly applied to the Lake Michigan and Des Plaines River watersheds.**

Despite the fact that the models meet the requirement of "best current engineering practice and scientific knowledge" the 7th TC (Espey et al., 2014) pointed out some key practical short-comings of the models. Two of the 7th TC recommendations are particularly important for the continued high quality performance of the LMDA. These recommendations are as follows (Espey et al., 2014):

> "6.2.1.1—The versions of HSPF, SCALP and TNET currently used in LMDA are DOS-based; may have future hardware and computer operating system issues.
>
> 6.2.1.3—The numerical processes employed by the H&H models are still current and appropriate. There are numerous newer models currently available that have similar

capabilities as the LMDA models currently in use. These newer models were developed for more modern computer technology, while older models are written in FORTRAN, which is increasingly difficult to support. Potential model replacements could be selected that are similar, but the development of model input and calibration would require significant effort in order to match or exceed the existing model system. The Corps should consider developing a plan for the eventual replacement of these models."

These two issues have exacerbated over the last 5 years. The following Section discusses the 8th TC's recommendations with respect to potential alternative models for SCALP and TNET. Since HSPF is fully supported by the USEPA it is regularly updated and can be easily run within USEPA's Better Assessment Science Integrating Point and Non-point Sources (BASINS) system, no alternative model is needed for HSPF. This is important because as noted earlier the accuracy of the HSPF model is much more important to the diversion computations than the other two models. Therefore, in future diversion accounting the most important model will not need to be changed in the course of "modernizing" the models used in the LMDA.

4.5 Updating/Replacement of Scalp and TNET

4.5.1 SCALP Updating

The USACE plans to take the original SCALP model and recode it into a more modern language and platform to facilitate the use of SCALP into the future. Whereas there are numerous models that perform similar modeling of combined sewer interceptor systems, such as the KOSIM model previously discussed, the effort necessary to apply and "calibrate/test" a new model to the interceptor systems feeding to the WRPs and TARP system in the diversion watersheds would be more substantial than that to recode and test the SCALP model.

The University of Illinois (U of I) has developed a suite of models to simulate runoff from the watersheds draining to the TARP systems, the combined sewer interceptors that carry the flows, and the deep tunnel system. For the Calumet TARP system hydrology layer (i.e. upper level pipes and surface runoff) are computed using the Illinois Urban Hydrology Model (IUHM) (Cantone et al., 2009). For the Calumet TARP system a USEPA Storm Water Management Model (SWMM) (Rossman, 2008) is used to model the interceptors. For the Mainstream/Des Plaines TARP system the Infoworks "City Model" is used for the upper level hydrology and some interceptors within the City of Chicago. IUHM is used for the upper level hydrology outside of the City of Chicago, and the interceptors are not modelled separately but are incorporated into the IUHM models for the Mainstream/Des Plaines TARP system (Andy Waratuke, written communication, 2/20/2019). Thus, the SWMM model of the Calumet TARP interceptors could be modified to accept runoff from HSPF and yield potential flows to the TARP model (see next subsection), but the U of I models for the interceptors in the Mainstream/Des Plaines TARP system would be difficult to combine with HSPF runoff computations. Thus, for consistency of modeling, it would be better to recode SCALP than to use the interceptor models used by the U of I.

The Committee supports the USACE's plan to recode and test the SCALP model for continued use in the LMDA.

4.5.2 TNET Replacement

As first noted in the 5th TC report (Espey et al., 2004) the University of Illinois (U of I) has been developing sophisticated hydraulic models for the TARP since the early 2000s under contract

with the MWRDGC. Three models developed by the U of I could potentially be useful to the USACE as they look to replace TNET, namely the (1) Illinois Transient Model (ITM), (2) Illinois Conveyance Analysis Program (ICAP), and (3) a USEPA Storm Water Management Model (SWMM) (Rossman, 2008) developed for the Calumet TARP system. Finally, the USACE also is considering developing new Hydrologic Engineering Center-River Analysis System (HEC-RAS) models of the TARP tunnels and reservoirs. The following subsections discuss these four options.

Illinois Transient Model (ITM)

The Illinois Transient Model (ITM) is a Finite Volume (FV) model capable of simulating free-surface flows, pressurized flows, and their simultaneous occurrence throughout a pipe network (mixed flows). The FV equations of mass and momentum conservation are solved using a Gudunov-type Scheme (GTS), which belongs to the family of shock-capturing methods that conserve mass and momentum and provide sharp resolution of discontinuities without spurious oscillations (León et al., 2006). Thus, a GTS is well suited to rapid transient flows in pipe systems. In the ITM, free-surface flows are modeled using the one-dimensional (1-D) dynamic-wave (i.e. de Saint Venant) equations, which are the same equations solved in TNET. The pressurized region is modeled using the classical compressible water hammer theory. The transitions between free-surface and pressurized flows are modeled by enforcing mass, momentum, and energy relations across the transitions (León et al., 2010). The ITM was developed to be able to simulate complex transient behavior that can be observed in TARP as a result of its complex layout and unique combination of free-surface and pressurized flow conditions (Luo et al., 2014, p. 3). Further, Luo et al. (2014, p. 25) state

> "The ITM model was developed to allow simulation of unsteady flow conditions that may result is transients/surges in the system that can potentially lead to geysering at dropshafts in the TARP system. ITM is designed to simulate the interaction of free-surface and pressurized flows, with the capability to track shocks and transients."

In the ITM the modeling of pressurized flows and transitions between free-surface and pressurized flows is substantially different from how these are modeled in TNET. In TNET the 1-D dynamic-wave equations are applied to pressurized flows and the transition between free-surface and pressurized flows is modeled using the Preissmann slot concept. The Preissmann slot is a fictitious slot added to the top of a pipe so that a fictitious free surface is present and the dynamic-wave equations can be applied. León et al. (2007, 2009a) point out that in order to properly model the pressurized pipe flows and transitions the gravity wave speed in the slot must be equal to the water hammer wave speed. This generally requires a very narrow slot. Yen (1986) reported that the combination of the large water level in the slot, representing high pressures of the type likely in the TARP system, and small slot width results in numerical instabilities. Such instabilities can be removed by making the slot wider. However, the wider slot width destroys the equivalence between the water hammer (pressurized) and the free-surface flow equations and results in incorrect wave speeds and pressure heads (León et al., 2007, 2009a). It is likely that TNET with its fixed slot width would be subject to numerical instabilities, incorrect wave speeds, or both. León et al. (2007, 2009a) developed a tapered entrance to the Preissmann slot that substantially reduced numerical instabilities while preserving wave speeds for fully pressurized flows. However, this approach was abandoned in ITM because the Preissman slot concept cannot model cases of sub-atmospheric pressure that can occur in full pipe flow as transient waves propagate through a pipe system.

The FV routines in the ITM have been extensively tested for a number of numerical and experimental test cases for (1) free-surface flow, (2) pressurized pipe flow, and (3) transitions between these flow conditions. León et al. (2006) demonstrated the capabilities of the ITM for five test cases of free-surface flow:

1) hydraulic bores,
2) the sudden opening of a gate separating two pools of still water in a frictionless horizontal sewer,
3) the sudden opening of a gate separating two pools of still water in a horizontal sewer with friction,
4) formation of roll waves, and
5) scaled experimental measurements of unstready flow in a pipe made by Ackers and Harrison (1964)

The results show that the GTS used in the ITM is significantly faster to execute that the fixed-grid Method of Characteristics (MOC) scheme with space-line interpolation, and in some cases, the accuracy produced by the GTS cannot be matched by the MOC scheme, even when a Courant number close to one (i.e. small Δt) and a large number of grids are used.

León et al. (2008) demonstrated the capabilities of the ITM for four test cases of pressurized pipe/water hammer flow:

1) instantaneous downstream valve closure in a frictionless horizontal pipe resulting in a strong transient and discontinuity,
2) gradual downstream valve closure in a frictionless horizontal pipe resulting in a strong transient and discontinuity,
3) instantaneous downstream valve closure in a frictionless horizontal pipe for two-phase flow, and
4) the two-phase flow experiments of Chaudhry et al. (1990).

In both (3) and (4) the two-phase flow could be modeled with the single equivalent fluid concept (i.e. the amount of gas in the conduit is small). The results for one-phase flows showed that, when a Courant number very close to 1.0 is used, the MOC scheme is more efficient than the ITM scheme. When the Courant number drops below about 0.95, the ITM scheme is more efficient than the MOC scheme and another FV scheme, especially for smooth transient flows (i.e. no discontinuities). The results for two-phase flows showed that the ITM scheme is much more efficient than the MOC scheme. The good performance for a wide range of Courant numbers is important because transient flows in sewer systems may result in a wide range of Courant number values (León et al., 2008).

León et al. (2010) demonstrated the capabilities of the ITM for four test cases of transitions between free-surface and pressurized flow:

1) a positive interface between free-surface and pressurized flow reversing direction and becoming a negative interface after the experiments of Trajkovic et al. (1999),
2) a case of sub-atmospheric pressures in the pressurized flow regime after the experiments of Vasconcelos et al. (2006),
3) air pocket entrapment with no air release after the experiments of Zhou (2000), and
4) air pocket entrapment with air release after the experiments of Zhou (2000).

The results showed that the proposed model is robust and it can accurately describe positive and negative interfaces between free-surface and pressurized flows, interface reversals, and it can simulate sub-atmospheric pressures in the pressurized flow regime.

The general conclusion of the foregoing tests is that the ITM represents an advance in computational efficiency, economy in terms of memory requirements, and improved accuracy relative to commonly used Method of Characteristics approaches. The ITM is capable of simulating dry bed flows, unsteady free-surface flows, unsteady pressurized flows, and the simultaneous occurrence of free-surface and pressurized flows in a pipe network. The ITM can accurately describe complex flow features, such as positive (moving toward the free-surface flow region) and negative (moving toward the pressurized flow region) interfaces between free-surface and pressurized flows including supercritical flow conditions, interface reversals, gradual and instantaneous valve closures, simple two-phase flows, and free-surface surges and roll waves. Thus, the ITM represents a substantial advance over TNET.

Despite its many powerful abilities the ITM has an important practical limitation. Luo et al. (2014, p. 25) state

> "ITM operates at minute time and spatial scales to allow it to capture the movement of high speed waves (on the order of the 1000 m/s). As a result of working at these time and spatial scales ITM has very slow run times, particularly under pressurized conditions. … ITM is not a model that should be used for extended period simulations such as those used for simulation in ICAP."

Finally, in the description of the ITM (Luo et al., 2014, p. D-4) gives the following Limitations: "Computation time is too long for practical application to many questions, such as optimizing gate and/or pump operations." **Thus, this Committee concludes that the ITM computation time would be far too long for use in the annual LMDA.** This conclusion is consistent with that of the 7th TC (Espey et al., 2014, p. iv) which states "The Seventh Committee concurs with the findings of the Sixth Committee, that the model (ITM) has impressive capabilities but may still be difficult to utilize within the current LMDA modeling system."

Illinois Conveyance Analysis Program (ICAP)

In the Annual Report for WY 2008 the USACE (2012, p. 11) stated "It is being evaluated that several of these models—in particular the Illinois Transient Model (ITM) and Illinois Conveyance Analysis Program (ICAP)—will take the place of the current TNET models." As noted previously, the ITM model is too computationally expensive for use in LMDA calculations. However, the ICAP model may be a good candidate to replace TNET because it has been fully set-up for both the Calumet and Mainstream/Des Plaines TARP systems on the basis of the most complete as-built geometric data and it includes consideration of the Thornton and McCook reservoirs which will affect the LMDA beginning with WYs 2016 and 2018, respectively. Finally, Luo et al. (2014, p. 24) note "ICAP is capable of performing extended period simulations aimed at identifying the ability of the TARP systems to fill and drain."

ICAP was developed primarily for analysis of the conveyance capacity of tunnels and reservoirs and to allow filling and dewatering of the tunnels and reservoirs to be simulated over extended periods (e.g., average water year) (Luo et al., 2014). Purposes/Objectives of ICAP are (Luo et al., 2014, p. D-2):

1) Determine the conveyance of a tunnel system
2) Evaluate the effect of different pumping rules
3) Determine reservoir performance
4) Determine CSO frequency and duration

In ICAP unsteady flows are simulated as step-wise steady. Luo et al. (2014, p. D-2) report routing results are good for time steps on the order of the gravity wave travel time through the system.

Luo et al. (2014, p. 25) state "Although capable of predicting the location of interceptor CSO's in the system, ICAP is not an unsteady-flow model and is unable to accurately predict volumes of CSO or simulate transient behavior." With respect to transient behavior/transient instabilities Oberg et al. (2017) notes the following with respect to ICAP "The effect of ignoring these instabilities is assumed to be negligible since for conveyance analyses the time steps of the model are orders of magnitude greater than the time scale of transient effects." The ability to accurately predict CSO volumes is related to the accuracy of the flow routing method used in ICAP. A number of tests have been done to compare the step-wise steady routing done in ICAP against the results of more sophisticated models applied to sewer pipes or the TARP system or laboratory data for sewer pipes. These comparisons are summarized in the following paragraphs.

Before reviewing the performance of the ICAP model, the routing technique applied in ICAP must be described. The Hydraulic Performance Graph (HPG) relates flow with upstream and downstream water-surface elevations (Yen and Gonzalez, 1994, 2000). Gonzalez-Castro (2000) was the first to use the HPG to represent the momentum equation in flow routing and he coupled this with a finite difference representation of the continuity equation to develop a step-wise steady flow routing approach. Gonzalez-Castro (2000) compared his model with laboratory data and the results of dynamic-wave routing for a number of case studies. He found the proposed method proved to be generally more accurate that the non-inertia wave approximation and less dependent on the selection of the time step than the dynamic-wave model.

Hoy et al. (2009) extended the flow routing method developed by Gonzalez-Castro (2000) by replacing the finite difference representation of the continuity equation with a Volume Performance Graph (VPG) representation. In developing the HPG, the water-surface profiles can be integrated over the entire reach length to obtain the volume of water stored in the reach for any constant flow and backwater condition in the reach, which Hoy et al. (2009) named the VPG. Hoy et al. (2009) showed that the approximation of the momentum of equation provided by the HPG can be coupled with the approximation of the continuity equation provided by the VPG to route unsteady flows through straight or branched channel reaches with accuracies approaching those of dynamic-wave models. Hoy et al. (2009) named this flow routing procedure the Storage Routing Model (SRM), and they found it has the following characteristics: (1) it is relatively independent of the time step selected, (2) it explicitly conserves mass, and (3) it incorporates junctions. The SRM is applied in ICAP.

A main limitation of the SRM method results from the level of approximation of the momentum equation, which implies the step-wise steady assumption is valid only when the effect of the local acceleration is small. Hoy et al. (2009, p. 34) note 'The bed slope term is two orders of magnitude greater than the local acceleration term for a case from Henderson (1966) for "an actual river" in a steep alluvial area with a "very fast rising flood".' Further, Hoy et al. (2009, p. 34) noted for subcritical flows, the acceleration terms typically will be much smaller that the

pressure term. Thus, the foregoing assumption of small local acceleration may be reasonable for most cases.

Hoy et al. (2009) tested the SRM model for the case of the laboratory sewer pipe data of Ackers and Harrison (1964), which were also used to the test the Full Equations (FEQ) model (Franz and Melching, 1997) which solves the dynamic-wave equations. Hoy et al. (2009, p. 51) found "SRM compares favorably with both the experimental results and those output from FEQ. As can be seen at each location, both the peak water depth and the time of the peak output from the SRM match closely the experimental results." Hoy et al. (2009) also tested the performance of the SRM to that of FEQ for a hypothetical pipe with the following characteristics: diameter = 5 ft, length = 5000 ft, slope = 0.0005, Manning's n = 0.015, a triangular input hydrograph, and two different downstream boundary conditions—a free overfall or a rating curve. The following table lists the accuracy of the SRM results compared to those obtained from FEQ.

Output Statistic	Free overfall (%)	Rating curve (%)
Absolute volume errors	< 0.2	< 2
Peak discharge errors	< 1	< 2
Peak timing errors	< 2	< 6
Peak depth errors	< 3	< 3

Hoy et al. (2009) also tested the performance of the SRM to that of FEQ for a hypothetical branched pipe network with the following characteristics: 4 pipes, 2 junctions, same pipe geometry as the previous hypothetic pipe, and a free overfall downstream boundary condition. They found the following key results:

> p. 62—"The results show that the SRM compares relatively well with the output from FEQ, but comparisons are not as accurate as when compared with an unbranched channel. In most cases, the SRM tends to overestimate the discharge and depth at their peak values."
>
> p. 63—"Comparison with a branched network showed that while the SRM could accurately simulate most flows, the conditions near the confluences were not accurately represented."

Catano-Lopera et al. (2009) compared the results of ICAP with those of the ITM for several storm events for the Calumet TARP system. The ultimate aim of the head (water-surface) elevation simulation with these models was investigating the likelihood of CSOs occurring on the Calumet TARP system for various storm scenarios. They found the following key results:

- For the April 24-26, 2007 storm event, ICAP underestimated maximum head within 4.5%,
- During the September 12-14, 2008 storm event, the maximum head difference at the selected nodes fell within 2.0% of the maximum heads computed with ITM (overestimate), and
- ICAP underestimated the peak heads during spikes occurring on September 13, 2008 between 2:00 and 7:00.

Catano-Lopera et al. (2009, p. 54) concluded that these results suggest "that the ICAP does, with all its limitations and assumptions, a very decent job when compared to the ITM model."

Zimmer et al. (2013) further tested the accuracy and usefulness of the SRM method. In this case, the most downstream subset of the North Branch interceptor system, consisting of four sewersheds in series along the southern bank of the North Branch Chicago River, was modeled. Results from the SRM model presented in Zimmer et al. (2013) are compared to USEPA SWMM simulation for all components of the interceptor system. The SWMM 5.0 model (Rossman, 2008) was implemented with dynamic-wave routing at a 0.5 s interval; conduit pressurization is represented by the Darcy-Weisbach equation; and both slope and Froude number are used to define supercritical flow. They found the following key results:

- At low flows (for the January 9, 2008, storm), the flow rates match well at all locations.
- For the increasing intensity of the April 25, 2007, event, most of the SRM and SWMM flow values are in close proximity except the initial peak at a location of 2,915 m upstream.
- Weir flows for both models, except for those at DS-NO1, are very close with a Nash-Sutcliffe efficiency, E, value above 0.94 for the storm events and gate positions considered.

Morales et al. (2017) tested the accuracy and usefulness of another model based on using the HPG for flow routing called TXC. TXC uses a step-wise steady flow routing approach based on: i) the energy and momentum equations applied to conduit hydraulics, and ii) the continuity equation for solving chamber levels and system storage. Conduit HPGs are used to help speed up the computations. TXC is capable of handling open channel and pressurized flow calculations. Thus, TXC is able to model various flow regimes, such as backwater, surcharging, and reverse flow. The purpose of this study was to predict the frequency and volume of CSOs as well as to evaluate the operation of gates and its effect in controlling the occurrence of CSOs in the Lawrence Avenue Tunnel (LAT) which was the first tunnel system built in Chicago. For the LAT, TXC was used to simulate the flow through the connecting structures, tunnel network, and the outfall to the river, taking into account the connectivity between all the elements, and including the operation of the gates.

The commercial model InfoWorks CS (IW) (Wallingford Software Ltd., 2006) also was applied to the LAT and was used to validate some of the results obtained with TXC. The MWRDGC monitors and keeps records of the CSOs occurrence from different outfalls in the TARP system including the one located at the downstream end of the LAT. For the study of Morales et al. (2017), the records of CSO occurrence during three historical storm events: August 22-26, 2007; September 12-16, 2008; and April 17-20, 2013, were provided by the MWRDGC. Based on TXC results, the system filled up quicker and the tunnel conduits reached surcharge conditions faster than IW results. The effect of unsteady routing was mostly felt during the period of initial tunnel filling, once the tunnels were full the difference between step-wise steady and unsteady flow routing is reduced. Morales et al. (2017) concluded (italics added):

> "Even though TXC is not an unsteady-flow model and its simplified flow assumptions might have led to misrepresenting the HGL and flow rates under highly unsteady flow conditions, this model proved effective in predicting volumes, frequency and duration of CSOs as it yields simulation results of existing conditions that match well with available MWRD records." *(note: HGL = Hydraulic Grade Line)*

To further validate the accuracy of ICAP, results were compared to results generated by the USEPA SWMM 5.0 hydraulic model (Rossman, 2008), using identical geometry and inflows for the Calumet TARP system (Oberg et al., 2017). For the SWMM 5.0 simulation, the model utilized the dynamic-wave routing model (the same as in TNET) including inertial terms, a 1 s

conduit lengthening step, and a 1 s routing time step. Oberg et al. (2017) obtained the following key findings (Committee comments in italics added):

- Comparison of results shows that for most cases, the ICAP model performs well with a maximum percent error of 8% (relative to the maximum head differential).
- ICAP flows peak sooner than the flow hydrographs in SWMM 5.0 simulation, which is attributable to the temporal assumptions made in ICAP. *However, peaking sooner may not affect the quality of the model results with respect to accurately estimating CSO volumes.*
- Most of the differences between the two models occur early in the simulation when the system is filling: this is primarily due to the configuration of the system with the main pipe having an adverse slope.
- ICAP overestimates depths during unsteady flows (e.g., the rising limb of storm events). A step-wise steady analysis means computed flow will lead the actual flow; the peak flow also does not diffuse, which would in reality occur due to the time of travel of the water. This is also seen as the hydrograph starts to fall: the diffusion of the peak flow does not occur in ICAP, translating into decreasing flow rates earlier than in the dynamic-wave model. *Again this may not affect the quality of model results with respect to accurately estimating CSO volumes.*
- While the results compare well in general, the ICAP model is not intended for simulation of unsteady storm events.
- A dynamic-wave model, such as SWMM, is both more precise and more efficient for simulating peak flow and head during unsteady flow events.

Whereas several of the studies considering the accuracy and usefulness of the step-wise steady flow routing procedure emphasize that the ICAP model is not intended for simulation of unsteady flow events, the studies comparing the results of step-wise steady flow routing using the procedure in ICAP (i.e. SRM or similar models, such as TXC) to dynamic-wave flow routing or laboratory data imply that the flow routing procedure used in ICAP may be sufficiently accurate to get a reasonable estimate of annual CSO volumes. Further, as it is currently implemented, ICAP can be run with "pseudo pumping operations" (Oberg et al., 2017), which could be made representative of actual pumping operations. Finally, ICAP is included in the MetroFlow suite of models developed by the U of I for simulating the Calumet and Mainstream/Des Plaines TARP systems (TARP Research Group, 2014). MetroFlow interfaces with the Hydrologic Engineering Center—Data Storage System (HEC-DSS) which will facilitate it receiving potential inflows from the SCALP model (original or re-coded).

ICAP has been developed on the basis of extensive as-built information on the Calumet and Mainstream/Des Plaines TARP systems and has been extensively tested for simulation of water levels, volumes of pumping, and storage in reservoirs, especially for the Calumet TARP system. **Thus, this Committee recommends that the USACE work together with the U of I to modify ICAP to compute CSOs using actual pump operations, and evaluate the potential usefulness of ICAP for LMDA computations.**

Storm Water Management Model (SWMM)

The USEPA SWMM model (Rossman, 2008) has been developed for the Calumet TARP system by the U of I and is included in the MetroFlow suite of models (TARP Research Group, 2014). This SWMM model solves the dynamic-wave equations for flow in closed conduits (similar to TNET). This SWMM model has been developed on the basis of extensive as-built information on the Calumet TARP system and has been extensively tested for simulation of water levels,

volumes of pumping, CSOs, and storage in reservoirs. Also, as part of MetroFlow the SWMM model for the Calumet TARP system can easily receive input from the SCALP model (original or re-coded) because of MetroFlow's compatibility with HEC-DSS. **Thus, this Committee recommends that the USACE work together with the U of I to evaluate the potential usefulness of the USEPA SWMM of the Calumet TARP system for LMDA computations.**

Hydrologic Engineering Center—River Analysis System (HEC-RAS)

The current plan of the USACE is to replace TNET with HEC-RAS (Brunner, 2016) models applied to the Calumet and Mainstream/Des Plaines TARP systems. It is assumed that similar procedures as used for TNET to mitigate computational instabilities (e.g., use of pilot channels, minimum flows, and storage at the drop shafts) will be applied in the HEC-RAS models developed for the TARP systems. Beginning with the WY 2006 Annual Diversion Accounting report, the USACE (2011a) began calling for a general housekeeping of the TNET model in the "Areas for Improvement". For this housekeeping the USACE (2011a, p. 49) noted the following tasks:

> "A general confirmation of the TNET model would involve checking and updating the structure of the model and confirming that it accurately matches existing conditions and is error free. A thorough check on the TNET model would require a detailed investigation of the as-builts of the tunnels and drop shafts, and would likely require coordination with the MWRDGC."

The U of I has coded all the as-built data into the ITEM, ICAP, and SWMM models of the TARP systems, thus, the USACE could coordinate with the U of I to get these data more efficiently then coordinating through the MWRDGC. Of course, the tasks of the TNET housekeeping would be direct tasks of the development of HEC-RAS models.

The Committee feels that building and testing new HEC-RAS models of the Calumet and Mainstream/Des Plaines TARP systems from scratch will be a large undertaking. Thus, this Committee feels that the LMDA funding might be more effectively spent if the existing, tested ICAP or SWMM models of the TARP system could be adapted for LMDA computations.

Model Testing

Whatever model is used to replace TNET—ICAP, SWMM, or HEC-RAS—it should be set up so that simulated water levels can be compared to measured water levels where available. The importance of this is related to Recommendation 6.2.8 of the 7th TC (Espey et al., 2014) which states

> "Tunnel water surface elevation data (from MWRDGC) may be of use to improve simulations, primarily to confirm dropshaft gate operation and pumping schemes employed by MWRDGC. Improvements to the simulation of dropshaft gate opening and pumping are critical to accurate simulation of tunnel flows, and ultimately the applicable S/R ratios."

The comparisons and measured and simulated water levels also can be used to get some appreciation of the overall quality of H&H models used for LMDA, keeping in mind that the simulated water levels are strongly influenced by the hydrologic simulations done using HSPF, the wastewater flows simulated in SCALP, and the determination of CSOs versus flows to TARP

determined by the interaction between SCALP and the TARP hydraulics model. Table 4.12 lists the water level sensors in the Calumet and Mainstream /Des Plaines TARP systems currently operated by the MWRDGC that can be used for the comparison of measured and simulated water levels.

Table 4.12. Locations, equipment, and installation time of water level sensors in the Tunnel and Reservoir Plan tunnels

System, Code	Instrument	Location	Installed
Mainstream			
G01	Pressure Transducer	Mainstream Pump Station	<2001
CS-2	SAAB TankRadar Pro	South of Stickney Water Reclamation Plant at River (South Mainstream)	2005
CS-4S	SAAB TankRadar Pro	Roosevelt and Wells (Mid Mainstream)	2006
Des Plaines			
G01	Pressure Transducer	Mainstream Pump Station	<2001
DS-D35	Bubbler	8010 W. 26 Street, North Riverside	<2001
CS-D02	Bubbler	200 N. Talcott, Park Ridge	<2001
Calumet			
Torrence			
GS-1 Upstream	Bubbler	130th and Stoney Island, Chicago, O'Brien Lock	2003
GS-1 Downstream	Bubbler	130th and Stoney Island, Chicago, O'Brien Lock	2003
Little Cal			
CWRP Wet Well	Pressure Transducer	Calumet Water Reclamation Plant	<2001

4.6 Comments on the Direct Application of Models in the Lake Michigan Diversion Accounting

4.6.1 Simulation of Runoff from the Des Plaines River Watershed

For the LMDA the runoff from the Des Plaines River watershed reaching the CAWS is among the primary flow deductions subtracted from the measured flow at Lemont, therefore, its correct computation, solely based on the output of the H&H models, is paramount. The simulated Des Plaines River watershed flows have several components:

1. Inflow and infiltration from the Upper Des Plaines River watershed which enters separate and combined sewers and becomes influent to the MWRDGC WRPs including inflow and infiltration that reaches the Des Plaines TARP system, which then is discharged to the CAWS,
2. Runoff from the Des Plaines River watershed which reaches the CSSC via CSOs,
3. Direct runoff from the Des Plaines River watershed to the CSSC (Des Plaines River watershed south of the CSSC),
4. Infiltration, inflow, and CSOs from the Lemont Service area,
5. Runoff from the Summit Conduit watershed, and
6. Spillover from the Des Plaines River into the CSSC.

No flow measurement data are available to confirm the accuracy of the simulation of these flows. The USGS installed an acoustic-Doppler velocity meter near the outlet of the Summit Conduit, which is a 2 mi^2 subsection of the diverted Des Plaines River watershed, but encountered many difficulties and inconsistent record (Johnson and Goodwin, 2012). So, in a practical sense the foregoing statement is correct. It has generally been reasoned that since the water budgets for the North Side and Stickney WRPs include the majority of the deductible Des Plaines River watershed runoff, the Des Plaines River watershed simulation is indirectly confirmed in WRP flow balance checks (Budgets 7 and 10) (USACE, 1994). Given the questions regarding the HSPF model parameters and the inability of the WRP balances to truly identify modeling inaccuracy (previously discussed), further examination of the Des Plaines River watershed runoff is necessary.

Ungaged lower Des Plaines River and Summit Conduit watersheds

The Annual Diversion Accounting reports include simulated annual flow values for the ungaged, separately sewered lower Des Plaines River watershed (57.91 mi^2) and the Summit Conduit watershed (2 mi^2). Annual flows for these areas may be estimated from the measured annual flows for Tinley and Midlothian creeks using a drainage area ratio (5.35 and 4.75 for Tinley and Midlothian creeks, respectively). Before the H&H models were applied to the diversion accounting, flows measured on Hart Ditch at Munster, Ind., were used to estimate the ungaged lower Des Plaines River watershed flows. In WYs 1983-1985, the Hart Ditch flows were used for comparison with the simulated lower Des Plaines River watershed flows. The Hart Ditch watershed is over 25 miles east of the lower Des Plaines River watershed, and the USACE (1990, p. 24) found "Because of the difference in localized precipitation between the watersheds, the Hart Ditch comparison does not provide any substantial insight on the accuracy of the lower Des Plaines runoff simulation." Thus, the USACE (1990, p. 25) discontinued the Hart Ditch comparison because "the Hart Ditch watershed does not provide a good verification and because the lower Des Plaines River watershed is indirectly verified by other (WRP) budgets". The Tinley and Midlothian creek watersheds are much closer to the lower Des Plaines River watershed (Tinley Creek borders the lower Des Plaines River watershed). Further, Shrestha and

Melching (2003) used flows from Midlothian Creek scaled by area ratio to estimate ungaged flows to the CAWS with good success in their hydraulic modeling of the CAWS. Therefore, the drainage area ratios to Tinley and Midlothian Creeks may be a good way to evaluate flows simulated for the lower Des Plaines River watershed.

Figure 4.3 shows the simulated annual discharges for the lower Des Plaines River and Summit Conduit watersheds and the annual discharges estimated for these watersheds by drainage area ratio with Tinley and Midlothian creeks. For nearly 70 percent of the years from WY 1984 to WY 1999 the simulated annual flow is less than the estimated annual flow, and the underestimations typically are in the range of 10-30 percent with average annual flows 5.4 and 12.8% low for Midlothian Creek and Tinley Creek, respectively. Thus, the Des Plaines River watershed flows may have been underestimated by the HSPF models used through WY 1999. After the CTE (2003a-c) recalibration of the grassland and impervious land parameters all the WYs between 2000 and 2005 were underestimated with average annual flows 19.1 and 19.2% low for Midlothian Creek and Tinley Creek, respectively. For WYs 2006 to 2015 the average annual flows are only 5.3 and 2.2% low for Midlothian Creek and Tinley Creek, respectively. This implies that the recalibrated forest land HSPF parameters derived by the USGS in 2008 have improved the estimates of flows from the ungaged lower Des Plaines and Summit Conduit watersheds.

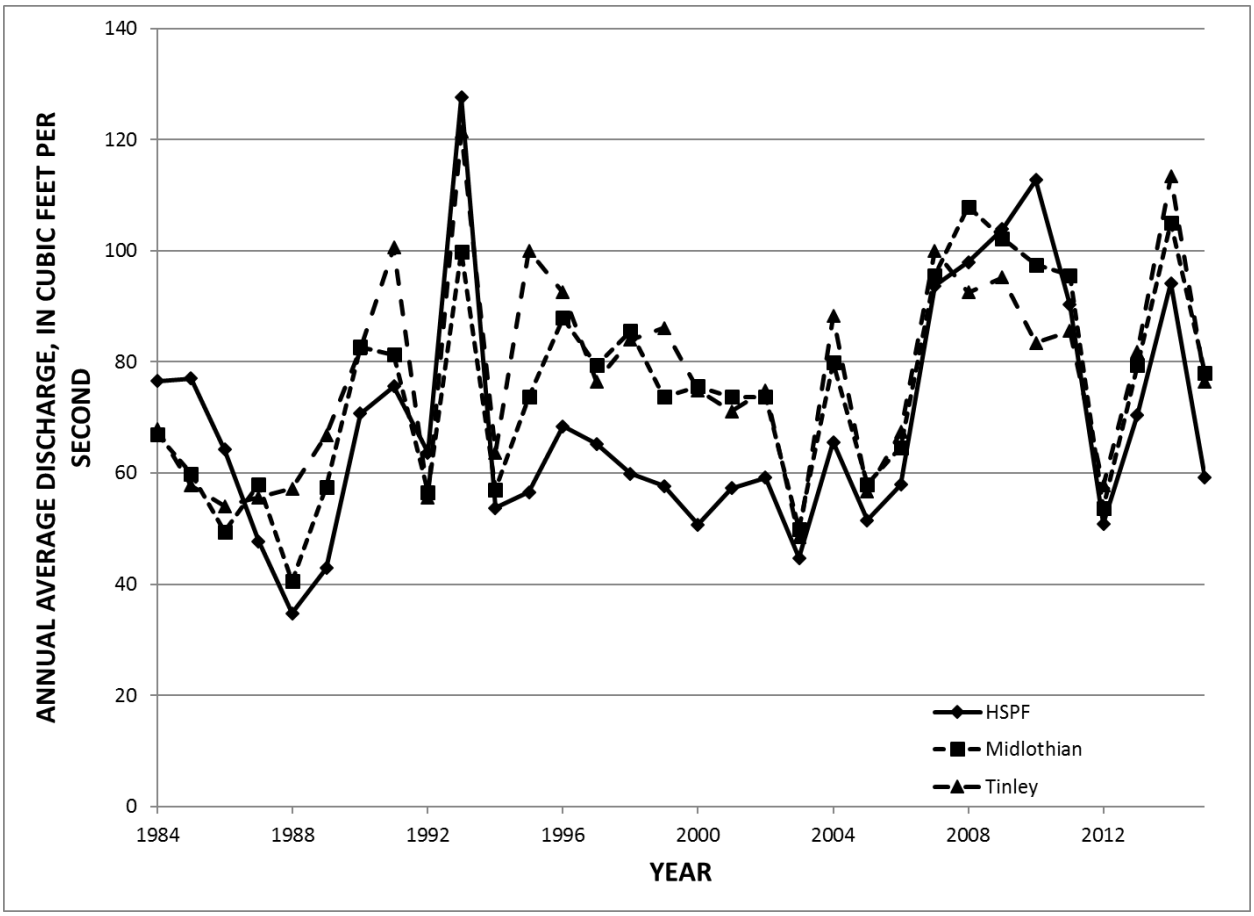


Figure 4.3. Comparison of annual average discharge for the ungaged, separately sewered lower Des Plaines River watershed and Summit Conduit simulated with the Hydrological

Simulation Program – Fortran (HSPF) and estimated by area ratio with Midlothian and Tinley creeks.

Upper Des Plaines Pump Station (UDPPS)

The Upper Des Plaines Pump Station (UDPPS) initially was considered to be a potential location where simulation of flows from the Des Plaines River watershed could be checked and, if necessary, used for model adjustment/calibration. However, as detailed in Section 4.5.1 of the 6th TC report (Espey et al., 2009), the orifice plates in the pump intakes and the related data recording had many potential errors.

In the "Areas for Improvement" section of the Annual Diversion Accounting reports it had long been recommended that (note: italics added) "Installation of better flow measurement equipment at the *(Upper Des Plaines)* pump station and measurement of bypass flows at the facility would allow for better model calibration." Such improved measurement equipment was installed by MWRDGC as part of a major rehabilitation of the pump station, the meters began collecting data on January 13, 2011. ISCO accQcomm Acoustic-Doppler Flow Meters (ADFMs) were installed in Upper Des Plaines Sewer Interceptor No. 3 upstream from the flow bypass point and in the intakes of each of the three pumps. This ADFM flow meter represents the "state-of-the-art" in sewer flow measurement (see Melching, 2006).

Once these ADFMs were active the USACE (2013b) began checking flow Budget 8 for comparing the measured and simulated flows at the UDPPS. For WYs 2011, 2012, and 2013 the USACE (2013b, 2015, 2016, respectively) noted that full records were not available for the UDPPS, but analysis was done based on the partial records available. The annual simulated to recorded (S/R) ratio at the UDPPS was 1.36, 1.16, and 1.23 for WYs 2011, 2012, and 2013, respectively. The correlation coefficient (R) between simulated and recorded flows at the UDPPS was 0.55, 0.32, and 0.74 for WYs 2011, 2012, and 2013, respectively. Whereas some of these statistics indicate satisfactory results, such as the S/R for WYs 2012 and 2013 and R for WY 2012, they are based on very limited measured data for each year (i.e. 226, 53, and 180 days for WYs 2011, 2012, and 2013, respectively). Thus, for the Annual Diversion Accounting reports for WYs 2014 and 2015 (USACE, 2019a,b) the USACE decided not compute fit statistics. For each of these years the Annual Diversion Accounting report states "Since the full records of the UDPPS were not available from the MWRDGC, a comparison of the simulated and recorded flows was not possible for WY"xx (where xx is 14 or 15 as appropriate).

Beginning in WY 2013 the Annual Diversion Accounting report added a subsection on the "MWRDGC Upper Des Plaines Pump Station" to the "Areas for Improvement". This subsection states (USACE, 2016, p. 46):

> "A review of the Upper Des Plaines pump station and its flow record indicates that the flow at the pump station is suspect and subject to operator error. Better flow measurements are needed at the pump station."

This statement is unclear and possibly incorrect. As noted earlier, ADFMs probably are the most accurate flow meters currently available for use in sewer pipes. An ad-hoc illustration of is provided next, On August 9, 2018, when this Committee visited the UDPPS, Dr. Melching took photographs of the flow read-outs for the inflow sewer pipe and the two pumps that were active on that day. These photographs are shown in Figure 4.4. Flow rates of 31.0 and 26.3 million gallons per day (MGD) are indicated for the two pumps and a flow rate of 58.8 MGD is indicated for the inflowing sewer pipe. The 2.6% difference between the sum of the pump flows and the inflowing sewer pipe flow indicates reasonable agreement among the meters (especially

considering that the photographs were taken at slightly different times). So, the quality of the flow measurements is reasonable. The larger problem is that the MWRDGC does not electronically record and store these values on a constant, continuous basis, hence the large gaps in the available data. Further, the flow rates are manually observed and recorded, similar to how the Committee observed the values shown in Figure. 4.4. The 8th TC inquired with Mr. Ed Staudacher of the MWRDGC (who acted as the TC's tour guide to various MWRDGC facilities) if the MWRDGC has any plans for developing a permanent record of flows from all the flow meters at the UDPPS. Mr. Staudacher's reply (written communication, August 16, 2018) was "We do not have schedule at this time for recording the data from the flow meters. It has been discussed with the DCS group and on their task list." **Given the importance of these data to the LMDA, the USACE should do whatever it can to encourage the MWRDGC to move the recording of the UDPPS data up on the DCS group task list.**

With regard to the "MWRDGC Upper Des Plaines Pump Station" the "Areas for Improvement" further state (USACE, 2016, p. 46):

> "With better flow measurements, this site will become the most important point for calibrating and verifying the simulation models for the Des Plaines watershed. … The Upper Des Plaines Pump Station is the only point at which a model of the inflow infiltration can be calibrated and extrapolated to the remaining portions of the Des Plaines River watershed."

The foregoing statement is not completely true. The UDPPS drainage area has no forest cover, and, thus, this site is not representative of the lower Des Plaines River watershed which has nearly 30% forest cover.

Finally, the subsection "MWRDGC Upper Des Plaines Pump Station" in the "Areas for Improvement" further states (USACE, 2016, p. 46-47):

> "MWRDGC completed replacement of the pumps and flow meters at the pump station in 2011 as part of the rehabilitation plan. In response to a request made by the USACE, MWRDGC agreed to install an acoustic flow meter in the intercepting sewer upstream from the pump station and a new TARP connecting structure. This additional meter will not only independently check flow measured through the pumps, but provide continuing data in case the pump station requires repairs in the future."

This meter in the intercepting sewer was already installed (as discussed earlier) by the MWRDGC as part of the rehabilitation of the UDPPS. The foregoing statement should be modified (or removed) in future Annual Diversion Accounting reports.

Des Plaines River spillover

In the Annual Diversion Accounting report for WY 2008 the USACE (2012) reported:

> "As a result of excessive rainfall that occurred during September 2008, the Des Plaines River overflowed its banks near Romeoville, diverting a portion of its flow into the CSSC. It was therefore necessary to model this system in order to estimate the net volume transferred between the two systems as it constitutes a diversion creditable to the State of Illinois."

Figure 4.4. The flow through the active pumps (top two photographs) and the flow through the inflow sewer (bottom photograph) at the Upper Des Plaines Pump Station measured using Acoustic Doppler Flow Meters (ADFMs) on the morning of August 9, 2018

The USACE (2012, p. 10) noted that using a HEC-RAS model (Brunner, 2016) originally developed for the Great Lakes Mississippi River Interbasin Study (GLMRIS) storm events will be simulated and a resulting hourly flow rate spilling to the CSSC will be determined. These flow rate values will then be converted to volumes and incorporated into Column 6 of the LMDA computation as an additional diversion from the Des Plaines River watershed. Specifically, to compute the spillover hydrologic inputs developed using an HEC-HMS model (Scharffenberg et al., 2018) and overflow constituents from the TNET model for the Des Plaines River watershed are used to complete an unsteady HEC-RAS simulation of the reach. A lateral weir simulates the overflow of the Des Plaines River from which an average daily discharge is defined (USACE, 2018, p. 9).

Whereas the spillover from the Des Plaines River directly to the CSSC was first detected during the flooding in September 2008, computation of the spillover was not done as part of the LMDA for WY 2008. However, the spillover computation has been done for WYs 2009-2015. Table 4.13 lists the computed spillover amount and the dates of the spillover for each of WYs 2009-2015. Table 4.13 also lists the peak daily flow at the USGS streamflow gage on the Des Plaines River at Riverside which is upstream of the spillover location. As can be seen in the table the amount of spillover is a tiny fraction of the peak flow of the floods that lead to spillover. Thus, no improvements can be made to the calibration of the HEC-HMS, TNET, and HEC-RAS models used to determine the magnitude of the spillover because the magnitude of the spillover is far smaller than the calibration tolerance for these models. **However, the USACE has considered collecting more detailed and accurate topographic data on the pathway between the Des Plaines River and the CSSC through which spillovers can pass. This Committee fully supports the USACE's attempts to better define the geometry of the lateral weir through which spillover events could pass.**

Table 4.13. Computed amount and time of spillover directly from the Des Plaines River to the Chicago Sanitary and Ship Canal and the measured daily peak flows on the Des Plaines River at Riverside during the spillover period (note: n/a means not applicable)

Water Year	Date of Overflow	Amount (cfs)	Peak Daily Flow in Des Plaines River during spillover period (cfs)
2008	September	Not determined	8910
2009		No spillover	n/a
2010	July 23-25	3.3	6720
2011	July 23-25	7.5	6360
2012		No spillover	n/a
2013	April 18-25	18.1	10700
2014	June 14-20; August 22-26	0.8	1950; 3550
2015	June 14-20	0.8	5800

4.6.2 Groundwater Infiltration in the Calumet TARP System

The 4th TC (Espey et al., 2001, p. 40) recommended that the analysis of groundwater infiltration into the Calumet TARP tunnels needs to be reviewed using data from more than one year, and the 5th and 6th TCs re-iterated this suggestion. This Committee further re-iterates this suggestion. The simulated groundwater seepage into the Calumet TARP tunnels is listed below.

1987	17.3	1993	6.7	1999	11.2	2005	12.4	2011	16.9
1988	17.0	1994	3.5	2000	13.2	2006	14.2	2012	8.5
1989	6.7	1995	6.5	2001	14.6	2007	9.3	2013	8.2
1990	6.6	1996	9.5	2002	11.0	2008	20.6	2014	14.1
1991	21.4	1997	9.5	2003	11.2	2009	24.5	2015	14.3
1992	21.1	1998	11.3	2004	12.4	2010	18.7		

The procedure for estimating the groundwater infiltration into the Calumet TARP tunnels was adjusted in 1989. Thus, the average of values from 1989 to 2015, 12.8 cfs, is representative of the current estimation procedures. Also from 1989 to 2015 the simulated annual mean flow for the Calumet TARP system was consistently less than the measured annual mean flow with a S/R ratio of 0.830 over this period or an average annual shortfall of 9.5 cfs.

In their revision of the H&H models of the Calumet watershed Burke (1999, p. 27) noted the contribution of groundwater seepage into the tunnels through the lining and joints "has yet to be accurately determined. MWRDGC estimate seepage flow in the range 7 to 30 cfs." Burke (1999, p. 30) further stated

> "Presently there is no reliable method for quantifying the amount of infiltration into the tunnels. For modeling purposes, base flow was included in the model as steady flow hydrographs of 2.5 to 5.0 cfs, resulting into a combined flow of about 32.5 cfs at the TARP pump station. The flow of 32.5 cfs was used as it is close to the MWRDGC estimates."

Since the TNET model used in design applied a base groundwater inflow of 32.5 cfs at the pump station and the average annual shortfall in Calumet TARP flows is 9.5 cfs from 1989-2015, a review of the value used in the diversion accounting modeling is needed since current estimates are around 20 cfs less than the value used by Burke (1999).

One factor complicating the review of groundwater inflows is that low flows to the Calumet TARP tunnels are affected by directly connected sanitary sewers. The USACE (2004b, p. 47) reports:

> "In the Calumet system, some sanitary sewers are connected to TARP. These sewers must be accurately accounted for in the modeling of groundwater infiltration since they contribute to baseflow, or dry weather flow, into TARP. Currently, some uncertainty remains as to the connection of the separately sewered areas. For accurate modeling of the Calumet TARP system, these connections need to be verified and adjusted if necessary."

Further, on page A.5, the USACE (2004b) reports:

> "Since actual boundaries have not been mapped for those areas, some assumptions as to the location of the separate sewer areas were made. These assumptions were necessary since effective (instead of actual) areas are used for separate sewer areas in the SCALP model. These assumptions will remain until separately sewered areas are modeled such

> that actual areas are used instead of effective areas in the hydraulic models. This has been discussed in the WY 90 diversion accounting report."

In response to the suggestions of the 4th and 5th TCs the USACE recognized the undersimulation of low flows in the Calumet TARP system, but they attributed this problem to improper approximation of drop shaft operations for the inflow from these separately sewered areas. The USACE (2004b, p. 35) stated:

> "The dropshaft operation data were changed significantly, and resulted in closing of the inflows at a higher elevation. The TNET model results from the early iterations indicated that the simulated capture (and pumpout) volumes were much lower than observed. This was determined by comparing the weekly average pumping volumes of simulated vs. observed, even though this comparison also includes the variance due to the hydrologic modeling."

By closing inflows at a higher elevation the gate closing scheme was modified to cause the model to capture more inflows without pressurizing the system. The improvement in the annual S/R ratios and correlation coefficients is shown below:

Output Statistic	WY 1989-1999	WY 2000-2015
Average Annual S/R	0.695	0.923
Average Annual Correlation of Weekly Volumes	0.565	0.590

The 8th TC agrees that the modified gate operations have substantially improved the simulation quality, but still wonders if the changed groundwater inflow could achieve the same or better improvements. The USACE also seems to be aware of this possibility, as the "Areas for Improvement" in the Annual Diversion Accounting reports from WY 2006 (USACE, 2011a) to WY 2015 (2019b) include the following statements:

> "Low flows, or dry weather flows, must be modeled accurately so that groundwater infiltration into the two TARP systems is properly modeled. These flows constitute a substantial deduction to the diversion and are included in the deductible groundwater flows in Column 4. Therefore, the estimate of simulated groundwater infiltration rates need to be updated periodically to better match the simulated to the recorded dry weather flow."

and

> "In the Calumet system, some sanitary sewers are connected to TARP. These sewers must be accurately accounted for in the modeling of groundwater infiltration since they contribute to baseflow, or dry weather flow, into TARP. Currently, some uncertainty remains as to the connection of the separately sewered areas. For accurate modeling of the Calumet TARP system, these connections need to be verified and adjusted if necessary."

The U of I has developed detailed hydraulic models of the TARP system (see for example, Catano-Lopera et al., 2009). As part of their studies the U of I team developed a detailed inventory of the various TARP drainage areas. The USACE should check with the U of I to see if these service area delineations for the Calumet TARP system could aid in the definitive

delineation of the directly connected sanitary sewers. This delineation would allow the sanitary flow and groundwater contributions to low flows to the Calumet TARP system to be clearly determined.

Finally, the Annual Diversion Accounting reports from WY 2006 (USACE, 2011a) to WY 2015 (2019b) include the following statement with respect to the Calumet TARP system:

> "it was difficult to improve the correlation. However, as the system is presently modeled, this does not impact the computed diversion, unless a substantial portion of the under-simulation results from under-estimated groundwater inflow, …"

In this case a substantial portion of the undersimulation could be underestimated groundwater inflow, so it is possible that the correlation coefficient also could improve with adjustments in the groundwater inflow.

4.6.3 Indiana Water Supply Reaching Illinois

Through the Grand Calumet River

The Grand Calumet River has a summit, i.e., a prominent height within the river channel. This feature is not (or rarely) found in natural channels. On one side of the summit, the flow is toward Lake Michigan and on the other side the flow is westward into Illinois. The position of this summit is variable and dependent on the elevation of Lake Michigan.

Prior to WY 1991 flow in the Grand Calumet River reaching Illinois was estimated on the basis of a statistical relation for which the independent variables were the elevation of Lake Michigan and the flow in Hart Ditch (USACE, 1990). This flow then was compared to the daily sum of water supply pumpage from Lake Michigan to East Chicago, Hammond, and Whiting, Indiana. If the Grand Calumet River flow was greater than the combined water supply pumpage, the daily deduction from the Romeoville flow was set equal to the combined water supply pumpage. If the Grand Calumet River flow was less than the combined water supply pumpage, the daily deduction from the Romeoville flow was set equal to the estimated Grand Calumet River flow. In WY 1992, a streamflow gage was added on the Grand Calumet River at Hohman Avenue near the Illinois-Indiana border by the USGS. The computation of the deduction continued in the same way with the measured Grand Calumet River flow replacing the estimated Grand Calumet River flow. No consideration of consumptive use was made in these computations.

Beginning in WY 1993, the deduction was computed on the basis of relations involving Lake Michigan elevations and the water supply pumpage for Hammond, Whiting, and East Chicago. These relations were determined on the basis of an UNET hydraulic model developed for the Grand Calumet River system (USACE, 1997a). The modeling study found that the summit normally occurs between river miles 5.54 and 4.229 (USACE, 1997a) where the Little Calumet River is river mile 0. The Hammond Sewage Treatment Plant (STP) is located near river mile 4.25. Thus, most of the time Hammond and Whiting water supply pumpage from Lake Michigan reaching this STP flows to Illinois and is a deduction from the discharge measured at Romeoville. The East Chicago STP is located near river mile 5.40. Thus, only during times of high lake levels does East Chicago water supply pumpage from Lake Michigan reaching this STP flow to Illinois. Beginning in WY 1997 the water supply pumpage has been adjusted using a 10 percent consumptive use factor (USACE, 2001).

In October 2009, the USEPA began remedial dredging on the West Branch of the Grand Calumet River, which is the flow path for Indiana water supply to the CAWS. As part of this operation,

sheet pile was driven across the channel producing a partial closure. The original plan was to use weirs to maintain water levels during dredging and to restore the bed to pre-dredging levels. Figure 4.5 shows the sheet pile in the reach immediately upstream of the Hohman Avenue gage and the drained channel being prepared for dredging in February 2011. The dredging project was completed in 2016.

After completion of the dredging project it appears that the flow through the Grand Calumet River into Illinois *has increased substantially*. Figure 4.6 compares the flow downstream from the Hohman Avenue gage before (January 17, 2008) and after (December 12, 2018) the USEPA dredging project. From this figure it is clear that the winter flow after the dredging project is much higher than that before the dredging project. The USGS also was making discharge measurements on the Grand Calumet River at Columbia Avenue on December 12, 2018. The measured flow near the time of acquiring the photo in Figure 4.6 was 176 cfs. Similarly, in July and August 2017, additional flow measurements on the Grand Calumet River made by the USGS found high flows in the range of 177-398 cfs. Daily flow data are available at Hohman Avenue from October 1, 1991 to October 20, 2015 (the record was discontinued when the Hohman Avenue Bridge was rebuilt as part of the dredging project). The flows measured post-dredging rank among the highest 15 days over the 24 years of record corresponding to flows that are exceeded less than 0.2 % of the time in the period before the dredging project was completed.

Figure 4.5. Grand Calumet River immediately upstream of the Hohman Avenue gage with sheet pile weirs in place being prepared for dredging, February 24, 2011 (photo provided by Paul Buszka, USGS)

Figure 4.6. Flow in the Grand Calumet River downstream from the Hohman Avenue gage before (January 17, 2008, top) and after (December 12, 2018, bottom) the USEPA dredging project.

The reasons for the high post-dredging flow rates could be attributed to:

(A) the improved conveyance in the post-dredging channel,
(B) the high water levels in Lake Michigan in recent years, or
(C) a combination of A and B.

To get a better understanding of flow patterns in the Grand Calumet River from late February 2017 to August 2018 the USGS established a network of five Mini Diver pressure transducers to measure water-surface elevation on the Grand Calumet River reach; two transducers on the East Branch (EB) at Kennedy Avenue and Cline Avenue, and three transducers on the West Branch (WB) at Torrence Avenue, Columbia Avenue, and Indianapolis Boulevard. The readings of these five transducers were combined with the water-surface elevation data acquired at the USGS stream gages Grand Calumet River at Hohman Avenue at Hammond, Ind., Grand Calumet River at Industrial Highway at Gary, Ind., (East Branch), and Indiana Harbor Canal at East Chicago, Ind., to explore the water-surface profiles in the Grand Calumet River system. Figure 4.7 shows the locations of these water-surface elevation measurement points. Figure 4.8 shows a sample water-surface elevation profile for April 30, 2017. It can be noticed in this figure that the water-surface elevation at the Indiana Harbor Canal is higher than that at Indianapolis Avenue on the West Branch. These example profiles indicate the possibility that water from Lake Michigan and/or the East Branch (which would include treated Indiana water supply from the Gary STP) could reach Illinois.

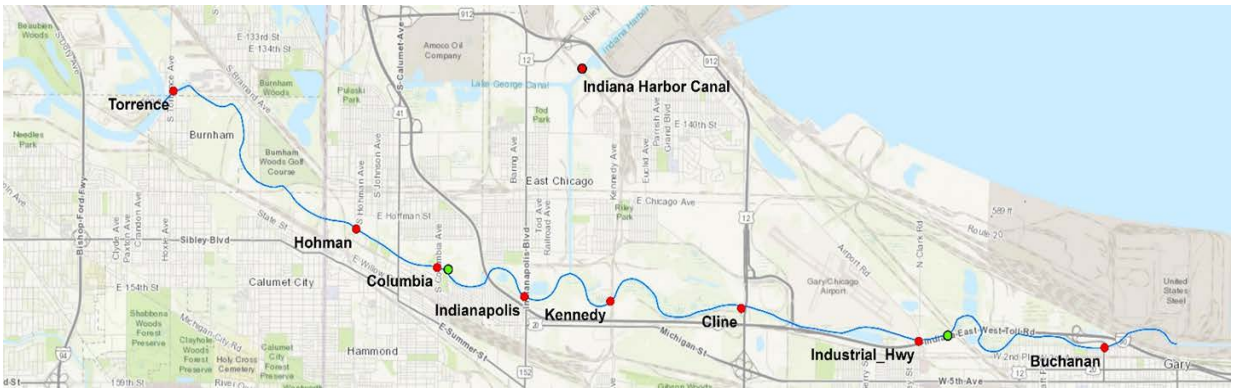


Figure 4.7. Locations of the sensors used to evaluate the water-surface profiles on the Grand Calumet River system (provided by the USGS)

The USGS has explored the possibility of water from Lake Michigan and/or the East Branch reaching the West Branch and possibly Illinois on the basis of the measured water-surface elevations. The results of this exploration were presented to the Committee by Dr. Jessica LeRoy of the USGS on December 12, 2018. The subsequent discussion is based on the presentation provided to the Committee. The comparison of the water levels at the Indiana Harbor Canal and Indianapolis Boulevard showed that in the vast majority of cases the water level at the Indiana Harbor Canal was lower than that at Indianapolis Avenue. The times when the water levels at the Indiana Harbor Canal were higher than those at Indianapolis Avenue appeared to be the result of short-term surges in water level rather than continuous periods that might result in flow being directed from Lake Michigan to the West Branch. The comparison of the water levels at the Kennedy Avenue (EB) and Indianapolis Boulevard (WB) showed that for the vast majority of

time the water surface slopes away from Illinois. However, when Lake Michigan is at higher levels, the water surface slopes away from Illinois between Indianapolis Boulevard and Kennedy Avenue, but the slope reduces with increasing Lake Michigan water levels. At very high Lake Michigan levels the water surface between Kennedy Avenue and Indianapolis Boulevard slopes toward Illinois.

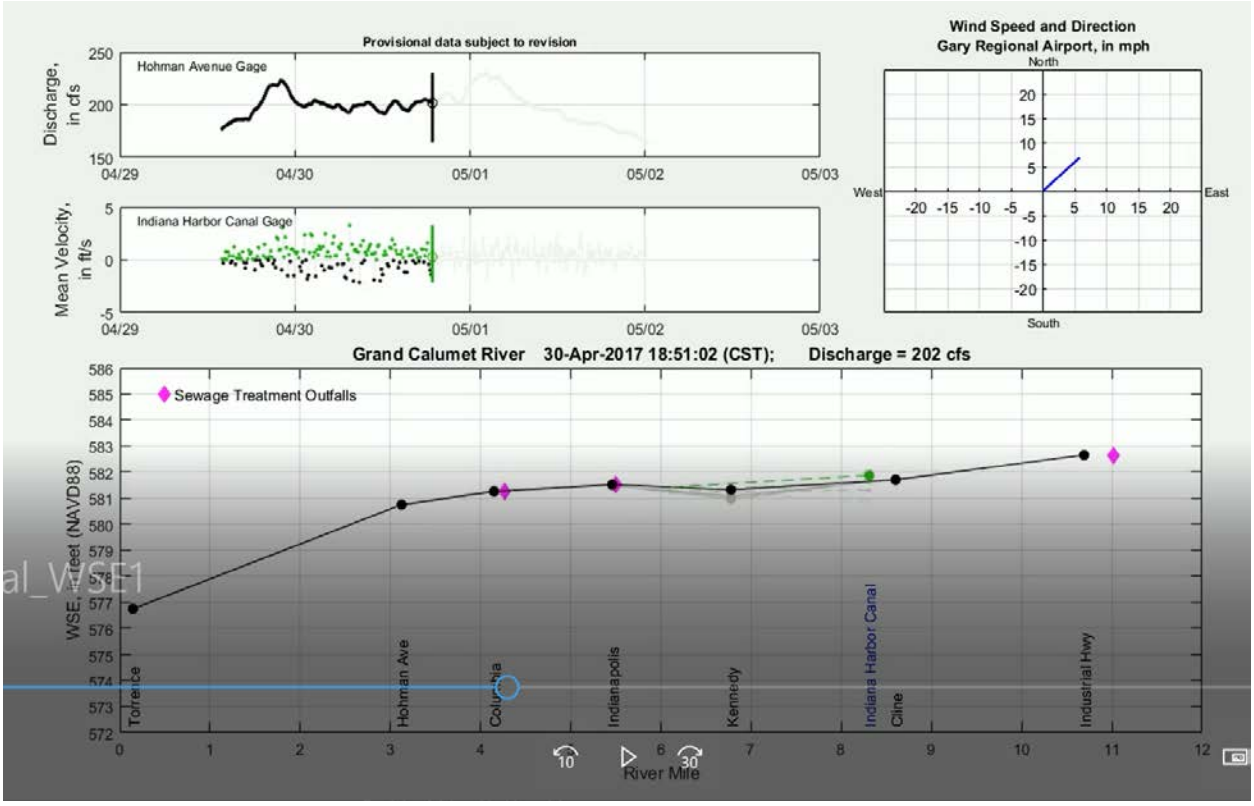


Figure 4.8. Example water-surface profile on the Grand Calument River system for April 30, 2017 (provided by the USGS)

The high flows in the WB Grand Calumet River after dredging, the higher water levels in Lake Michigan in recent years, and the possibility of flows from the EB reaching the WB indicate that a complete re-evaluation of flows from Indiana reaching Illinois needs to be done using a new hydraulic model of the Grand Calumet River system. The 7th TC (Espey et al., 2014) recommended that "After dredging is complete, HEC-RAS model should be updated and recalibrated. Regression equations used for LMDA should be reviewed and revised as appropriate." The Committee fully concurs with the recommendation that a new HEC-RAS model should be developed for the post-dredging Grand Calumet River system. Further, the derivation of new equations should be completely detailed in a report for review by a future Technical Committee for Review of Lake Michigan Diversion Accounting. The U of I is developing a HEC-RAS model of the Grand Calumet River system for the MWRDGC. Thus, the Committee recommends that the USACE should work together with the U of I in the development of the new HEC-RAS model and based of the modeling outcome to develop new relations between Lake Michigan water levels and Indiana water supply reaching the CAWS through the Grand Calumet River for possible boundary condition scenarios.

An additional complexity in understanding the flow in the Grand Calumet River is that the gaging stations on this reach are also problematic. For example, The streamflow gage at Hohman Avenue has always been known to be a difficult location to determine reliable flow estimates. For WYs 2002-2013 the flow record at this site was rated "poor" and in WYs 2014 and 2015 this rating improved to "fair except for estimated discharge values, which are poor". The USGS Station Analysis for WY 2003 for this station states:

> "Since this station was established, there has been much scatter in discharge measurements requiring changes in the rating and frequent shifting, due most likely to backwater from various sources including heavy week growth in the channel and debris on the culverts. … The exact cause of a shift has always been difficult to ascertain because of complex control."

The USGS Station Analysis for WY 2015 offers additional insight:

> "The control for this station at all stages appears to be the channel and the four roughly circular corrugated metal culverts (always subject to tail water control) that pass under the Railroad bridge downstream of the gage, and the channel downstream of the culverts."

The reconstruction of the bridge at Hohman Avenue and the clearing of the downstream channel might produce an improved rating Hohman Avenue streamgage station. However, the preservation of the railroad bridge culverts downstream from the station might complicate the hydraulics at this site.

In an effort to develop reliable measurements in this river reach, the USGS installed a new temporary gaging station at Columbia Avenue (located 1 mile upstream from Hohman Avenue) in October 2018. This gage is composed of a side-looking Acoustic Doppler Velocity Meter (ADVM, Sontek SL3000) mounted on a 2-in. diameter aluminum pipe on the left bank upstream culvert guidewall 20 ft upstream of Columbia Avenue. This Committee visited the new gaging site on December 12, 2018, when a calibration measurement at this location was acquired. The Committee commends the USGS on the establishment of this new gage, and it encourages the USACE to evaluate the use of the Columbia Avenue gage for the development of new relations to determine Indiana water supply reaching the CAWS (to be used as a deduction in the LMDA). This recommendation is necessary in view of the history of poor rating conditions at the Hohman Avenue gage previously discussed.

Through the Little Calumet River

In the case of the Little Calumet River, a drainage divide exists east of the confluence with Hart Ditch. Therefore, flows from Hart Ditch, including virtually all dry weather flows, normally flow westward into Illinois. Under high flow conditions, the drainage divide may shift westward and a portion of the Hart Ditch flows may be diverted eastward to Burns Ditch and ultimately Lake Michigan. However, it is believed that the occurrence of the shift in the drainage divide is infrequent and the flow that is diverted eastward is insignificant. Therefore, it is assumed that all effluent discharged into Hart Ditch and the Little Calumet River west of the divide flows westward. The 6th TC (Espey et al., 2009) recommended that the USACE should initiate a project to evaluate the position of the flow divide on the Little Calumet River. This Committee reiterates this suggestion, and it notes that the U of I is developing new models of the Little Calumet River for the MWRDGC. Thus, the USACE could consult with the U of I on the issue of the flow divide in the Little Calumet River.

5.0 Flow Measurement

5.1 Overview

This section of the Eighth Technical Committee (labeled herein for convenience as the 8th TC) report is aimed at reviewing the measurement protocols for all monitoring activities supporting the Lake Michigan Diversion Accounting (LMDA) including the statistical analysis of the flow data and estimation of the measurement uncertainties. Finally, recommendations are made for upgrading both the measurement systems and the ancillary analysis at the level of **"the best current engineering practice and scientific knowledge"** in the hydrometric area. For this purpose, the 8th TC critically examined selected flow measurement components, techniques, and instrumentation used in the Lake Michigan diversion accounting. Special attention was dedicated to the analysis of the data acquisition issues observed in the operation of the precipitation network, the status of all streamflow gaging stations in the Chicago watershed, and water abstractions from Lake Michigan. Besides the review of the previous reports of the U.S. Army Corps of Engineers (USACE) and various monitoring agencies involved in the accounting, the 8th TC requested special presentations on these flow measurement components, follow up reports, and documentation through site visits as described in Section 2. The aforementioned activities led the Committee to conclude that, excepting the issues with funding of the streamflow monitoring at the 9 USGS stations (stage and discharge) and the advancements made at the Lemont gaging station, there are no significant changes in monitoring, operation, and processing of the acquired data of any of the other diversion accounting components.

The main focus of the analysis in this section are the measurements of streamflow in the LMDA system as a whole and the quality of the monitoring conducted at the Lemont station. The distribution of the USGS discharge measurement and controlling works within Chicago Area Waterway System (CAWS) is provided in Figure 5.1. The primary reason for monitoring flows within the CAWS is to maintain compliance with the U.S. Supreme Court decree on Lake Michigan Diversion accounting (Duncker & Johnson, 2015). Monitoring water levels at various points within the CAWS insures appropriate depths for navigation within the waterway. The waterway is also a critical component of a regional flood-control program, which is dependent on waterway monitoring. The monitoring of flow within the waterway is a critical component to maintaining compliance with State and Federal water-quality standards. Flow monitoring provides critical information for several power plants and industries located along the CAWS that use the CAWS for cooling water.

5.2. Evaluation of Streamflow Monitoring Activities

5.2.1. Measurement environment in the CSSC system

The measurement environment in the Chicago Sanitary and Ship Canal (CSSC) is highly complex from several perspectives: low flow channel gradients and low velocities, formation of temperature and density gradients in the system occasionally leading to flow reversals, oscillations triggered in the closed canal network due to the operation at controlling structures located at the lakefront and watershed outlet, release of large point source discharges (from water reclamation plants), and barge passages through the station. These disturbing monitoring factors are acting alone or in combination creating a measurement complexity that poses multiple challenges for both direct synoptic discharge measurements and implementation and usage of any of the conventional continuous monitoring protocols. A tremendous amount of effort was carried out by the CSSC stakeholders to analyze the impact of these adverse conditions on the ability of the USGS gaging stations operating in the system to accurately monitor flows (Jackson et al., 2012). Given its importance in monitoring withdrawals from Lake Michigan and other components of the diversion, the Lemont and Romeoville (the predecessor of Lemont) gaging stations

have become among the most highly scrutinized gaging stations in the country. To date, most of these disturbances were locally observed and quantified with respect to their impact on the accuracy of monitoring for LMDA purposes.

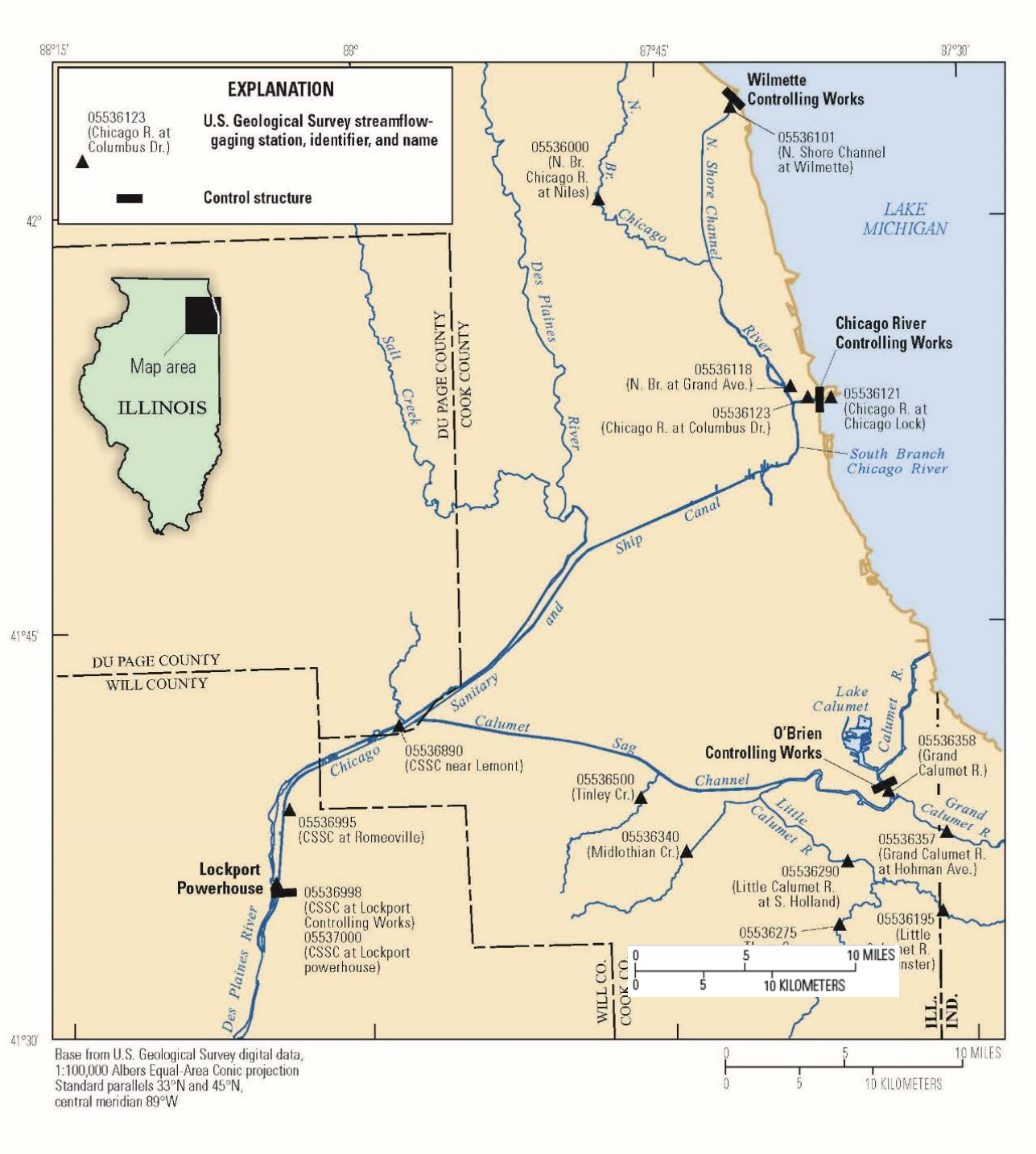


Figure 5.1. Primary elements of the Chicago Waterway System, controlling works, and gaging stations

Density & temperature currents. The present-day Main Branch of the Chicago River (hereafter MB) flows west from Lake Michigan, through downtown Chicago, IL, and joins the North Branch (hereafter referred to as NB) where it empties into the South Branch (hereafter SB) (Jackson et al., 2008). Flow in the MB was reversed in 1900 to keep sewage effluent from reaching Lake Michigan. The MB flow is now controlled by the Lockport Powerhouse and Controlling Works near Joliet, IL, by the Chicago River Controlling Works (hereafter referred to as CRCW) and by the Chicago Harbor Lock at Lake Michigan. During summer, water from Lake Michigan flows into the MB through sluice gates and lockages (the passage of ships through the lock) at the CRCW. This sluice gate flow, called discretionary diversion, is used to preserve the CSSC in a reasonably satisfactory sanitary condition. During winter, diversions from Lake Michigan into the MB are small compared to summer and typically result from lockages and leakage through the gates and sea walls at CRCW. The NB carries watershed runoff and treated municipal sewage effluent from the North Side Water Reclamation Plant located 10 mi upstream from the MB. Sewage effluent accounts for as much as 75% of the discharge in the NB during winter months.

During routine discharge measurements in 1998 as part of the discretionary diversion accounting, the U.S. Geological Survey (USGS) observed bidirectional flow in the MB at the Columbus Drive station. Bidirectional flow consists of two layers moving in opposite directions (i.e. one layer flowing downstream while the other layer flows upstream). Such flow irregularities introduced large uncertainty into discharge measurements made at this station using an acoustic velocity meter and the index velocity technique (Morlock et al., 2002). The bidirectional flows occur in the MB because of currents driven by differences in density between fresh and more saline waters from the NB and MB. The source of the salinity in this freshwater system likely is road-salt contamination of upstream reaches. The road salt appears to be entering the system as direct runoff and through effluent from the O'Brien (formerly North Side) Water Reclamation Plant that treats combined sewage. Synoptic measurements of hydrography and water velocity revealed the occurrence of both underflows and overflows in this branched, urban channel.

Following these preliminary observations a dedicated study investigated the issue of density currents in the Chicago River (Garcia et al., 2007; Jackson et al., 2008). Detailed field observations of bidirectional flows were made in the Chicago River in Chicago, IL. in the winters of 2003-04 and 2005–06. Using multiple acoustic Doppler current profilers simultaneously with a water-quality profiler, the formation of upstream propagating density currents within the Chicago River both as an underflow and an overflow was observed on three occasions, as illustrated in Figure 5.2. Density differences driving the flow primarily arise from salinity differences between intersecting branches of the Chicago River, whereas water temperature is secondary in the creation of these currents. The Garcia et al., (2007) study hypothesized that the density differences might be caused by temperature differences, high concentrations of dissolved salts, suspended-sediment concentrations, or by some combination of these three factors. Evidence in Jackson (2018) indicated that density currents can also be observed elsewhere in the CAWS including in the CSSC at the Lemont gaging station. Currently, the discharge records at the Lemont gaging station on the CSSC are not corrected for temporary effects that affect all the measurements acquired with acoustic instruments (due to the change in the speed of sound during the propagation through uncharted layers).

Flow unsteadiness. The flows in the CSSC near Lemont, cover a wide range of velocities and are highly unsteady (Jackson et al., 2012). Flow variability arises from a range of sources: operation of the waterway through control structures, lockage-generated disturbances, commercial and recreational traffic, industrial withdrawals and discharges, natural inflows, and storm events. The primary source of unsteadiness appears to be the control of the CAWS through three primary lock and dam structures. Control changes and lockages at the downstream end at Lockport, cause changes in the stage and flow elsewhere on the system, and the disturbances propagate through the system in the form of flood waves and seiches.

Withdrawals and discharges from powerplants and industry on the canal and wastewater inflows from three large water-reclamation plants further add variability to the flow. Storm-driven inflows from several tributaries on the Calumet-Sag Channel and North Branch Chicago River and inflows from local runoff and combined-sewer overflows are yet other sources of flow variability, primarily during high flows.

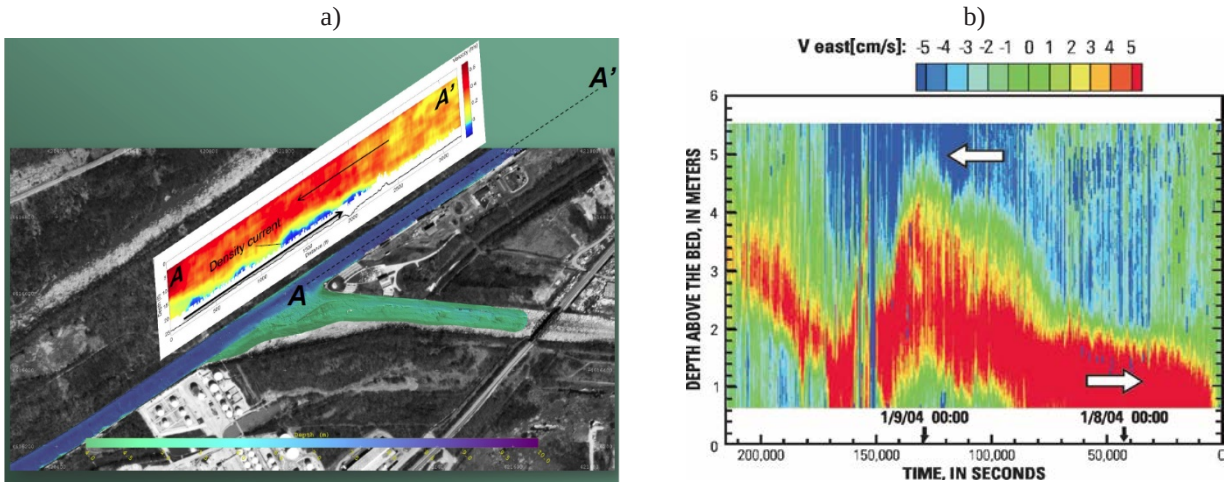
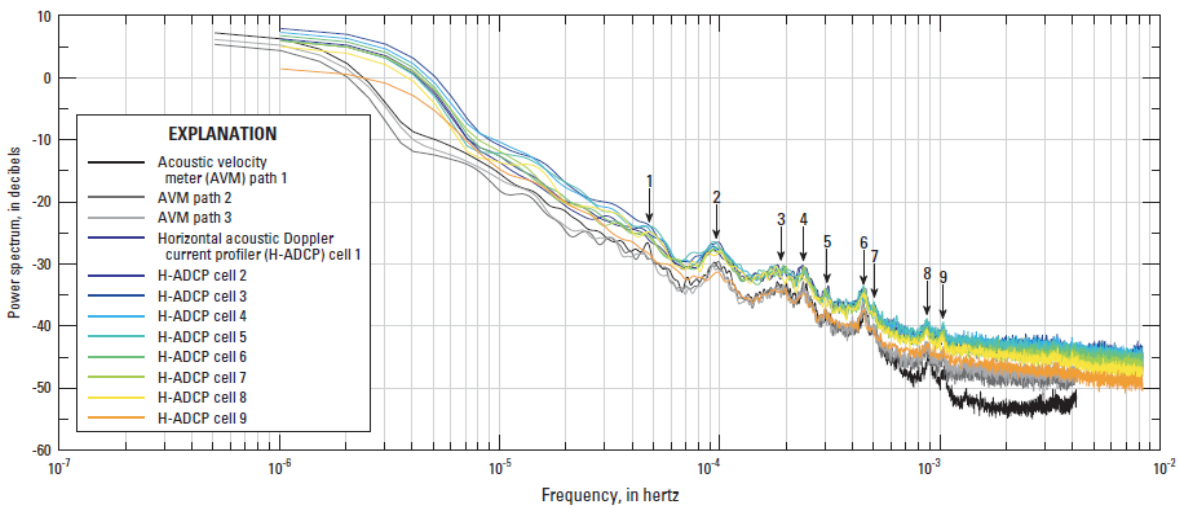


Figure 5.2. Effects of temperature and density stratification in the CSSC system; a) formation of density currents at the junction of CSSC with Calumet-Sag Canal, December 2010 (Jackson, USGS, December, 2018, personal communication); b) Contour plot of water velocity at Columbus Drive station (arrow indicate flow directions in each surveyed region and bidirectional flows) after Garcia et al. (2007)

An innovative frequency analysis applied to streamflow time series recorded by Acoustic Velocity Meters (AVM) during the 10/2007-01/2010 and horizontal acoustic Doppler-current profiler (H-ADCP) during 11/2006-01/2010) at Lemont station was conducted by Jackson et al. (2012). The analysis identified 9 peaks in the power spectra as illustrated in Figure 5.3a. The primary unsteadiness source in the system is the lockage at Lockport Lock and Dam structure. Each time the lock is filled, the flow in the canal increases and a flood wave propagates upstream causing much of the variation in discharge at low flows (see Figure 5.3b). The magnitude of the wave is proportional with the type and number of barges passing through the lock. The largest pulse in the lockage process is created when the chamber is filled and no barge is in the lock. The flood waves generated by the lock arrive at Lemont 40 to 51 min after the start of filling of the lock chamber (for 25-ft depth in the channel). The next large pulse is produced by just one vessel passing through the lock irrespective of the vessel direction. This type of pulse, lasting 33 to 37 min, is associated with the lock fillings (see peaks 6 and 7 in the power spectrum analysis and see Table 2 in Jackson et al., 2012). In addition, periodic shutdowns of flow through the Lockport Powerhouse for maintenance and worker safety can cause disturbances propagating upstream and even flow reversals.

In addition to these system-wide flow disturbances, localized and short-term flow variation near Lemont is caused by commercial barge traffic, which can be heavy in the Lemont area as documented by Jackson (2018) and illustrated in Figure 5.3c. The passage of the barge is nicely captured in the uplooker signal data (RSSI--return signal strength intensity) which normally shows a peak at the water surface. As the barge passed, the beams bounce off the bottom of the barge and the data show a peak at the depth of the fully loaded barge (9 ft below the surface). All the unsteadiness sources previously discussed are not corrected for during the real-time data acquisition. The full understanding of the flow variability in the CSSC near Lemont requires tracing each individual fluctuation in flow back to its source, a task that is best accomplished using detailed hydrodynamic modeling. However, numerous studies have been conducted since the 6th TC (Espey et al., 2009) triggered this subject of concern that evaluate the impact of the unsteadiness on the flow monitoring time windows involved in the LMDA reporting.

a)



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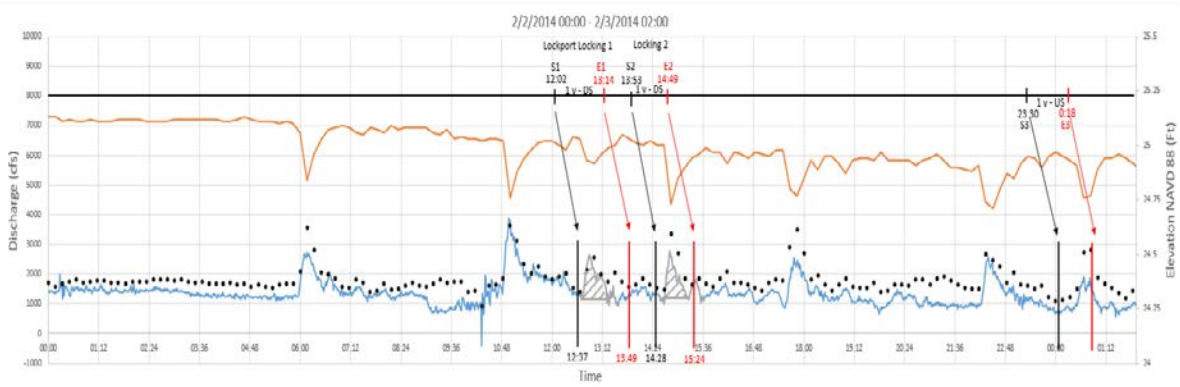

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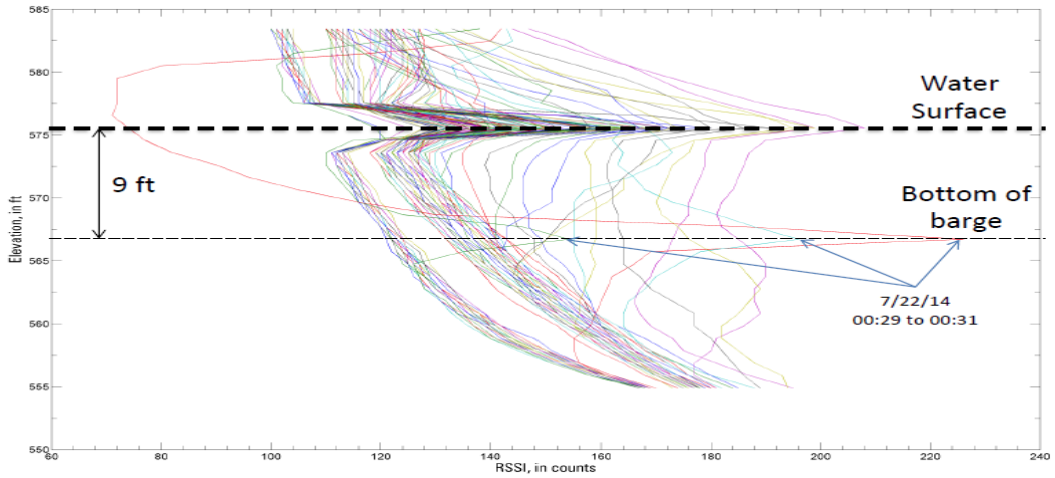


Figure 5.3. Effects of flow unsteadiness in the CSSC system; a) Power spectra in the velocity time series recorded at the Lemont station (November 2006-January 2010). The dominant–frequency peaks correspond to various modes of oscillations (seiches) occurring in CSSC due to controlling work structures at the lakefront and Lockport Lock and Dam (Jackson et al., 2012; b) impact of lockage at Lockport Lock & Dam on the flow parameters measured at the Lemont station for a low flow discharge in the CSSC of about 1386 cfs (yellow lines – stage measurements; black dotted line – Acoustic Velocity Meter (AVM) measurements; blue line – Acoustic Doppler Velocity Meter (ADVM) measurements). Abrupt changes in the stage and discharges in the plot indicate lockage at Lockport Lock and Dam; c) impact of a barge passing as captured by the return signal strength intensity of an up-looking ADCP (Jackson, USGS, July 2017, personal communication).

Changes in cross-sectional velocity distributions and flow reversal. The flow at the primary gaging station located at Lemont displays a temporarily skewed distribution generated by the operation of the powerhouse and lock at Lockport (Jackson et al., 2012). The instruments located at this station show that the transverse flow distribution near Lemont is skewed to the right bank (looking downstream) for flows less than 3.0 ft/s and skewed to the left bank for flows greater than 3.0 ft/s, as illustrated in Figure 5.4. As the flow velocity increases in the cross section near Lemont, the velocity on the left bank increases by as much as 60 percent, whereas the flow velocity on the right bank decreases by about 3 percent. This skewness in the velocity distribution, not captured in the synoptic measurements for verification of the rating curve at the station, can be problematic for the accuracy of the ratings and deserves more attention in the future (Jackson et al., 2012).

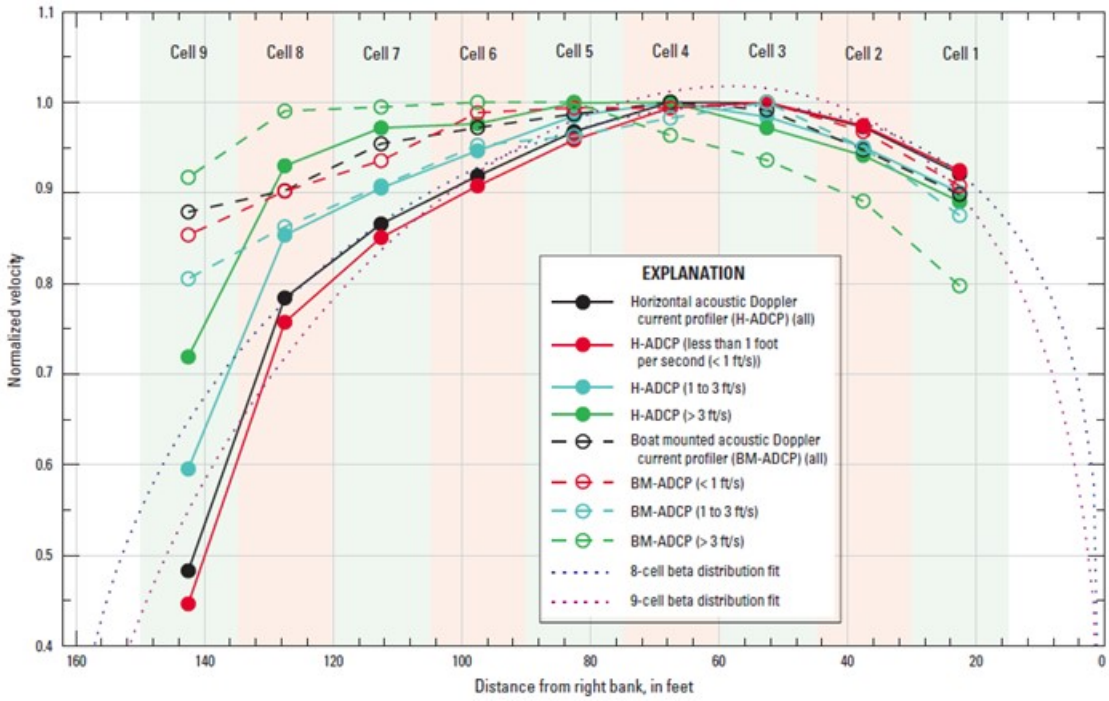
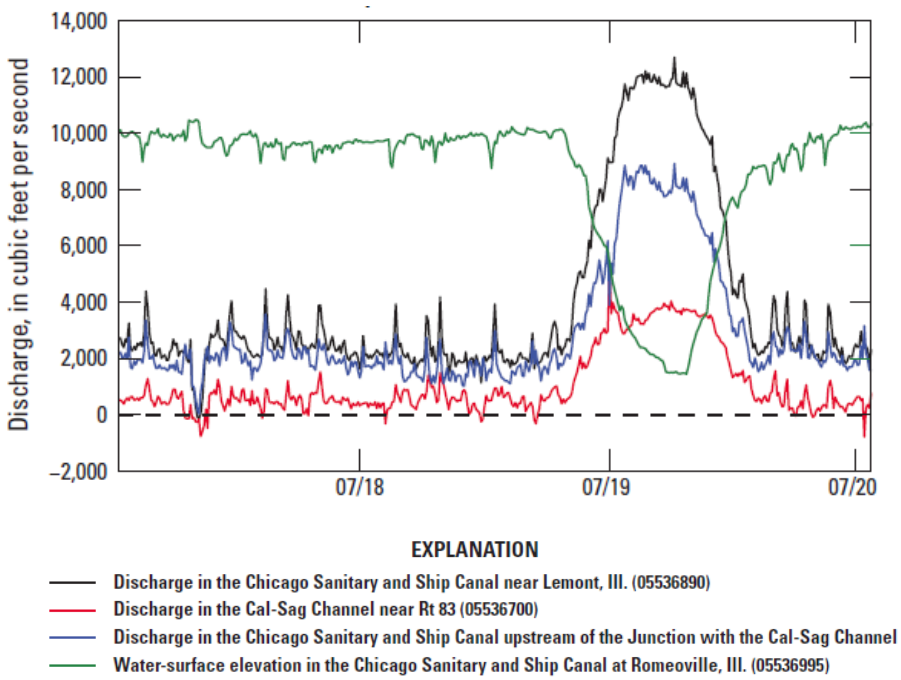


Figure 5.4: The variation of the transverse normalized velocity profiles at the Lemont gaging station as captured in the bins of the horizontal acoustic Doppler current profiler (H-ADCP) and simultaneous boat-mounted ADCP velocities for a range of flows in the channel (Jackson et al., 2012).

Draw downs. These man-made, large-scale disturbances propagating through the entire CSSC system are the typical response of the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) operators in anticipation of heavy precipitation to allow for storage in the canal to accommodate for a large influx of runoff to the canal. These controlled events are triggered when the MWRDGC increases flows through the powerhouse and opens sluice gates at the powerhouse and at the controlling works upstream of Lockport to withdraw water from the canal (see Figure 5.5). These rapid drawdown events in the canal and the flood events that follow appear to generate a range of flows with peak velocities around 4 ft/s and, through the seiches produced by draw-down oscillations, even reversed flows (Jackson et al., 2013). The drawdown lowers the water-surface elevation while increasing discharge (a.k.a. inverse proportional stage-discharge relationship). Such a situation is not encountered in natural channel systems, only in catastrophic situations such as dam breaks. If high precipitation events occur following the draw down, this leads to rapid supply of runoff in the canal creating an increase in stage and discharge (thus, producing a positive stage-discharge relationship).

Figure 5.5. Measured hydrographs in the CSSC and Calumet-Sag Channel for a storm (12,697 cfs) event on July 17, 2012 (Jackson et al,, 2013). The initiation of the draw down is indicated by the abrupt change in the water-surface elevation measured at the Romeoville gaging station



5.2.2. Streamflow monitoring at the Lemont Gaging Station

5.2.2.1 Location

Discussions among the USACE, Chicago District, USGS, and the Fifth Technical Committee in 2003 led to the decision to relocate the Romeoville gaging station to Lemont, 5.9 mi upstream. The Lemont streamflow gaging station currently is the primary streamflow station for the LMDA. The gage is located at lat 41°41' 29" N, long 87°57' 52" W (NAD of 1983), in the SE1/4NE1/4SW1/4 sec. 15, T.37 N., R.11 E., Du Page County, Hydrologic Unit 07120004, on the right bank, approximately 1.5 mi upstream from the Lemont Road (Stephen Street) bridge, and at mile 12.0 of the CSSC (Illinois Waterway mile 302.0). Figure 5.2 illustrates the station location within CSSC and Figure 5.6 contains a map of the station vicinity. Construction at the Lemont gaging station began in January 2004. On April 17, 2004, a common gage datum of 551.76 ft NAVD 1988 was determined for the Lemont and Romeoville gages. Global Positioning System (GPS) levels were run from the National Geodetic Survey bench mark ME1728 (BM-1 at the gage Chicago Sanitary and Ship Canal near Lemont) to BM-2 at the gage Chicago Sanitary and Ship Canal at Romeoville. A bronze tablet, BM-2, was set in the gage house pad, and it is recommended that BM-2 be used as the basic point for future levels. The purpose of the levels was to establish a gage datum NAVD 1988 at the new site at Lemont. Although the Romeoville station is discontinued, it is recommended that any future work use the gage datum of 551.76 ft NAVD 1988.

The limestone canal at this location has near vertical walls 34 ft deep and a top width of 170 ft. The channel bottom is almost horizontal with some rounding at the face of each bank. The control for low and medium flows is the MWRDGC Powerhouse and the USACE Lock at Lockport, 11.1 mi downstream. High flow is controlled by the Lock and Powerhouse and the MWRDGC Controlling Works, 8.9 mi downstream, which divert water to the Des Plaines River. The water-surface elevation in the canal is maintained at about a 25 ft stage at the gage. When heavy rains are forecast, the water surface is drawn down about 2-3 ft by opening the Controlling Works to temporarily lower the water level in the canal and to increase flows from the Chicago area as discussed earlier.

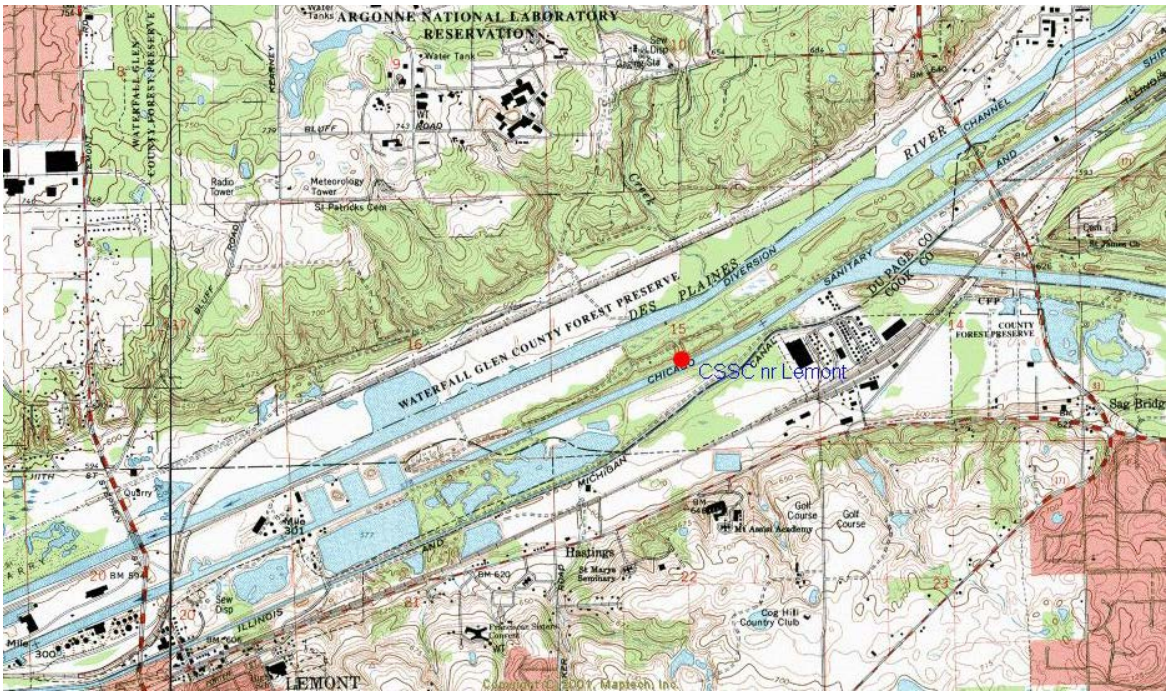


Figure 5.6: Location of the CSSC Lemont streamflow gaging station

5.2.2.2 Discharge measurement methods

5.2.2.2.1 Overview

Field measurements use a wide range of instruments and methods for measuring discharge (Rennie et al., 2017). However, there are no widely-recognized reference instruments or methods for verifying the accuracy of the discharges acquired in natural-scale open-channel flows. Discrete values of discharge can be obtained by measuring one or more flow variables and subsequently combining them through analytical methods to estimate discharge. Contemporary instruments often use the same housing for probes to measure different flow variables. This arrangement enables discharge measurement from one deployment in the stream (*e.g.*, the Acoustic Doppler Current Profilers, ADCPs). Alternatively, discharge can be obtained indirectly from measurements of water level, free-surface slope, or velocities in conjunction with governing laws for open channels (conservation of mass, energy, and momentum) or with empirical relationships that link discharge to flow variables measured at one or more locations in the stream. These relationships (termed ratings) are developed through calibration measurements acquired over a wide range of flows with alternative measurements. The established relationships are valid only for the site where the measurements were acquired. As conditions at a site can change due to natural causes (*e.g.*, changes in the stream morphology or vegetation), periodic field surveys may be needed to verify the reliability of the discharge estimates over time.

Establishing reliable relationships for continuous discharge measurement in field conditions is a challenging task for both normal flow conditions as well as for large flow events. Challenges arise because estimation of discharge depends not only on the instruments and methods used for the measurement but also on the gaging site characteristics. The most challenging measurement situations occur in natural channels where the flow is affected by bed evolution, variable backwater (*e.g.*, due to the presence of structures in the stream or of a confluence), where a substantial portion of the discharge is conveyed by floodplains, and/or unsteady flows (*e.g.*, propagation of a natural flood wave). These special

situations require the development of customized empirical or analytical methods. Streams affected by variable backwater are sometimes approached by empirical stage-fall-discharge rating curves (Rantz *et al*., 1982b; Herschy, 2009) whereas unsteady flow situations are corrected using analytical methods (Rantz *et al*., 1982b; Schmidt, 2002). An additional complexity in such channels is flow stratification due to density difference that is troublesome for acoustic-based instruments.

Traditional hydrometric guidelines group the methods for continuous estimation of discharge in terms of the independent flow variables directly measured for the estimation: free-surface water level (or stage), free-surface slope, and velocity (*e.g.*, Rantz, 1982a,b; Herschy, 2009; WMO, 2010). The most common approach for stage-based, discharge estimation is the simple stage-discharge method. The limitations of the stage-discharge approach to measure in areas with backwater and in unsteady flows have led to development of monitoring techniques that include continuous measurement of an index-velocity in addition to stage. The nature of the measurement environment does not offer any monitoring alternatives for the streamflow tracking in the CSSC besides the index-velocity method. This approach is without question the best one, as the stage or free-surface slope based continuous measurements are challenged by the small range of depth variations and flat terrain within the CSSC system. The index velocity has proven to be well suited for monitoring streamflows in spite of the large range of velocities and highly unsteady flows at the site. There are multiple references that describe the methods and instruments used over time at the Lemont station as well as at other stations in the CSSC (e.g., Duncker and Johnson, 2015). A summary of the past and current methods used for continuous flow measurement using the index-velocity at the Lemont station is provided in the following subsections, to place their evolution in perspective.

5.2.2.2.2 Current Discharge Estimation Methodology

Rantz *et al*. (1982b) provide extensive descriptions of the index-velocity method used in conjunction with several conventional instruments. Today, the range of instruments used with the index-velocity has extended considerably to include velocity measurements at a point, along a line, or over a surface of the moving body of water. These measurements can be related (via an index) to the bulk-flow velocity and further combined with continuous measurement of the cross sectional area to readily determine discharges. Recently, the velocity-index method has become widely used due to the adoption of acoustic and radar velocimetry that can efficiently and continuously measure velocities across natural streams. The most popular instruments from this category are the horizontally-positioned ADCP (H-ADCP) and the vertically-positioned ADCP (V-ADCP).

Acoustic instruments are rapidly replacing conventional current meters for measurement of velocities in natural and man-made open channels. Greater efficiency, improved performance, and numerous safety considerations at comparable costs have provided the motivation for their broad adoption in hydrologic data collection operations. They have no moving parts, offer relatively high spatial and temporal sampling resolution, and require fewer calibrations. Moreover, they allow measurements in field settings where conventional measurements are very difficult or costly to obtain. These technologies have profoundly changed the way that hydraulic data are collected by researchers, engineers, and technicians alike, being applied to measure velocity, and, thereby, estimate important velocity-derived hydrodynamic quantities in support of riverine research and to complement numerical simulations and laboratory studies. Acoustic instruments currently are used for routine operations on water delivery projects, water treatment plants, stream gaging stations, and many other water resources-related projects.

A brief summary of the index-velocity approach for estimation of streamflow is provided herein using the H-ADCP as the instrument for providing the index-velocity. Repeated calibration measurements of stages (G) and index velocities, V_{index}, are used to develop associated ratings for the channel cross section (A)

and mean channel velocity (U), respectively. V_{index} is the average value of the individual in-bin velocities measured by an H-ADCP across the channel width. The channel cross section is determined from a detailed survey of the river bathymetry at the gage location. The mean channel velocity is determined using the direct discharge measurement divided by the cross-sectional area at the time of the calibration measurement. Discharges can be measured with any of the conventional methods (*e.g.*, a propeller-type current meter) but recently, the most often used measurement method relies on ADCPs deployed on moving boats (Mueller *et al*., 2013).

A "stage-area" rating is obtained by relating the stage to the corresponding cross-sectional area. Stages are measured with methods used by the stage-discharge method (see Figure 5.7). Multiple mean-channel velocities and simultaneously acquired index velocities are paired to build the "index-velocity rating", typically by using least-squares regression. Direct and continuous measurements of depth (h_*) and index-velocity acquired with permanently deployed instruments in conjunction with the two ratings provide area and mean channel velocity that, multiplied, give continuous discharge estimates. Continuous observations of the index velocity can be obtained by averaging measurements at a point or along lines (as is done by the H-ADCP shown in Figure 5.7).

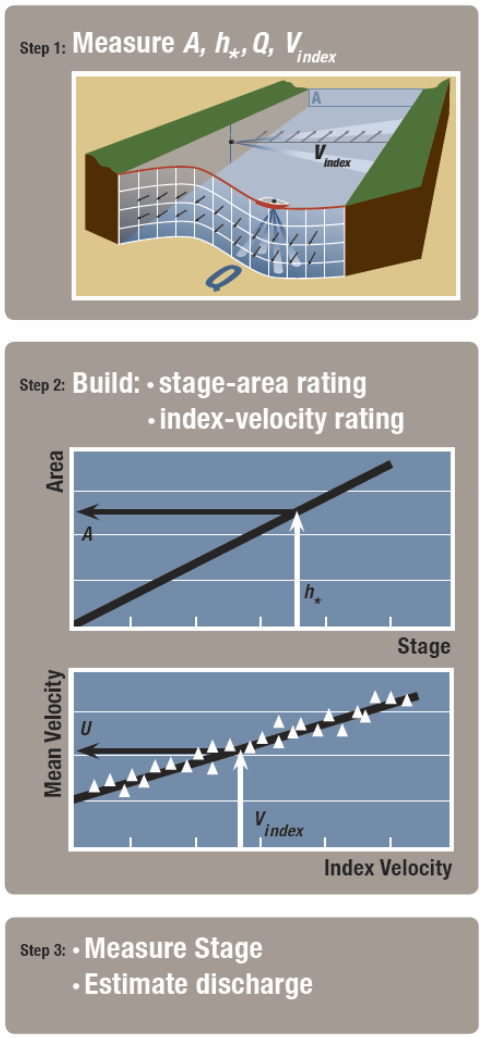


Figure 5.7. Schematic diagram of the estimation of discharges using the index-velocity method.

The index-velocity ratings are conveniently built with regression models that find the best fit for pairing velocity measurements obtained with various instruments and the cross-section velocity, U. The functional relationship between the mean channel and measured index velocity, V_{index} is of the form:

$$U = g_o(V_{index}) \tag{5.1}$$

The index velocity, V_{index}, can be the average of a velocity time series acquired at a point ($\bar{u}_{i,j}$), or an average taken over the measurement volume of the flow velocity measurement device ($V_{index} = \sum_{i=1}^{n} \bar{u}_{i,j}$, for j = constant, *i.e.*, a horizontal line) as shown in Figure 5.7. The relation between V_{index} and U may display a degree of ambiguity when the flow varies in magnitude or over time for several reasons. For example, for gauging stations close to bends, the variation of flow velocity close to the channel banks generally precedes the mean flow variation because of inertia that is most pronounced in that region (Muste *et al*., 2015). For simple channel geometries where the law of the wall applies, the location that best represents the mean velocity is close to the channel center, at a relative depth of about 0.4, where it is assumed that the local velocity equals the depth-averaged velocity. Closer to the bed, the velocity magnitude decreases and hence the measurement error in V_{index} is amplified. Closer to the surface, velocities may be impacted by wind shear or by side wall effects.

When residuals of the linear regression model show systematic patterns in the index-velocity rating, several steps can be considered to expand the model complexity. A multi-linear or nonlinear function can be employed to achieve a better fit to the pairs of V_{index} versus U points. These approaches are appropriate when the relation between these variables is unambiguous. Theoretically, any form of systematic behavior of the residuals can be accounted for by increasing model complexity. A multiple linear regression approach may be required to eliminate heteroscedasticity, the systematic behavior of the variance of the residuals. Typically, the water surface stage, G, adjusted by the zero-flow elevation to obtain h_*, is the first candidate to be added to the regression model (Levesque & Oberg, 2012):

$$U = aV_{index} + bh_* + ch_*V_{index} + I \tag{5.2}$$

where a, b and c are coefficients and I is an intercept. Analysis of numerous data sets has shown that the term representing the stage variable alone, bh_*, is typically insignificant for practical situations (Levesque & Oberg, 2012). However, there is no statistical basis to guarantee that a model accurate in one or more situations can directly be applied to other circumstances. The accuracy of the index-velocity method for discharge estimation is intrinsically linked to the quality of the regression model adopted to translate index velocity to cross-section averaged velocity. For channels with a simple geometry, this relationship often is linear. The index velocity method is assumed to be relatively accurate for measurements of non-uniform flows. For unsteady flows, it is expected to improve the accuracy of the estimation as the method is based on two direct and simultaneous measurements collected continuously at a high sampling rate.

5.2.2.2.3 Main instruments

Operation principles. The primary and secondary (backup) discharge measurements at the Lemont gaging station are provided by index-velocity method associated with acoustic instruments. Specifically, Acoustic Velocity Meters (AVM), Acoustic Doppler Velocity Meters (ADVMs, an alternative name for H-ADCPs), and Acoustic Doppler Current Profilers (ADCP) have been applied in the diversion accounting. The configuration and principle of operation for these instruments are shown in Figure 5.8. AVMs work using the "time of travel" principle (Ruhl and Simpson, 2005). An AVM system is comprised of a pair of acoustic transducers that are aimed at each other and are mounted at the same depth diagonally across a channel (Figure 5.8a). An AVM measures the water velocity by sending an acoustic pulse between the transducers in both directions. The acoustic pulse that has a component in the same direction as the water velocity (from A to B in Figure 5.8a) will arrive earlier than an acoustic signal that is traveling against the water velocity (from B to A in Figure 5.8a). The water velocity in the channel is proportional to the difference in time it takes for the acoustic signal to travel between the two transducers. AVMs sample the velocity over the full cross section at the transducers elevation.

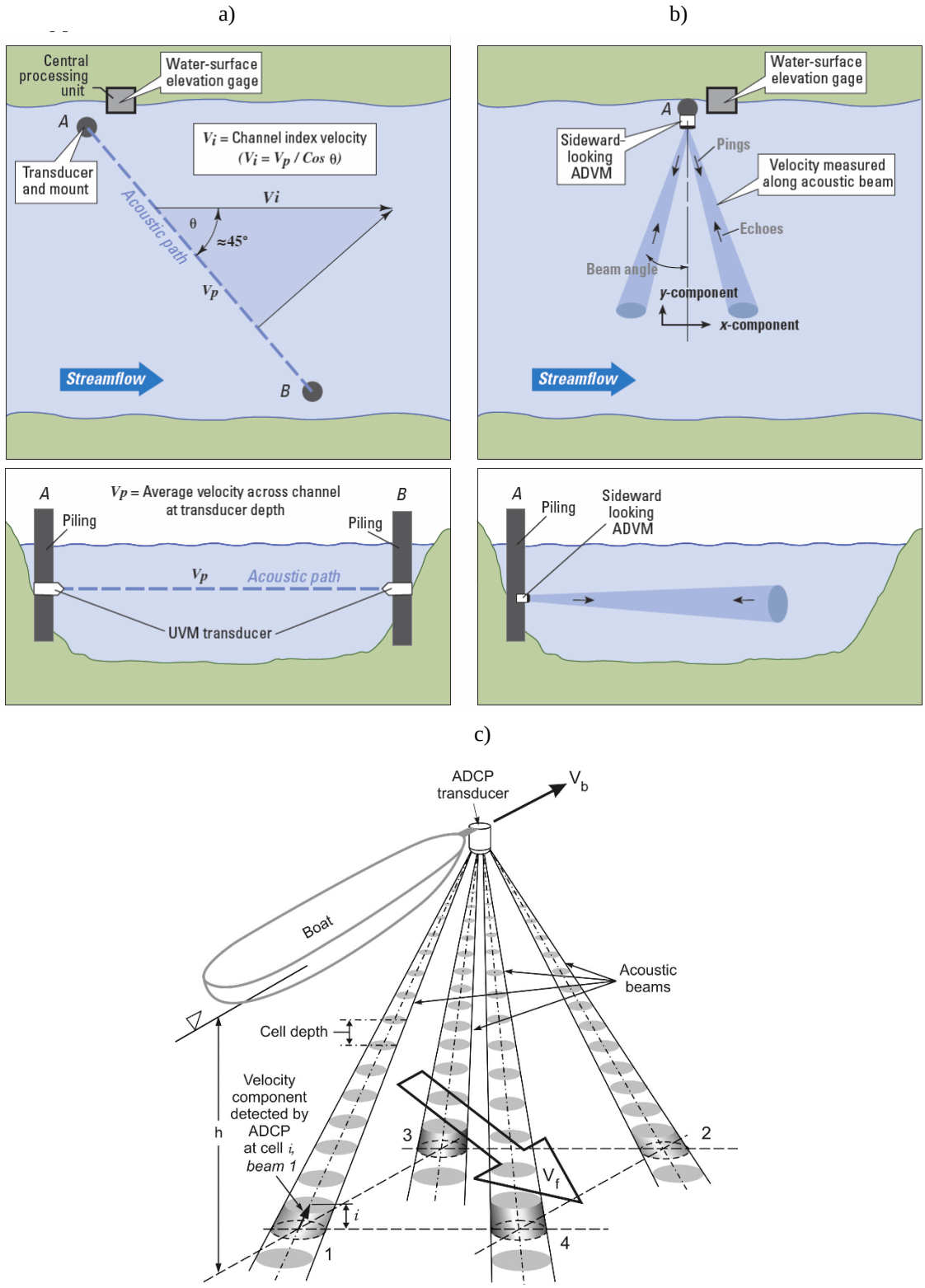


Figure 5.8: The configuration of the main acoustic measurement instruments utilized at the CSSC gaging station at Lemont: a) Acoustic Velocity Meter (AVM); b) side-looking Acoustic Doppler Velocity Meter (ADVM – in actuality a conventional H-ADCP); and c) Acoustic Doppler Current Profiler (ADCP)

ADVMs (an alternative name for the H-ADCP instrument described in the methods Section 5.2.2.2.3) utilize monostatic transducers, or transducers that both send and receive an acoustic pulse (see Figure 5.8b). An acoustic pulse of a known frequency is sent out into the water column along the acoustic beam. A fraction of that acoustic pulse is reflected by small particles in the water, returning to the transducer at a frequency that has been shifted due to the Doppler effect. The water velocity within the acoustic beam is determined from the Doppler shifts of sound waves reflected off of particles moving with the water. ADVM profilers use diverging beams for velocity measurement, but contain sophisticated, high-speed, signal processing software that can calculate multiple velocities from numerous range-gated sample volumes (bins) along the beam path. Both the size and number of these bins can be controlled from the ADVM firmware and usually are spaced evenly along the main beam axis. In contrast to the AVM, the ADVM samples only a fraction of the cross section at the level of the ADVM because of the initial blanking distance near the probe and the near-wall interference at the far side of the channel. The ADVM profiler used in the CSSC is of the side-looking configuration type (see Figure 5.8b).

Finally, ADCPs operated from moving boats are used to directly obtain discharge measurements (see Figure 5.8c). ADCP transducers emit a sound burst directed downward. The echoes returned from the particles carried by the currents and from the streambed are recorded by the same transducer similarly to the ADVM. Sound echo analysis allows ADCPs to measure the speed of the particles moving along the beams. Using measurements along multiple beams (three or four oriented at divergent beam angles in different directions), the magnitude and direction of the water velocities at many levels through the water depth can be obtained, similar to a "current profiler". Using the echoes scattered by the bed, ADCPs determine the speed-over-ground and path of travel, this process is often referred to as "bottom tracking."

Actual deployments. The original gage consisted of a Campbell Scientific electronic datalogger (CR10), Campbell Scientific satellite transmitter (DCP), ParaScientific pressure sensor (PS-2), three-path Accusonic O.R.E. 7510 GS AVM, Teledyne RD Instruments ChannelMaster ADVM, and a staff gage. The base gage is the staff gage bolted to the north (right) canal wall, in the notch near the AVM transducers, velocity meters, and orifice lines. Orifice lines for the PS-2 are attached to the north (right) canal wall and run underground back into the gage house through the same 4-in. PVC conduit as the AVM transducer cables. On December 7, 2004, AC power was connected to the gage and AVM operation began. December 8, 2004 was the first full day of AVM data. On April 29, 2004, the USGS installed a ParaScientific pressure sensor (PS-2), the two Campbell Scientific electronic dataloggers (CR10X), with a Teledyne RD Instruments ChannelMaster acoustic Doppler velocity meter (ADVM). On May 21, 2004, commercial divers installed the cross-channel cables for an acoustic velocity meter (AVM). On July 1-2, 2004, AVM transducers were installed on aluminum pipes on both sides of the channel. An Accusonic ORE 7510 GS acoustic velocity meter was installed during August 2004. On April 26, 2005, the USGS activated a Campbell Scientific high data rate satellite transmitter (DCP). The layout of the arrangement of the velocity instrumentation is shown in Figure 5.9a.

The actual, original AVM system located at Lemont comprised six velocity transducers placed at two locations along the canal walls with one location on each bank and a path length of 229.1 ft. The velocity transducers were mounted on 2-in. aluminum pipes, which were fabricated to be adjusted from the top of the canal wall. These pipes are located within the notches blasted into the limestone canal walls and formed with concrete above the water-line to provide protection from barges and debris. They are secured to the canal walls by a horizontal strut and mounting brackets located above the water surface to hold the pipes in a fixed position. One set of three transducers (upper, middle, and lower paths) is along the north (right) bank about 120 ft upstream from the gage (See Figure 5.9b). The other set of three transducers is along the west (left) bank. The AVM transducer path lengths are 229.1 ft. Each pair (path) of transducers is at the same elevation, across the canal from one another at a 45-degree angle to the canal

sides, and at different vertical locations within the cross section. Each pair forms a velocity path. The elevations of the velocity paths are 18.4, 13.2, and 7.8 ft. All transducers are linked to the AVM by individual electrical wires. The wires from the south (left) bank are attached to the canal wall, submerged along the canal bottom, attached to the north (right) wall within the notch, and buried under ground in 4-in PVC conduit to the gage house. Electrical service provides power to the gage. A heater in the gage house is used to maintain proper operation of the equipment. A Teledyne RD Instruments Channel Master ADVM is used as the other velocity meter used with the index-velocity method at Lemont station at the location illustrated in the Figure 5.9c. The ADVM was installed at the same time as the AVM. The ADVM elevation is 13.3 ft.

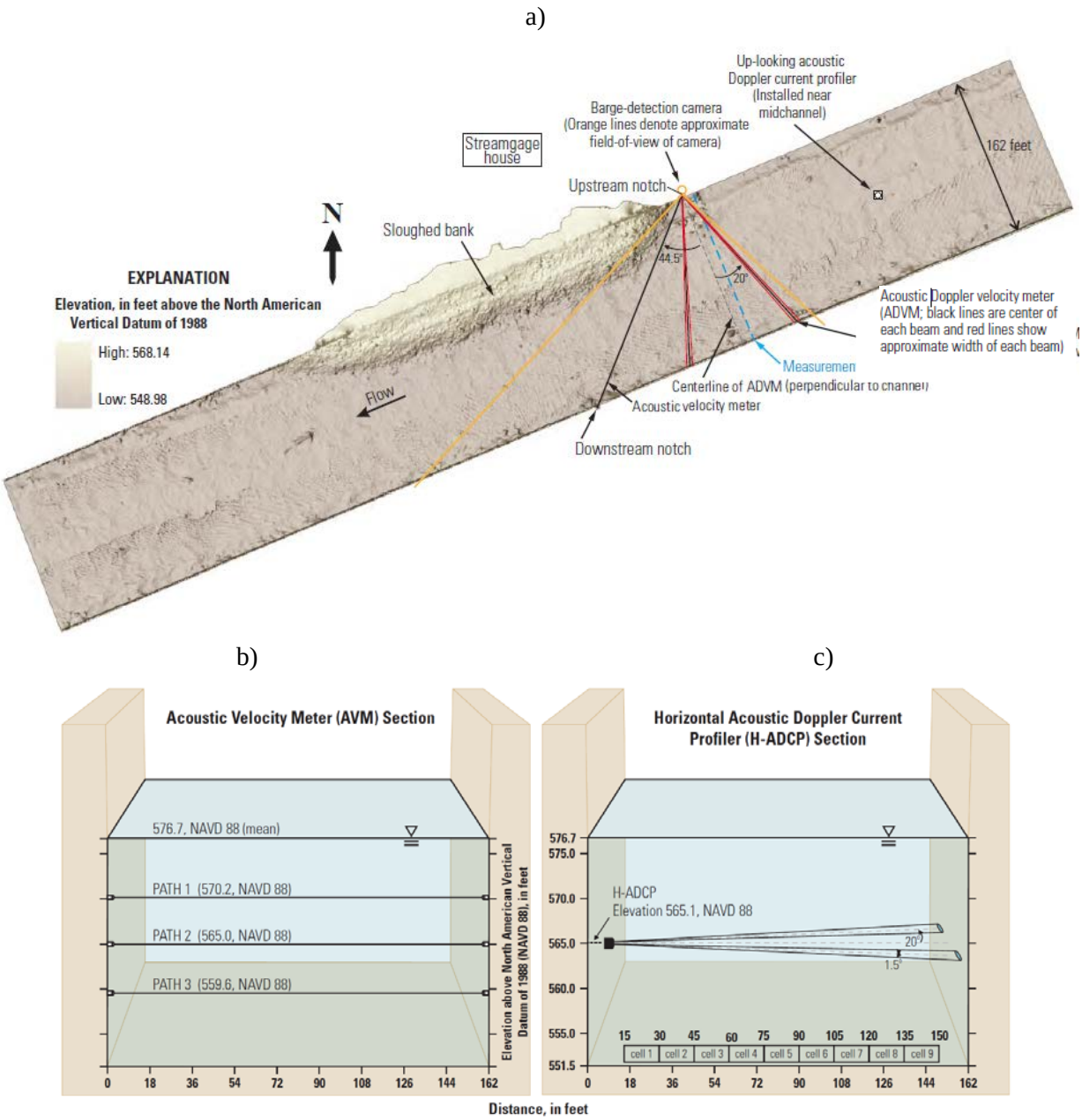


Figure 5.9. Setup of the primary and secondary velocity instrument utilized at the Lemont station (Jackson et al., 2012, Jackson, 2018): a) general layout of the instrumentation; b) positioning of the AMV transducers; c) positioning of the ADVM

In an ideal measurement environment, AVMs provide highly accurate measurements. Melching and Meno (1998) cite average errors between 0.3 to 2.7% for velocities larger than 0.6 m/s (2.0 ft/s). For field applications where the path length is larger than 50 m (165 ft) and the velocities are low, they expect that these errors are minimal. Given the high accuracy in the path velocity and in surveying methods used to determine the stage-area relation, the primary source of error in discharge measurement with AVMs results from the relationship between line velocity and mean channel velocity. This relationship is obtained using calibration measurements using alternative measurements such as those obtained with an ADCP. With proper calibrations, the accuracy of the AVM for a multipath system such as those applied at Lemont, is on the order of 1% (Melching and Meno, 1998).

The ADVMs are newer instruments, therefore, they do not benefit from sufficient data to make sound assessments of their accuracy. Le Coz et al. (2008) found that for streams with widths less than 60 m (200 ft) the deviations of the ADVMs from the reference ADCP velocity measurements were less than 5%. Consequently, the overall finding is that sufficient data are not available to conclude on the accuracy of the ADVM-based discharge using the index-velocity approach.

Direct discharge measurements at the Lemont gaging station are made using a boat-mounted ADCP and a tagline, or using an ADCP mounted on a boat. During the ADCP measurements the AVM is set to collect 1-min. data that is logged on a laptop computer. This is done so the AVM velocities and discharge can be compared with the ADCP measurements. Actually, since early 2018, all instruments (stage, ADVM and new AVM once installed) are collecting data at 1-minute intervals all of the time. Given the unsteady nature of the flow in the canal, up to fourteen transects are made during the ADCP synoptic measurements (Duncker, USGS, December 2018, personal communication). The AVM discharge during the time of the ADCP measurement are weighted based on data recorded during the synoptic discharge measurement (Duncker, USGS, December 2018, personal communication).

At the Lemont gaging station, the index-velocity approach has been used to estimate discharge from the primary and backup instruments. From 2004 to 2016 the AVM was used as the primary instrument and the ADVM was used for backup. Since 2016 the ADVM has been the primary instrument for discharge estimation with the AVM as backup. While many successful applications of index-velocity methods have been reported, their feasibility for the entire range of flow conditions that can occur at a stream gaging location has not yet been fully analyzed. The increased use of these methods requires better understanding of the assumptions behind the hydroacoustic measurements, consideration of the physical characteristics of the flow being measured, and establishment of the proper methodologies to develop the ratings such that the measurement uncertainty is minimized.

The measurement protocols for the streamflow stations on the CSSC prescribe that the missing records for the AVM are filled, to the extent possible, with velocity and discharge records from the backup ADVM measurements or vice versa since 2016. The ADVM discharge record uses the same stage-area rating as the AVM, and an index-velocity rating curve developed specifically for the ADVM. If both the AVM and ADVM fail then the daily discharge could be estimated by using multivariate regression equations based on daily flows at Lockport reported by the MWRDGC, provided by the Illinois Department of Natural Resources-Office of Water Resources (IDNR-OWR). The regression equations for estimating discharge at the upstream gaging station on the basis of MWRDGC discharge estimates at the Lockport Powerhouse, Lock, and Controlling Works are dependent on discharge estimates through various outlet components: turbines, lockage, and leakage; powerhouse sluice gates; and controlling works. The regression equations used to estimate discharge at Lemont have been developed by the USGS using methods similar to those applied by Melching and Oberg (1993). These regression equations have not been used since the installation of the Lemont gage in 2004.

5.2.2.2.4 Complementary Instrument Deployments

5.2.2.2.4.1 Up-looking ADCP

Discussions with the 6th and 7th TCs focused, in part, on unsteadiness in the CSSC and the overall effect of the unsteadiness on the methods used to measure discharge in the canal near Lemont, IL, as a part of LMDA. The 6th TC recommended that additional instrumentation (an up-looking ADCP, for example) should be deployed at the site to quantify the effect of flow transients in the system (Espey et al., 2009). Those discussions identified a need to understand the vertical distribution of velocity in the canal near Lemont, IL, and the evolution of the vertical velocity profile over time during high-flow events and transients created by operation of the lock at the Lockport Lock and Dam and other sources in the system. On June 18, 2013, a 1,200-kilohertz Teledyne RD Instruments (RDI) Rio Grande up-lookingADCP was installed on the bottom of the canal by commercial divers. The relative positioning of the up-looking ADCP with respect to the permanent velocity measurement instrumentation at Lemont station is shown in Figure 5.9a. The up-looking ADCP was mounted in a custom-built aluminum mount and bolted to the bedrock at the bottom of the canal by divers (see Figure 5.10a). The mount is located approximately 170 ft upstream of the right bank notch and at the center of the channel. The ADCP is connected to a Campbell Scientific CR-1000 data logger through a 300 foot armored cable. An up-looking ADCP measures velocities from the head of the instrument to a specified distance from the head and divides this range into uniform segments called bins (see Figure 5.10b). A collection of bins yields a velocity profile. The up-looking ADCP is configured with thirty 0.98-ft bins and a 0.82-ft blanking distance (Teledyne/ RDI, 2013). The center of the first bin is 4.3 ft above the channel bed. The instrument was configured to use water mode 12 with 100 subpings per 1-min ensemble and a time between subpings of 0.55 s. Therefore, each 1-min ensemble represents an average over about 57 s of each minute. This configuration produces 1-min time-averaged velocity profiles with an estimated standard deviation of horizontal velocity of about 0.04 ft/s. Analysis of more than 3.5 years of data (starting from 2013) from this instrument provides a detailed understanding of the evolution of the velocity profile over the vertical during highly unsteady flows in the canal and the response of the velocity field to passage of commercial tows (Jackson, 2018). In addition, the data produced by this study have revealed additional complex hydraulics and stratified flows at this site and allowed two additional methods of computing discharge at this streamgaging station.

a) b)

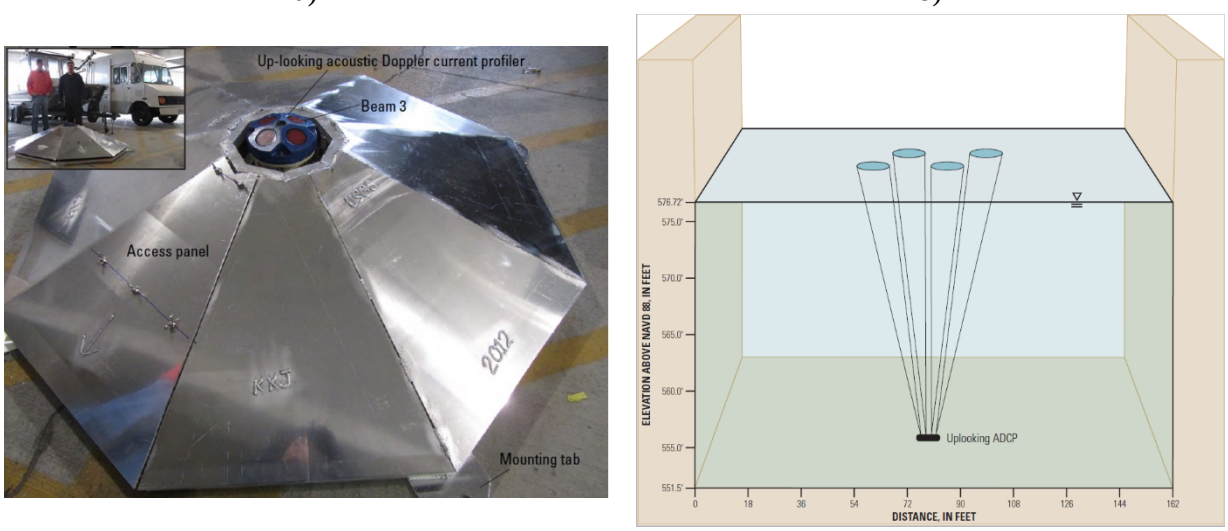


Figure 5.10. Setup of the up-looking ADCP at the Lemont gaging station: a) instrument mounting; b) layout of the 4-beam ADCP

5.2.2.2.4.2 Barge- detection Camera

In May 2016, a Hikvision DS–2CD2142FWD 4-mega-pixel dome camera with infrared night vision and motion detection was installed on the right bank of the Chicago Sanitary and Ship Canal at the Lemont streamgage to record and document the passage of commercial vessels through the reach (Jackson, 2018). The barge-detection camera is mounted on a 12-ft mast near the upstream notch and oriented about 45 degrees downstream toward the downstream notch (see Figures 5.19a and 5.11a). The camera is programmed to collect 30s of video if a vessel passes by in either direction across the programmed motion detection line illustrated in Figure 5.11b. Videos are recorded to an external hard drive that is retrieved and replaced with an empty drive. The barge-detection camera provides excellent ground-truth data to document the passage of commercial tows (hereafter tows, defined as a tow vessel and attached barge raft) through the measurement reach of the CSSC near Lemont, IL. (05536890).

a) b)

Figure 5.11. Barge-detection camera at the Lemont gaging station (Jackson, 2018): a) camera positioning on the CSSC bank; b) image acquired with the camera.

5.2.2.2.4.3 Q-Track (Vertically-scanning H-ADCP)

The Q-Track is the name adopted by the USGS for defining a vertically-scanning H-ADCP system (see Figure 5.12a). The mobile arrangement for the H-ADCP contains the same instrumentation as the fixed deployment with the difference that the "mobile" H-ADCP is attached to a vertical traversing mechanism that can move the instrument at successive locations in the vertical as shown in Figure 5.12a. The number of sampling locations and durations for the velocity acquisition at each location is contrplled by programmable hardware. There are several versions of the traversing mechanism since the mobile H-ADCP was introduced in 2005 (Wang & Huang, 2005; Nihei & Kimizu, 2008; Vougioukas et al., 2011).

The scanning H-ADCP system deployed at the Lemont station consists of a Teledyne RD Instruments Channel Master acoustic Doppler velocity meter (CM ADVM) that is mounted to an automated track system (K. Oberg, Dec. 2018, personal communication). The track system moves the CM ADVM vertically, such that a discharge measurement includes velocity profiles at five vertical positions: 3/10, 4/10, 5/10, 6/10, and 7/10 of the depth as illustrated in Figure 5.12b. This greatly reduces the amount of unmeasured area compared to a standard index velocity gage and allows a direct computation of discharge similar to a boat-mounted ADCP measurement. Currently, the Q-Track is programmed to measure every day at 1pm CST and any time the flow velocity exceeds 1 ft/s or is less than 0.1 ft/s. The Q-Track was initially installed in Spring 2017 and modified and improved over the course of the year. The Q-Track has collected ~5,000 measurements for analysis of the method since January 1, 2018.

The considerable advantage of the Q-Track compared with the fixed H-ADCP is that it provides a considerably larger number of quasi-simultaneously acquired velocity over the cross section. From this respect, the Q-Track is similar to the measurements with the vertical beam ADCP where the direction of translation during the measurements is along the cross section rather than in the vertical direction. Most of the time, however, the vertically scanning H-ADCP does not provide as many points across the section as the conventional vertical beam ADCP can offer. The capability of Q-Track to measure in one run an increased number of velocities over the cross section is critically important for complex sites (where the morphology or flow structure is changing at the gaging site) or the flow is affected by unsteadiness or backwater. At complex sites such as CSSC (where the flow is exposed to frequent unsteadiness and the flow structure for the same location is changing with the flow magnitude), the accuracy of index-velocity method with fixed H-ADCP measurements is limited as the working assumption for this protocol is that the index velocity sampled along a line correlate with the mean velocity in the cross section. However, this assumption lacks physical relevance (Le Coz et al., 2008). At such complex sites, the measured index-velocity can have the same average value for situations where the vertical of spanwise velocity profiles are different which undoubtedly correspond to different discharges (Cheng et al., 2018). The additional velocity points acquired with the Q-Track offer (order of magnitudes larger than with the fixed H-ADCP), open new possibilities of discharge estimation. The Q-Track can be used to estimate discharges in two ways: a) in conjunction with the index-velocity method (presented in Section 5.2.2.2.2) or b) as a stand-alone method to directly measure discharge in real time without the use of the index-velocity rating as described in the following paragraphs.

The simplest approach in using the measured the index-velocity for discharge estimation is to make recourse to theoretical assumptions for the velocity distribution in the vertical (e.g., power or log laws) or spanwise (Wang & Huang, 2005, Yang et al., 2004). Newer versions of the index-velocity implementation are promoting hybrid methods whereby the measurements acquired with the index-velocity instrument are used in conjunction with physically based assumptions for velocity profiles in the vertical and across the stream (Hoitink et al., 2009). Nihei & Kimizu (2008) assimilate index-velocity directly in numerical models developed for the gaging site. An innovative “extended index-velocity method” is proposed by Vougioukas et al. (2011) to be used in conjunction with vertically-scanning H-ADCP measurements in streams with irregular bottom. In this method, instead of correlating mean and index velocities in the entire cross section, a correlation is established off-line between the manually measured mean velocities of trapezoidal subsections and corresponding index velocities computed in the range of depths covered by the sliding H-ADCP (see Figure 5.12c). This way, the correlation is performed on mean and index velocities which are closer in space and time.

For stream cross sections where the bottom is parallel to the surface, such as is the case for the man-made CSSC, the vertical velocity profiles acquired with the Q-Track are similar to those acquired with vertical beam ADCPs deployed at fixed locations. For these situations, the discharges can be directly estimated by depth-averaging the measured vertical profiles in conjunction with the velocity area method under any of its alternatives, i.e., the mean-depth or mean-velocity methods (Herschy, 2009). Currently, the USGS is exploring various algorithms for estimation of direct discharge measurements at the Lemont station that take advantage of the transformative capabilities of the Q-Track. During the exploration stage, additional instruments are planned to be deployed to the station to collect velocities in the areas unmeasured by the Q-Track. Conventional transect ADCPs will be collected over long-term intervals to validate the established protocols. The proposed intensive data acquisition plan will not only be critical for the assessment of the Q-Track performance for determining discharge but also a valuable source of information for the evaluation of algorithms currently used in practice for vertical-beam ADCPs.

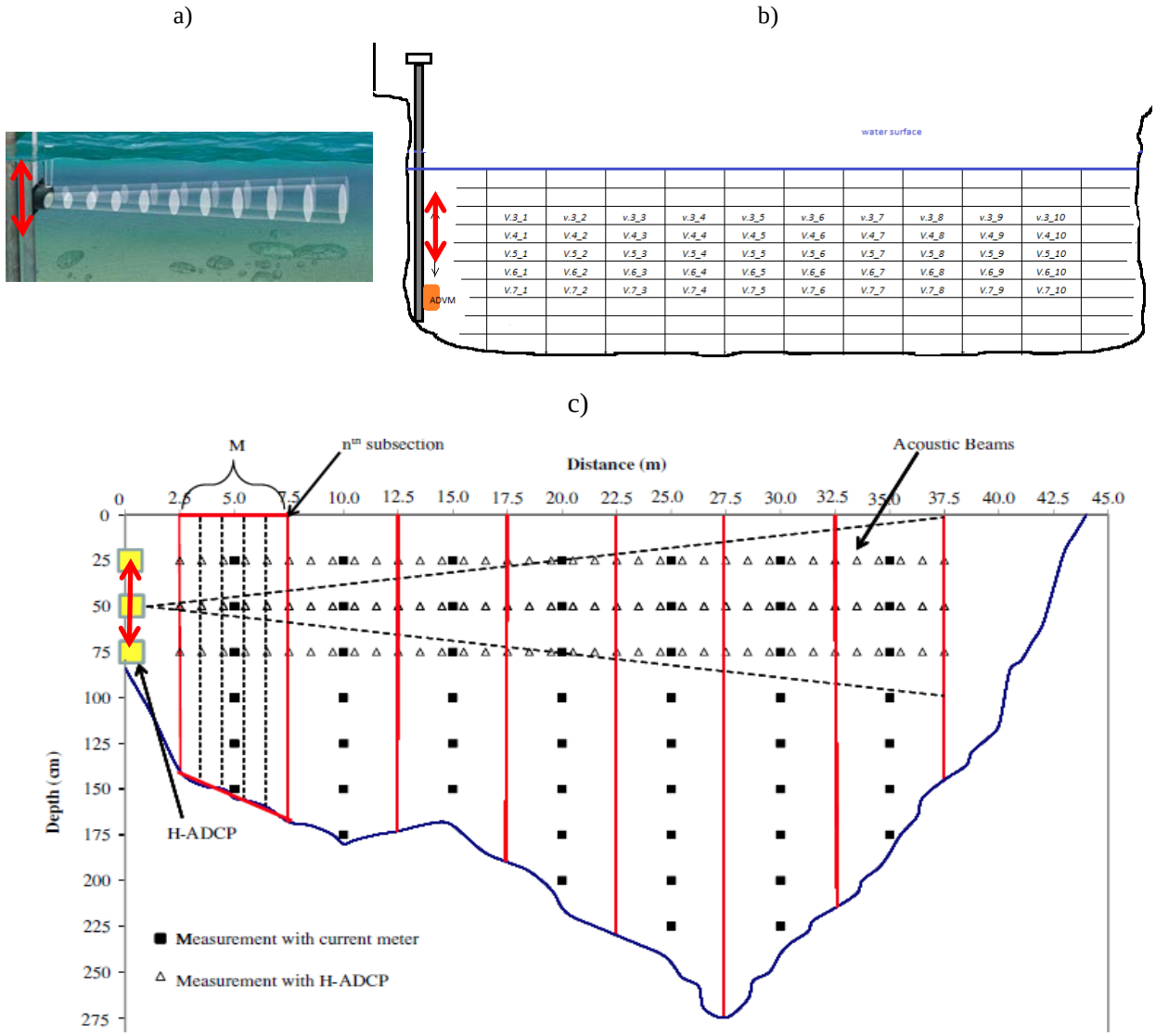


Figure 5.12. Q-Track installed at the Lemont gaging station: a) measurement concept (K. Oberg, Dec. 2018, personal communication); b) current measurement layout over the cross section (K. Oberg, Dec. 2018 personal communication); and c) sample approach for calculation of discharge over the cross section in streams with irregular bed (Vougioukas et al., 2011)

5.2.3. Relevant findings from studies on streamflow monitoring at Lemont gaging station

5.2.3.1. Overview

In the first five years following the movement of the LMDA primary streamflow station from Romeoville to Lemont, the focus of the USACE and USGS personnel engaged in the stream gaging was on building the new ratings for the AVM and ADVM and checking their performance through periodic verification measurements. Once the rating equations were established and calibrated, the discharge estimates produced by the new station were periodically compared with direct ADCP measurements and with the discharges estimated at the Romeoville gaging station. In addition, the discharge records acquired at the MWRDGC's Lockport Controlling Works and Lockport Powerhouse are occasionally used for checking the Lemont station performance over time. The comparison with the Romeoville AVM did not benefit

from a long enough record for a complete evaluation and were affected by some quality issues in the ADVM measurements at Romeoville (Espey et al., 2009). The MWRDGC records at Lockport were established in mid 1980s (Hart and McGee, 1985) and their accuracy have been, and continue, to be questioned to date. The USGS has attempted to improve these backup ratings (see Straub et al., 2012), but since the ratings at Lockport have never been used to estimate missing record at Lemont it is suggested that further rating work at Lockport be given a low priority for LMDA work in the future.

The next decade was almost exclusively focused on addressing the recommendations of the 6th and 7th TCs (Espey et al., 2009, 2014). These committees raised a number of questions concerning the flows and streamgage practices in the CSSC near Lemont. In particular, the TC expressed concern that the index-velocity rating—the method used to estimate mean cross-sectional velocity from a measured index velocity—may be subject to influences from the flow complexities developing in the CSSC (see Section 5.2.1). Among these complex factors, hysteresis has been the first concern because of the unique, unsteady hydraulics of the canal. Hysteresis in index-velocity ratings can occur at sites where the flow distribution in the channel varies significantly between the rising and falling limbs of the hydrograph. The report of the 6th TC dedicates a full section on observations on CSSC flows that the unsteadiness of the flow is a matter of concern and recommends a series of actions (Espey et al., 2009).

In addition to system unsteadiness, changes in the flow structure for various flow ranges (produced by draw downs and point flow releases) might introduce uncertainties both in the rating establishment as well as in their routine use. Despite the caution on the accuracy of the discharge estimates expressed by these committees, there is a total agreement that the use of the index-velocity method as a measurement protocol at the Lemont gaging site is the best solution for routine monitoring (Espey et al., 2009, 2014). Given the complexity of the measurement environment at the Lemont station a constant recommendation of several TCs was to assess the overall uncertainty of the discharge estimation using best analytical approaches and accounting for uncertainties in the instruments, measurement-environment induced uncertainty, and the additional uncertainties stemming from the construction and usage of rating curves over time. A summary of the findings gathered in the last decade of research at the Lemont station is summarized in Table 5.1. The table includes previous works reviewed by the 7th TC and the new relevant Lemont gaging station studies. The previous works are included because some of the findings in the reviewed works are still under investigation and because some of the newer studies reveal trends that complement or adjust findings of previous studies.

The studies summarized in Table 5.1 represent a logical succession for the investigation of the monitoring complexities in the CSSC and especially at the Lemont station. These studies attempt to isolate complexities one by one despite that they rarely occur as such. The approach is, however, justified from a logistical perspective, as it is extremely challenging to investigate multiple factors that are inherently connected. For example, the CSSC is under backwater, hence any unsteady flow created by, say, an operation at the Lockport Controlling Works will produce oscillations propagating in the CSSC closed system. These oscillations are more pronounced in the CSSC environment than in a typical open channel flow (Espey et al., 2014, p.101). If this effect is also combined with a draw down, the analysis becomes intractable through in-situ observations as the process includes superposed effects in a closed system prone to irregularly distributed friction losses and reflections from boundaries. The complexity of the flow conditions in the CSSC system challenges the interpretation of the results leading to conflicts in their interpretation; e.g., the initial findings ensuing from the power spectrum analysis developed by Jackson et al. (2012) are challenged by Espey et al. (2014, p. 102). From this respect the interpretation of some of the previous findings is still open to debate and requires even more investigation.

Table 5.1. Summary of the findings from the last decade of research on the Lemont gaging station

Reference	Main findings
Jackson et al. (2012)	The report analyzes the flow structure and index velocity measurements in the CSSC near Lemont, for a better understanding of the flow characteristics at this critical gaging site for LMDA. Among the main findings of the study are: • Despite that instantaneous flow profiles may be highly variable, time-averaged velocity profiles over larger time intervals (on the order of several days or larger) are generally consistent with open-channel flow theory. • The length of the averaging intervals is a work that needs to be further considered to establish an averaging interval that minimizes the error in monitoring for LMDA purposes. • Secondary currents developed at the gaging site are introducing errors in monitoring, especially for low flows. • Comparison of the rating curves for the AVM and H-ADCP demonstrates that the H-ADCP is a suitable replacement for the AVM as the primary index velocity meter in the CSSC near Lemont.
Jackson et al. (2013)	This report investigates whether hysteresis can occur at the Lemont gaging site, and the conditions under which it is likely to occur, by using both a theoretical approach and a three-dimensional hydrodynamic model. Among the main findings of the study are: • the theoretical analysis indicated the possibility of hysteresis occurrence at this site; however, the hydrodynamic conditions required to generate hysteresis are not present at this site based on historical data. • no substantial hysteresis was observed in the model-derived index-velocity ratings for any of the six simulated high-flow events ranging between 7.200 and 19,000 cfs. • a slight hysteresis occurs for the highest flows simulated in the model (cases 1 and 2 in the study) that is associated with the inability of the model to accurately capture the stage and discharge during the peak of the large flow events. This hysteresis is not supported by the field measurements captured for the same events. • The study concludes that if hysteresis in the index-velocity rating occurs at this site, it is small and likely to be well within the range of uncertainty due to other sources in field measurements of discharge and index-velocity used to develop the rating.
Muste and Lee (2013)	The study focuses on the impact of temporal flow variations in the CSSC on the accuracy of index-velocity rating curve (I-VRC) in use at the Lemont gaging station. Currently, the literature does not offer comprehensive criteria for evaluation of the methods for estimation of the departure of the looped rating curves from the steady ones nor for identifying the most appropriate means to dynamically capture hysteresis for different flow conditions. Among the main findings of the study are: • The superposition of the multiple types of perturbations occurring simultaneously in CAWS diminishes the overall impact of hysteresis at the Lemont station compared with a situation where each perturbation acts alone • Most of the calibration points currently used to develop the index-velocity ratings are collected during draw down episodes. Consequently, the I-VRC might be representative of this type of event but can display different trends for other types of unsteadiness in the system. • The index-velocity rating protocol for discharge estimation at Lemont captures more accurately the dynamics of the flow compared with the steady stage-discharge approach. • There is a need for re-thinking the index-velocity construction whereby the calibration points for the ratings are clustered according to the phase of unsteadiness propagation and the considerations of the sources of unsteadiness active during the acquisition of the measurements. Also important is to correlate the data acquisition with the lifetime of each unsteadiness source.

Over et al. (2017)	An end-to-end analysis of computed discharge uncertainty is being conducted for the streamgage at Lemont. Among the main findings of the study are: • In the first stage, the elemental error sources for stage, index velocity, and discharge are identified and estimated. • The elemental sources for stage and ADVM index velocity are estimated as 0.11% and 3.6%, respectively. The largest contributions to the velocity uncertainty are instrument accuracy and the change in the spatial flow distribution with the change in discharge. • These elemental errors were combined using rigorous uncertainty analysis methods using the GUM (1993) standard framework to obtain measurement error estimates, which appear reasonable. • The errors in velocity measured with the ADVM and AVM and the derived discharges are less than 10% except at very small and rare magnitudes. The estimates are incorporated into the index-velocity rating curve estimates by different linear regression methods. Implications for the computed discharges and their uncertainties also are investigated.
Jackson (2018)	This report presents results from more than 3.5 years of continuous monitoring data from the up-looking acoustic Doppler current profiler deployed at the Lemont gaging station. Among the main findings of the study are: • Substantiation of the flow variability in the vertical profile of streamwise velocity over a wide range of highly unsteady flows. Specifically, it was found that the flow becomes less uniform, develops higher gradient profiles, and becomes more logarithmic in shape as discharge increases. • Inverse stage-discharge relationships for the 0 to 12,000 cfs range and a positive one above 12,000 cfs. • The negative surges created by lockages at Lockport Lock propagate upstream creating hysteresis in the stage-discharge relationship and a differentiation of the peaks for discharge, velocity, and stage. The differences between surge velocity profiles for rising and falling limbs at the same discharge are attributed to the spatial separation of the instruments that translates in associated time lags. • Presence of seasonal, density-driven underflows driven by a combination of environmental variables at the gaging site. Most underflows occur during the winter, without substantially affecting the discharges reported by the USGS for the LMDA program. • The barge passes produce substantial decreases and increases in the median streamwise velocity; however, the discharges estimated at daily, monthly, and annual scales are not affected by these short-duration transitions that are relatively infrequent and equally distributed in the two directions of transport. • The uplooking ADCP discharges slightly underestimate the daily mean flows. These differences become statistically insignificant in the monthly and annual mean flows. • Following the 6th TC recommendation a new direct method for computing discharges with the up-looking and ADVM real-time measurements was developed. Although the computed mean discharges for the new computation method are higher than the ADVM-derived discharges, the monthly and annual means obtained with the two methods are not statistically different.

The other investigative alternative of the CSSC flow complexity is to tackle the problems one-by-one with numerical approaches rather than observed data. Such an effort is the complementary study carried out by Jackson et al. (2013) to investigate hysteresis in the CSSC. The study complements the companion experimental study carried out by Jackson et al. (2012). The numerical investigative alternatives used in the Jackson et al. (2013) study are also of limited value for the CSSC environment as even the most sophisticated models (that presumably can realistically replicate the fluid and structural changes in the

system) are associated with assumptions and they would also require accurate boundary and initial conditions that currently do not exist. Obtaining such input for the model require a full understanding of the overlapping processes in the CSSC system first, followed by the implementation of a measurement strategy to acquire the needed data with high spatial-temporal resolution with each process isolated to the maximum extent. Some of these aspects were exemplified in the study by Muste and Lee (2013). Actually, the later study conducted by Jackson (2018) using direct measurements with the uplooking ADCP do not confirm some of the numerical study conclusions as discussed below.

5.2.3.2. Recent Findings

This section discusses the findings of the studies that have not been reviewed by the 7th TC in Espey et al. (2014). These findings are the results of the work carried out by Over et al. (2017) and Jackson (2018) and they were triggered by the recommendations formulated by the 6th and 7th TCs. Those recommendations were mostly focused on a) the discharge data collection program at the Lemont gaging station; b) the improvement of the procedures implemented to improve the accuracy and reliability of the data collected at Lemont and at other gaging stations in the CSSC, and c) thorough evaluation associated in the monitoring program in the complex measurement environment in the CSSC, especially at the Lemont gaging station.

The first work reviewed in this section is the report prepared by the Jackson (2018) based on a design elaborated by the USGS in collaboration with the USACE. This study builds on previous investigations concerning the complexity of CSSC measurement environment and diligently ingests recommendations proposed by the 6th and 7th TCs to produce the most compressive and relevant study conducted so far. The findings of this study are obtained by supplementing the instrumentation used for routine measurements of discharge at the Lemont gaging station with an uplooking ADCP located just upstream of the station, as illustrated in Figure 5.9a. The 1200 kHz Rio Grande ADCP was operated in Mode 12 collecting 1-min and 15-min average profiles for 3.5 years. The addition of this instrument and the continuous data collection program shed light on several aspects of flow monitoring at the CSSC Lemont station from the evolution of the velocity profiles over the vertical in the presence of density-driven currents and tow passages to the impact on the larger-scale unsteadiness produced by operations at the Lockport controlling structures. Most important for the present context is the investigation of the implications of these perturbing factors on the streamgaging results and practices. The addition of the uplooking ADCP led to the development of two new methods for computing discharge that were subsequently evaluated to verify if they are of sufficient quality for LMDA purposes. The main findings of the Jackson (2018) study are briefly summarized below.

Changes in the flow structure with the flow range. As discharge in the CSSC increases, the vertical profile of streamwise velocity becomes less uniform, develops higher gradient profiles with the near-surface velocity increasing faster than the near-bed velocity, and becomes more logarithmic in shape. The median velocity computed for the 1-min ADVM data in cells 4 to 6 at 565.1 ft (i.e., the elevation of the ADVM) shows excellent agreement with the up-looking ADCP profiles for discharge ranges between 4,000 to 15,000 cfs. The ADVM shows a slightly lower median velocity than the up-looking ADCP for discharges below 4,000 cfs and a slightly higher median velocity than the up-looking ADCP at discharges above 15,000 cfs (see Figure 5.13). The difference between the uplooking ADVM and ADCP profiles is attributed to the physical separation between the two instruments and the effect of the negative waves propagating upstream when the Lockport Lock is filling.

The foregoing observations indicate the departure of the CSSC flow characteristics from those encounterd in natural-scale open channels due to the peculiarities of the pertubing factors acting in the CSSC system. Notable is that the combined impact of these factors also varies with the flow magnitude in the channel.

This variability is not natural either; for example the discharge range 6,000 to 12,000 cfs in the canal is primarily due to draw down events, which lowers the water surface elevation and produce the largest aspect ratio (i.e., width to depth) at the Lemont site. For this discharge range the velocity maximum is well below the water-surface height. Despite having lower aspect ratios, median velocity profiles at discharges less than 6,000 cfs and greater than 12,000 cfs do not show consistent evidence of a sub-merged velocity maximum. The depth of these velocity maxima below the water surface are substantially deeper than theoretical predictions from empirical equations (e.g., Yang et al., 2004). The cause of these submerged velocity maxima remains unclear.

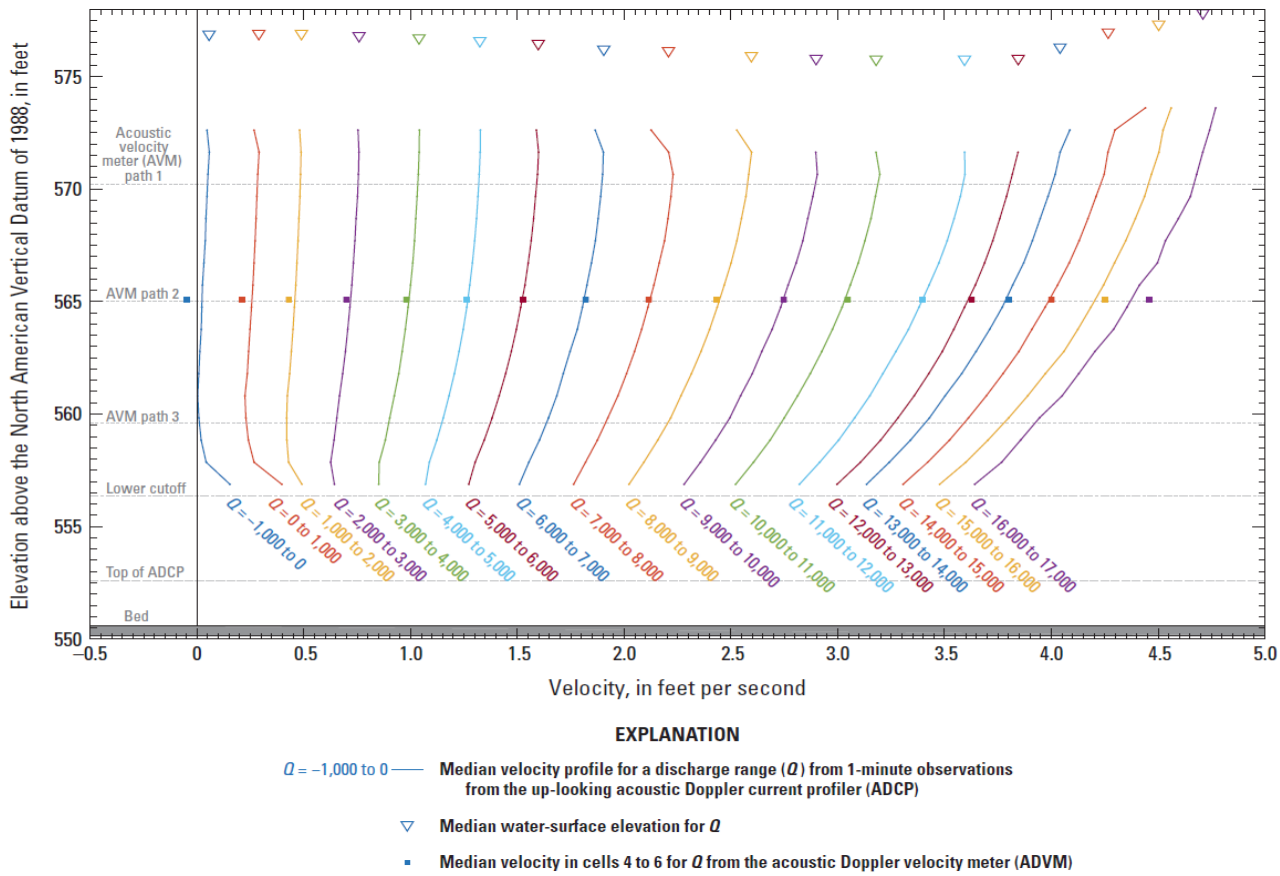


Figure 5.13. Median streamwise velocity profiles acquired at the Lemont gaging station (01/14/2014 – 07/10/2017) with the uplooking ADCP grouped by discharge magnitude (Jackson, 2018).

Density-driven seasonal changes in the flow structure. When the data collected with the uplooking ADCP are grouped seasonally, an inflection point in the median streamwise velocity profile and an increase in near-bed velocities are evident for flows as high as 5,000 cfs during the winter, because of flow features that are not present the summer, as illustrated in Figure 5.14.

The seasonal dependence of these features suggests that these near-bed velocity anomalies are real, are driven by environmental factors, and are not caused by flow disturbance by the ADCP mount on the canal bed (Jackson, 2018). This experimental evidence shows that the flow acceleration near the bed and shape of the winter velocity profiles are consistent with profiles of gravity currents (density-driven underflows) documented in CSSC before. Density-driven underflows have been observed in the Chicago Sanitary and

Ship Canal near Sag Junction (Jackson, 2016) and in the main branch of the Chicago River (Jackson et al. 2008) but this is the first time it has been reported at Lemont, contrary to what was concluded by the Espey et al. (2014, p. 101).

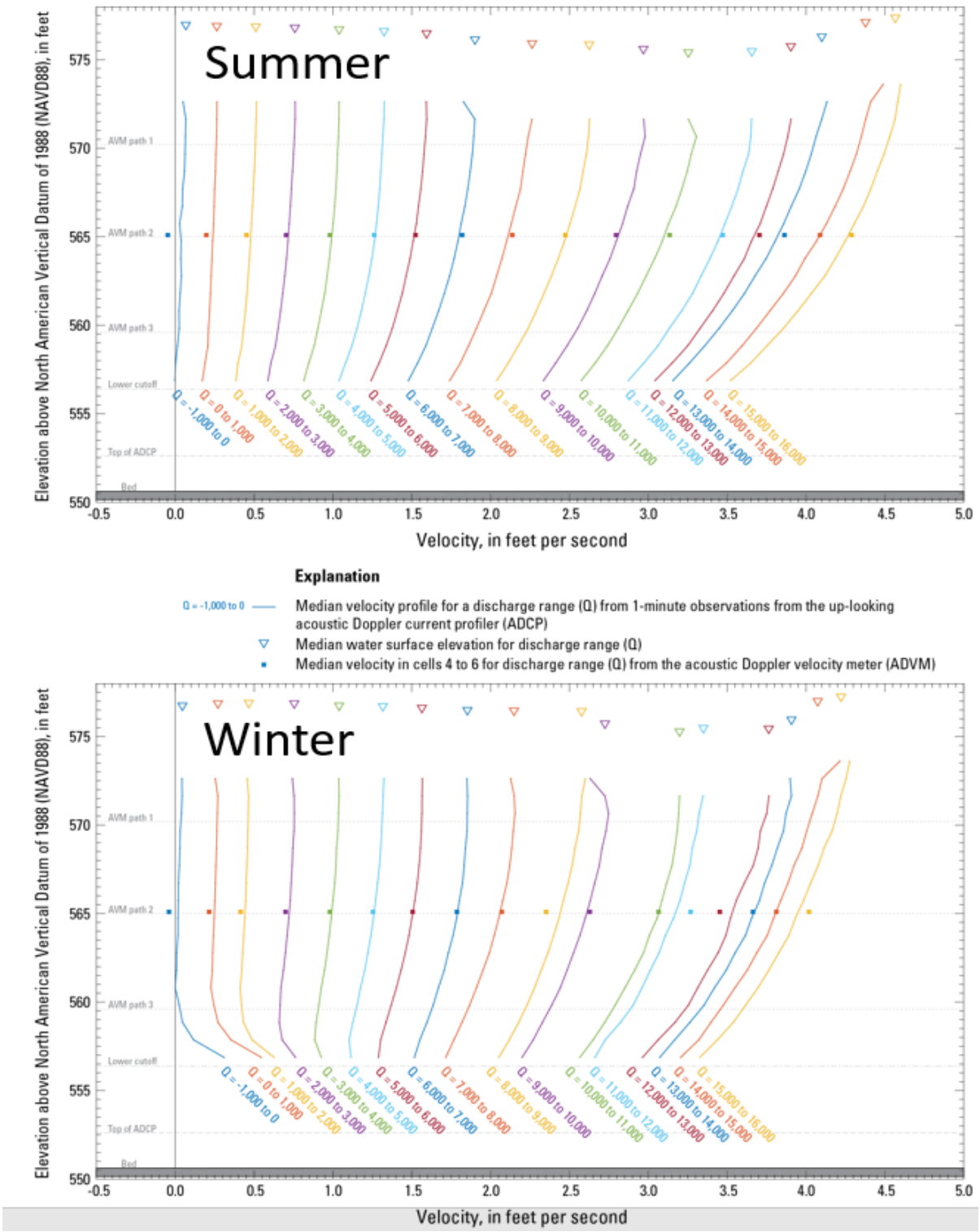


Figure 5.14. Median streamwise velocity profiles for the summer and winter months as documented by the uplooking ADCP at the Lemont gaging station (01/14/2014 – 07/10/2017)

Histeretic behavior in the flow phases of the hydrographs. When the 3.5-year dataset from the up-looking ADCP is sorted into observations on the rising or falling limb of a hydrograph, the median profiles for discharge less than 12,000 cfs show a slightly greater velocity and lower water surface elevation for the falling limb compared to the rising limb of the hydrograph for the same range of discharge (see Figure 5.15). For Q < 12,000 cfs, the difference in velocity was generally greatest in the upper part of the water column. Overall, the velocity difference was most pronounced between 2,000 to 6,000 cfs. Above 12,000 cfs, there is little to no difference in the velocity profile for the rising and falling limbs. The ADVM data show no consistent variation in velocity between the rising and falling limbs. Any differences observed are smaller in magnitude than those observed for the up-looking ADCP.

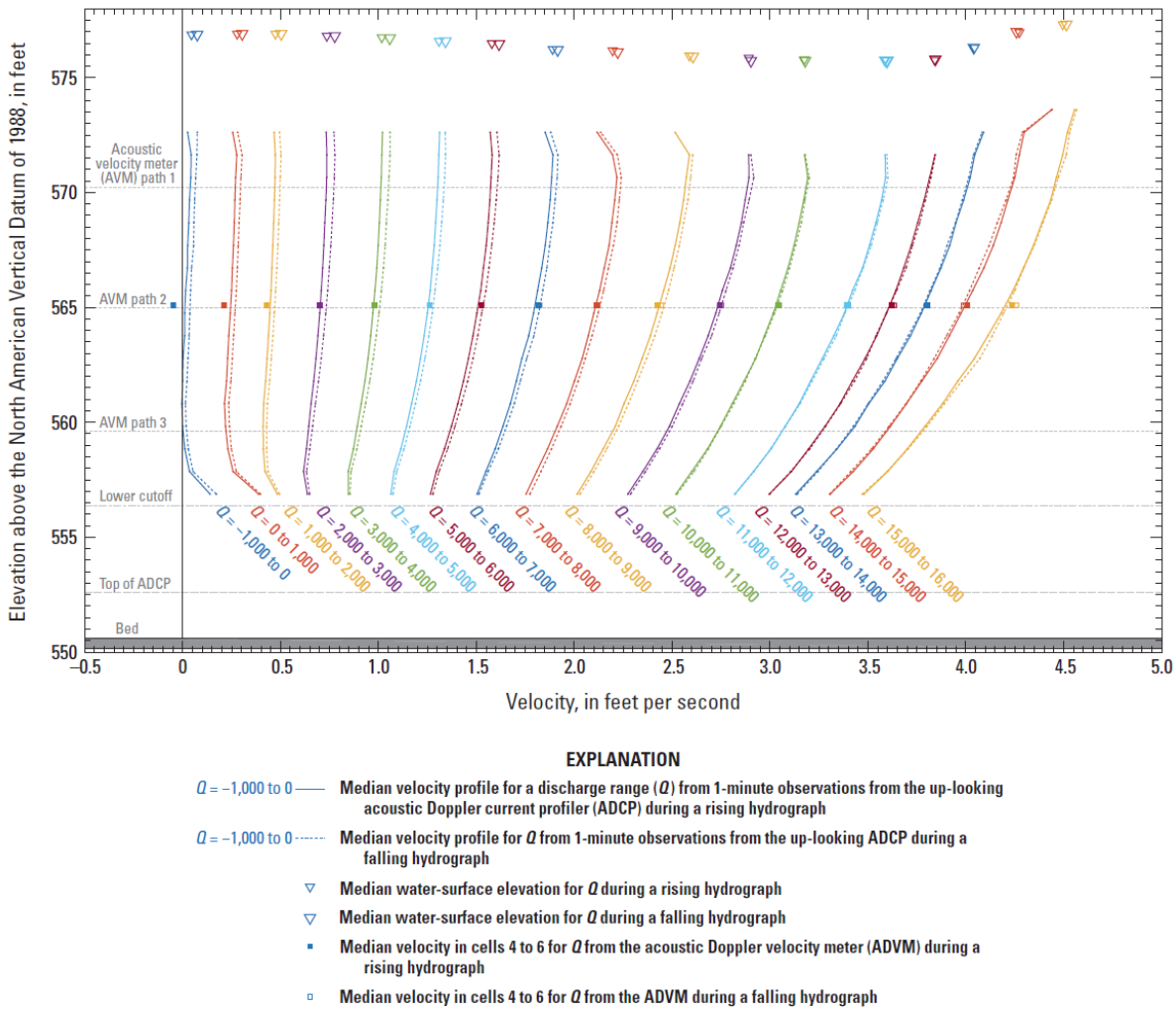


Figure 5.15. Median streamwise velocity profiles grouped by the phase of the hydrograph and discharge magnitude. Data collected with the uplooking ADCP at the Lemont station ((01/14/2014 – 07/10/2017)

The most pronounced hysteretic behavior is associated with the lockage surges (Jackson, 2018, Figure 15, p. 26). The separate analysis of the 8,545 lockage surges during the period of the up-looking ADCP deployment show trends that are consistent with the analysis of the entire dataset (as shown in Figure 5.15). The lockage surge dataset displays, however, a greater overall difference in velocity between the rising and falling limbs. According to Jackson (2018), a surge produced by a lockage at Lockport lasts 33.2 min to propagate to O'Brien Lock and Dam, resulting in a total accumulated time of 197 days of flow disturbance in the system for a total observation time of 1,278 days, revealing that this perturbation acting alone affects the CSSC system for 15 % of the CSSC data collection time.

The intriguing aspect of the hysteretic behavior is that the observed data indicate that the vertical profile of the streamwise velocity from the up-looking ADCP are generally faster on the falling limb of a hydrograph compared to the rising limb for the same discharge. This is quite opposite from the hysteretic behavior that is produced during the propagation of a flood wave in a natural channel where the rising limb experiences higher median velocities than on the falling limbs (Song & Graf, 1996). The hysteretic behavior in natural channels displays phase (time) shifts between the hydraulic variables peaks. The velocity is coming first followed by discharge and then stage (Song and Graf, 1996). A reverse trend is observed for the hysteresis due to lockages in the CSSC (i.e., the discharge peak at the uplooking ADCP occurs after the discharge peak at the ADVM). The explanation for this inconsistency is attributed by Jackson (2018) to the spatial separation of 170 ft between the instruments that translates to a 2-min median time lag in the time series of the variables. It is deemed that the shift in time of the time series brings the peak sequences to the expected order.

Tow passages through the station. The presence of the uplooking ADCP also allowed the timing and the changes produced by barges passing through the gaging station to be determined. Neither the ADVM nor the AVM currently are suitable for barge detection (Jackson, 2018). The ADVM is too deep in the water column to detect tows. Path 1 of the AVM (highest in the water column) is consistently blocked by passage of loaded tows making the AVM a possible barge-detection tool. Unfortunately, path 1 of the AVM began intermittently failing during the duration of Jackson's (2018) analysis so there is no final conclusion on the AVM to sense barge passings. Detection of the barge passing presented in Jackson (2018) is solely based on the uplooking ADCP complemented by the barge detection camera deployed at the site (See Figure 5.11) that was also used as reference for the analysis.

During the 3.5 years of data record with the uplooking ADCP, there were 2,500 downstream-bound and 3,990 upstream-bound loaded tows. The loaded tows produce a decrease in streamwise velocity of about 0.47 ft/s for downstream-bound tows and an increase in streamwise velocity of about 0.54 ft/s for upstream-bound tows. The empty tows naturally produce less disturbance and currently are not reliably detected by the uplooking ADCP. Based on the analysis of more than 6,400 loaded-tow passages, it was found that despite producing a substantial change in the velocity field as a tow passes the gage, the short duration (typically less than 1 min) and relatively infrequent passages result in negligible changes in discharge when discharge is computed at the daily, monthly, and annual time scales. The evaluation of the 1-min tow passage duration for a 10-min discharge measurement made during a tow passage would change the daily mean discharge with less than a 0.2 percent. For this reason, data screening to remove data affected by tow passages is not deemed necessary at this time. Therefore, the effect of navigational traffic on discharge measurement in the canal near Lemont, Ill., is negligible compared to other sources of error.

Inferences on streamgaging practices from the use of the uplooking ADCP data. Following the thorough documentation of the flow perturbations generated by various sources as previously reviewed, the study by Jackson (2018) assesses the performance of two methods of using the index-velocity in conjunction with the uplooking ADCP measurements as index-velocity. The first method (labeled M1) uses in the index ratings calibration points obtained with multiple-transect ADCP discharge measurements. This method compares well with the index-velocity rating curve using the ADVM as the instrument for the index velocity. While differences are found between the daily mean flows determined with the ADCP- and ADVM-based methods at high flows (> 5,000 cfs), the monthly, and annual averages are not significantly different. The second method (labeled S1) builds the index-velocity ratings by pairing the uplooking ADCP data and calibration points obtained with single-transect ADCP discharge measurements. Similar to the M1 rating, only the daily mean flows differ statistically at the 5-percent significance level. The S1 method performs slightly better than M1. However, given that the longer-term

discharges obtained with the two methods are close to the discharges computed from the ADVM ratings, there are no reasons to deviate from current practices of building the rating curves with ADVM index velocities (Jackson, 2018).

Finally, a direct method for estimation of discharges at the Lemont station was developed by Jackson (2018). Specifically, direct measurements are obtained by combining the direct uplooking ADCP and ADVM data as recommended by the 6th TC. The combination uses a modified velocity profile whereby the velocity profile over the vertical from the up-looking ADCP is shifted across the width based on several assumptions, ultimately yielding an estimate of the mean velocity for the cross section and discharge (Jackson, 2018). This newly developed method produced discharge records that compare well with the official discharge records produced using the ADVM index-velocity for the period of record (01/14/2014 – 07/10/2017). The direct method also adequately reproduces high, low, and reverse flows; and captures the highly variable flows related to passage of lockage surges.

Similar to the findings from the other two alternatives to estimate discharges (i.e., M1 and S1 previously discussed), the daily mean discharges for the direct computation method are higher than the ADVM-derived discharges, while the monthly and annual mean discharges computed using the direct computation method are not statistically different. Given that for the purposes of LMDA, the assessment of the withdrawals from Lake Michigan is based on an annual mean discharge, Jackson (2018) concludes that the use of the proposed direct computation method using both the uplooking ADCP and ADVM data is an acceptable alternative method for this study. However, the proposed method is more expensive (relies on two instruments being operational compared to one for the index-velocity method and additional analytical work) without producing better results for the study purpose, so it is not justified to replace the current discharge estimation protocols at this time.

Uncertainty analysis. The study of Over et al. (2017) advanced the work on uncertainty analysis by: a) adopting for the first time a standardized methodology for the estimation of uncertainty, and b) estimating sources for the instrument involved in the estimation of discharge at the Lemont station. The uncertainty analysis is applied to the streamgage near Lemont, IL, that measures ≈ 90% of the Lake Michigan diversion. Since 2005, this station has been the primary measurement point for diversion accounting. The methodology used for uncertainty estimation and propagation of uncertainty to discharge estimates follow closely the framework of the Guide to the Expression of Uncertainty in Measurement (GUM, 1993) developed by the Joint Committee for Guides in Metrology (JGCM, 2008). This framework was recently adopted as the recommended uncertainty analysis standard for hydrometry (Muste, 2017). This is a commendable effort that aligns well with the efforts of the USACE and USGS to adopt the most recent developments in the area of hydrometry.

The Lemont streamgage station utilizes a non-contact pressure transducer in conjunction with a gas-purge bubbler system for stage (water level) measurements and an ADVM in an index-velocity rating (IVR) approach to compute continuous discharge at this location. The elemental sources of uncertainty for each instrument are identified and characterized using manufacturer's specifications, field experience, and best engineering judgement. Elemental sources of error associated with the measurement of stage and velocity were combined by using QMSys (www.qsyst.com), a software package developed for the World Meteorological Organization (WMO) that works within the GUM framework.

Sixteen elemental sources of error were identified as being associated with the measurement of stage. These include the following: datum errors; local disturbances; accuracy; resolution; calibration; water surface-sensor-recorder; timing; datalogger; gage offset; data recorder; data retrieval; periodic stage correction; operational issues; and hydraulically-induced, temperature, and temporary flow disturbances. Sixteen sources of errors were deemed to have no effect or near-zero contribution to the total uncertainty.

A typical value for the total uncertainty in stage measurement is 0.00826 m, representing 0.11% of a typical stage in the CSSC at the Lemont gage (7.55 m). The largest contributor to the total uncertainty is associated with the local disturbances related to the very unsteady flow conditions within the CSSC (i.e., 54.4%) followed by equal contributions from resolution, gage offsets, and periodic stage corrections, and accuracy of the stage sensor.

Fifteen elemental sources of uncertainty were evaluated for inclusion in the uncertainty analysis of ADVM-measured velocity (see Figure 5.16a). Of these, eight were judged to contribute measurably to final uncertatinty. Using the QMSys software the typical estimated standard uncertainty is 3.63% of the measured velocity of 0.0981 m/s (0.32 ft/s). For the whole range of measured velocities from -0.45 to 1.83 m/s (-1.5 to 6.0 ft/s), the standard uncertainties vary from 87% at 0.0030 m/s (0.01 ft/s) (the smallest-magnitude velocity) to 2.5% for 1.83 m/s (6.0 ft/s) (the largest-magnitude velocity), as illustrated in Figure 5.16b. Based on the QMSys analysis, the two largest contributors to the uncertainty for the aforementioned velocities are the errors due to instrument accuracy (30.8%) and changes in spatial flow distribution (29.7%) as shown in Figure 5.16c. The AVM results for the AVM is shown in Figure 5.16d.

An important practical aspect for the implementation of a rigorous method is the fact that the uncertainty analysis not only provide a defendable statement of the accuracy of the measurements but also informs the users about the relative contribution of the elemental uncertainty sources to the final result of the measurements. For example, the uncertainty of the elemental sources of uncertainty in the measurements with the ADVM illustrated in Figure 5.16c indicates the ranking of the elemental sources of uncertainty contributing to the total index-velocity measurement accuracy. The availability of the budget of elemental uncertainties for each instrument guides the operator on the priority that needs to be implemented in that measurement to enhance the overall accuracy. The use of the software also allows a sensitivity analysis to be conducted of the impact of various components of uncertainty.

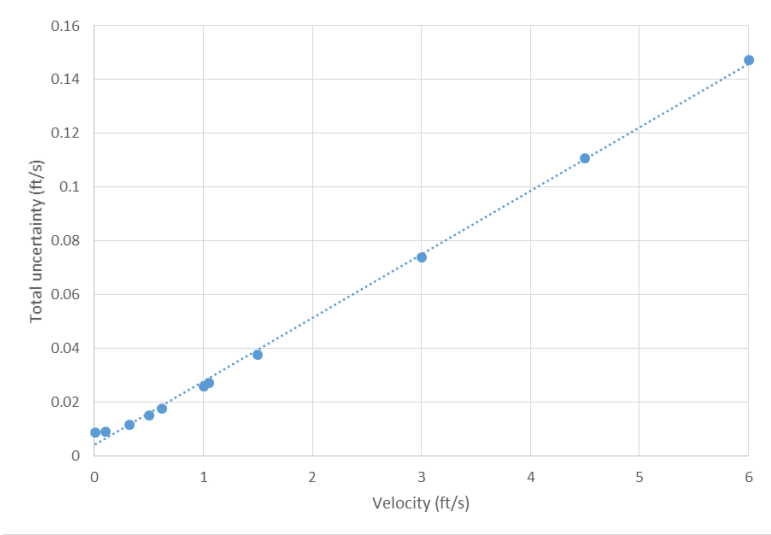
The availability of the total uncertainties for each instrument involved in the index-velocity measurement allows to subsequent estimation of the overall uncertainty of the discharge estimated as determined with the index-velocity method. In the index-velocity approach, the stage data are used to compute a wetted cross-sectional area. A stage-area rating curve based upon channel survey data is used to compute the wetted cross-sectional area from the stage data, and, in turn, to convert the measured discharges to velocities for use in constructing the index-velocity rating (IVR). Following Duncker et al. (2006), the uncertainty of the stage-area rating is neglected in the preliminary analysis because the effects of stage-area rating errors on the measured velocities are reversed when the stage-area rating is used to compute discharge. Combining the ADCP-based measured velocities and the ADVM-based index velocities during the ADCP measurements allows construction of the IVR (Over et al. 2017).

Typically the IVR is fitted using ordinary least-squares linear regression. Variable independent and correlated errors in the dependent variable (ADCP velocity) can be accounted for by using weighted least squares (WLS) and generalized least-squares regression, respectively. These different regression methods provide a hierarchy of increasingly general ways to account for uncertainties in the ADCP and ADVM velocities. The estimation of the ADCP direct measurements used in building the IVR and the IVR uncertainty associated with its construction are ongoing. Currently, the USGS is exploring the adoption of a Bayesian approach for discharge estimation whereby hydraulic information and uncertainty in gaging estimates are continuously combined over time (Le Coz et al., 2014).

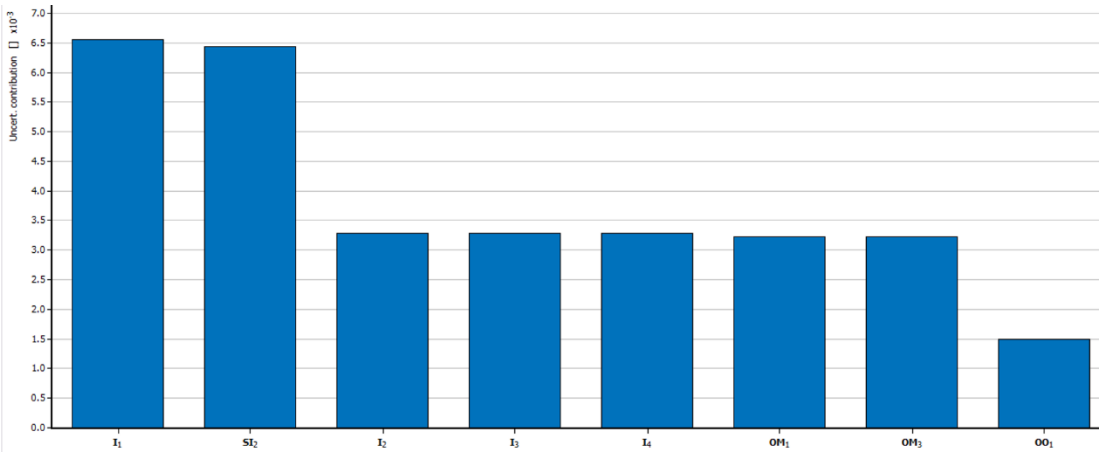
a)

Error source	
SI_1	Beam orientation
SI_2	Spatial flow distribution
I_1	Accuracy
I_2	Resolution
I_3	Factory settings
I_4	Analytical methods
OC_1	Measurement volume setting
OC_2	Sampling frequency
OC_3	Sampling time
OC_4	Time synchronization
OC_5	Data Logger
OC_5	Compass
OO_1	Salinity input
OM_1	Wind-induced shear
OM_2	Acoustic path deflection
OM_3	Temporal flow distribution

b)



c)



d)

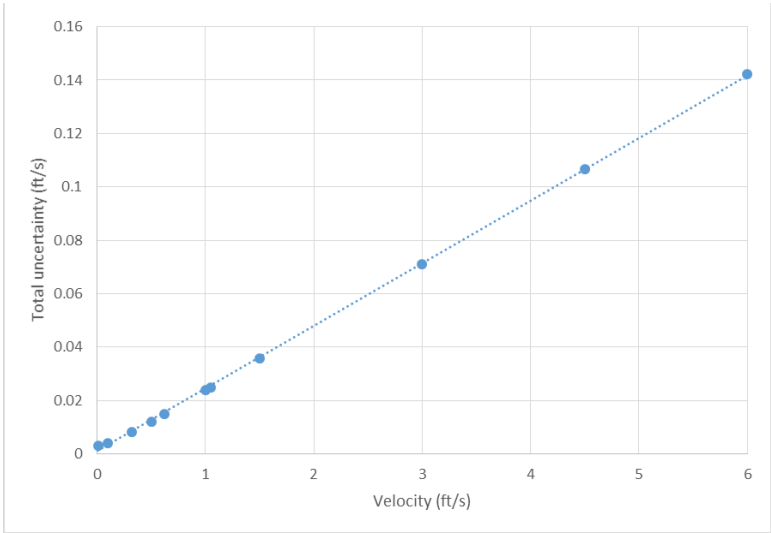


Figure 5.16. Results of the GUM (1993) uncertainty framework applied to the instruments used for estimation of discharges via index-velocity method at the Lemont gaging station: a) elemental error sources in ADVM measurements; b) uncertainty in ADVM measurements for the instrument flow range; c) budget of the elemental uncertainty sources for the measurements with ADVM; and, d) uncertainties in AVM measurements for the instrument flow range

5.2.3.3. Concluding Remarks

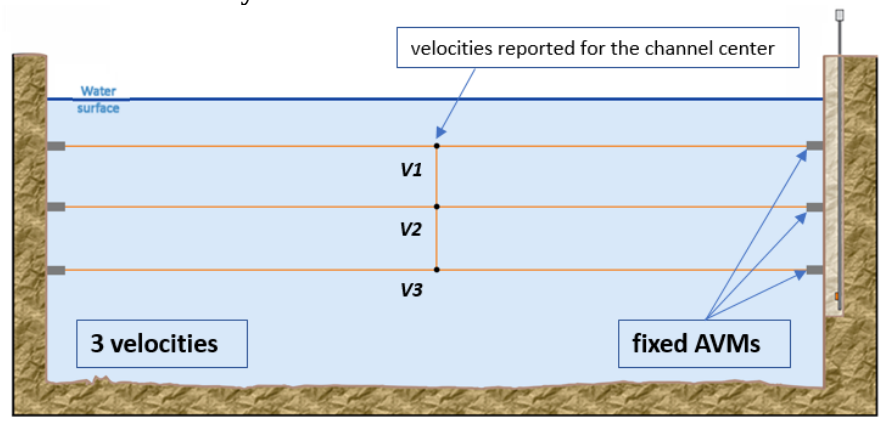
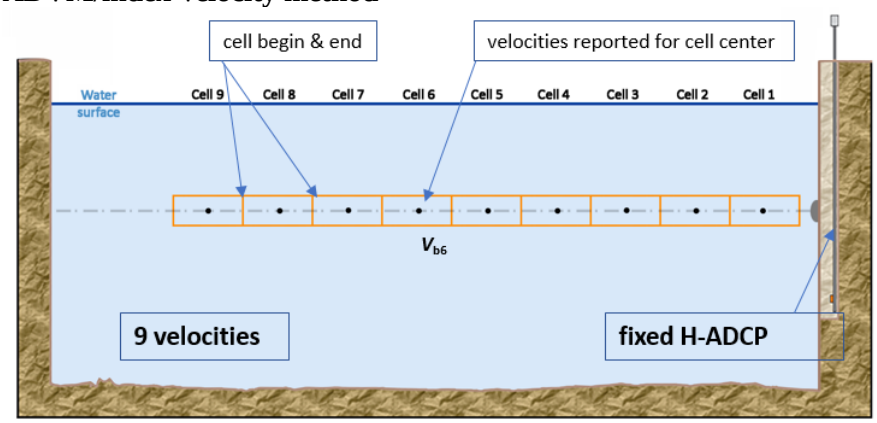
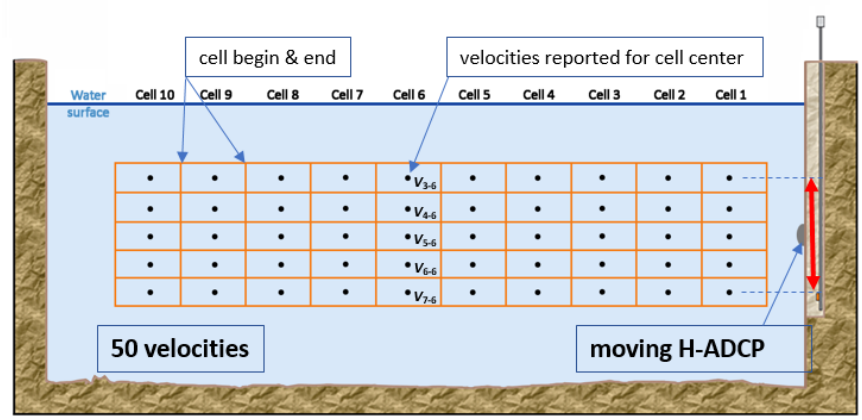
The 8th TC is pleased with the efforts and progress achieved by the USGS with support from the USACE. The monitoring team have not only adopted and met the **"best current engineering practice and scientific knowledge"** but contributed through their pioneering efforts in CSSC flow monitoring to the developing of cutting-edge protocols supported by the most advanced measurement technologies. The results of this work can be applied in many other complex measurement environments. This statement is compellingly supported by the intensive work conducted over the last 15 years as well as the continuous innovation in the flow monitoring protocols flows applied at the Lemont gaging site (the primary source of directly measured data for the LMDA). Especially relevant for this statement are: a) the results ensuing from the up-looking ADCP deployment (Jackson, 2018), b) the work initiated on the estimation of the uncertainties at the Lemont gaging station, and, c) the ongoing efforts to develop the Q-Track, a new protocol to measure the discharge in real-time with high temporal resolution. Given the importance of the current and future developments for the overall assessment of the LMDA study, they are summarized succinctly below. Recommendations of several aspects of the flow monitoring associated with the LMDA study are summarized in the next section of the report.

Currently, most of the streamflow at the nation's index-velocity gaging stations is typically provided by rating curves that relate variables through a one-to-one V_{index}-V_{mean} relation. This relation is unquestionably valid if the flow through the cross section is uniform, steady, and without backwater effects. Any complications that produce changes in the flow structure through the station with the magnitude of flow needs special attention. The rating curve estimated on the basis of a single-valued rating curve assumption becomes inaccurate if any of the foregoing assumptions are violated. Levesque and Oberg (2012) prescribe criteria for validating the type of rating (analysis of the coefficients of determination trends, standard errors, and residual plots). They also prescribe protocols to adjust the ratings with additional variables; typically, the flow stage. The main concern for the present context is the effect of the flow unsteadiness as this is ubiquitous in the CSSC measurement environment.

Following the study by Jackson (2018), the problem of time transients is well documented. The long-term application of an up-looking ADCP in the CSSC near Lemont, has enabled examination of the monitoring at this station from a new perspective: one that is not possible with the horizontally oriented instrument deployed at the site. Jackson (2018) summarizes results from more than 3.5 years of continuous monitoring data from an up-looking ADCP at the study site allowing the characterization of the variability in the vertical profile of streamwise velocity over a wide range of highly unsteady flows, from tow passages to operation at the controlling structures in the CSSC. These data also revealed other complexities active in CSSC such as the seasonal, density-driven underflows triggered by a combination of environmental variables. Two new methods for computing discharge were developed using this instrument and were of sufficient quality for LMDA purposes. Finally, the up-looking ADCP and barge-detection camera allowed the effect of commercial tows on streamgaging at the site to be evaluated. The results ensuing from Jackson (2018) address most of the concerns expressed by the flow measurement experts of the 6th and 7th TCs regarding the current streamgaging practice.

A full characterization of the flow unsteadiness is expected from the implementation of a new direct discharge measurement method (i.e., the Q-Track) installed by USGS in the Spring of 2017. The successful implementation of Q-Track system will offer a state-of-the-art methodology to directly measure discharges with high spatial and temporal resolution on par with the data directly acquired with ADCP transects currently used to build the ratings at the station. Table 5.2 illustrates the time progression of the continuous improvement of the gaging protocols at the Lemont gaging station and the transition from index-velocity ratings to direct discharge measurements.

Table 5.2. Progression of the velocity measurement instrumentation at the Lemont station (2004-present)

Velocity measurement layout	Specifications
AVM/index-velocity method	
	Mean V_{index}: $V_{AVM} = \frac{1}{n_p}\sum_{i=1}^{n_p} V_i$ $i = 3$, $n_p = 3$ Sampling time: 2, 10 mins Reporting time: 10 mins
ADVM/index-velocity method	
	Mean Vindex: $V_{H-ADCP} = \frac{1}{n_c}\sum_{i=1}^{n_c} V_{b_i}$ $i = 9$, $n_c = 9$ Sampling time: 1min Reporting time: 1 - 10 mins
Q-Track/Direct discharge velocity area method (mid-section) & other possible options	
	• depth-averaged velocity: mean of 5-cell velocities/vertical • 10 depth-averaged velocities over the cross section are X area of the associated panel • unmeasured area filled with extrapolation algorithms Sampling time: 10 mins Reporting time: 10 mins

In parallel, the LMDA monitoring team adopted internationally accepted standards for the conduct of uncertainty analysis and implemented them in practice (Over et al., 2017). This adoption enables to currently state with confidence that the Lake Michigan Diversion Accounting is accomplished within specified uncertainties in a complex measurement environment that for many other agencies appear intractable. Valuable information on uncertainty sources are expected from the proposed investigation

with the Q-Track. It is expected that the successful implementation of Q-Track will not only quantify unknown uncertainties but will offer a state-of-the art methodology to directly measure discharges with high spatial and temporal resolution on par with the quality of the direct ADCP transects currently used to build the ratings at the station. Once the methodology and implementation aspects are finalized, the Q-Track can become the primary measurement standard at the Lemont gaging station with the time- and cost-intensive index-rating becoming secondary (backup) measurement methods.

5.3. Recommendations for flow measurement area

Similar to the preceding review committees, the 8th TC overall is pleased with the efforts of the USACE to address the plethora of issues raised by the committees over time and the follow-up work carried out with distinguished attention and ingenuity by the USGS streamgaging team. It is a known fact that the measurement environment at Lemont, and in general in the whole CSSC system, represents a continuous challenge irrespective of the methods and instruments used for flow monitoring. From this perspective, the tasks tackled by this team is in many respects pioneering work in the area. The technical level of these efforts exceeds the level of **"the best current engineering practice and scientific knowledge in hydrometry"**. Many of the lessons learned during the investigation of the problems at the Lemont station became integral parts of the guidelines and operations for other stations in the nation.

5.3.1. Status of the recommendations formulated by the 7th TC

The recommendations of the 7th TC - Flow Measurement issues have been the subject of actions during and after the activity of the previous committee and were reiterated on the item agenda of the 8th Technical Committee as necessary when observed that they have not been addressed or solved at that time. Excerpts below are from Espey et al. (2014) and contain the relevant issues still pending during the 8th TC activity. The recommendations/findings of the 7th TC and the degree of resolution of each resolution at this time are provided in Table 5.3.

5.3.2. Summary of 8th TC Flow Measurement Expert findings and recommended action items

It is apparent from the analysis previously presented that the USGS with the considerable support of the USACE has applied **best current engineering practice and scientific knowledge** to the measurement of flow at the Lemont gaging station. Factoring in all of the complexities of attempting to measure extremely low and unsteady velocities in the CAWS, it appears that the flow records developed for WYs 2010 through 2015 are reasonable. The series of direct interactions and associated discussions along with the site visits and interactions with the people from agencies involved in the LMDA led to a productive dialogue that illustrated the continuous effort of the agencies involved in the local management of Lake Michigan resources to upgrade the infrastructure and methods used to monitor the flow diverted in the CSSC. The dialogue progressed from meeting to meeting narrowing the focus to the most important issues confronting the current monitoring activity. Table 5.4 lists the recommendations of the future actions needed in the flow measurement area.

Table 5.3. Recommendations of the 7th TC and their resolution status

Topic	Item description (observation code)	% resolution/ Relevant reference
Uncertainty Analysis (UA) & Quality Assurance (QA)	Once standard uncertainty procedures are developed, measurement uncertainty should be estimated for the ADCP measurements. These should then be used to estimate the uncertainty of the LMDA estimated from AVM and ADVM measurement sites (6.3.1).	**60%** Over et al. (2017)
	ADVM Measurement: UA should be performed on the ADVM measurement site. (6.3.1.2)	**100%** Over et al. (2017)
	Periodic check if the cross-sectional at AVM and ADVM sites should be part of the USGS Quality Assurance Plan (6.3.1.1).	**100%**
	Frequency of index-velocity re-calibration should be included in the USGS Quality Assurance plan (6.3.2).	**100%**
Flow Unsteadiness	The USGS should continue ADCP data collection during the rising limb of a hydrograph (6.3.3).	**100%** Q-Track installation
Velocity Distribution Over the Vertical	The USGS should continue use of the up-looking ADCP to evaluate the vertical velocity distribution at the Lemont gauge, and its influence on the uncertainty of diversion accounting (6.3.4).	**100%** Jackson (2018) & Q-Track installation
Rating Curve Improvement	During ADCP calibration events, the USGS should experiment with using individual transects in the calibration, resulting in multiple values for a single calibration point. This might identify whether or not reflection waves are influencing the calibration of the index-velocity method (6.3.5).	**On-going**
Summit Conduit	USGS should evaluate the possibility of locating the Summit Conduit measurement station at the downstream end of the conduit, and placing a small weir there to increase flow depths during low flow periods (6.3.6).	**On-going**
Reliability of Lemont Gaging Station Measurements	Back-up power should be considered for the Lemont Gaging Station (6.3.7).	**100%**
AVM System	The AVM should be maintained as long as maintenance costs are reasonable. If the system needs replacement or the cable is cut again, the USGS should consider changing to a system that does not require a cable (6.3.8).	**100%**
Lockport Powerhouse and Controlling Works	The USGS should continue to explore improved calibrations of discharge measurements at Lockport Powerhouse and Controlling Works (6.3.9).	**On-going**

Table 5.4. Recommendations of the 8th TC Flow Measurement Expert

Topic	Recommendation description	Comments
Uncertainty Analysis & Quality Assurance	5.3.2.1. Using the GUM standard uncertainty procedures (JCGM, 2008) estimate the total uncertainty in the discharge used for calibration and verification of the index-velocity ratings collected with ADCP transects at the Lemont station.	Acquire companion measurements with Q-Track
	5.3.2.2. Using the GUM standard uncertainty procedures estimate the total uncertainty in the discharge estimates obtained from the index-velocity method used in conjunction with AVM, ADVM, and ADCPs with appropriate considerations of the uncertainties associated with the construction of the ratings themselves.	Guide analysis with Over et al. (2017)
	5.3.2.3. Using the GUM standard uncertainty procedures estimate the total uncertainty in the other direct measurements used in the LMDA annual reports, i.e., precipitation gages, and flow meters at water intakes.	Guide analysis with Over et al. (2017)
	5.3.2.4. Assemble uncertainty analysis results obtained above to estimate the overall uncertainty in the LMDA with consideration of all directly measured variables and uniform estimation of the uncertainties in measured flow components.	Guide reporting structure by USGS preliminary template.
Stream Flow Monitoring at the Lemont gaging station	**Q-Track related**	
	5.3.2.5. Accelerate the implementation of the Q-Track instrumentation and ancillary protocols at the station.	
	5.3.2.6. Rethink the vertical traversing mechanism for the Q-Track by adopting a “dry” actuator (located on the top of the traverse rather than the current submersed solution) for the scanning mechanism.	Guide system design with Vougioukas et al. (2011)
	5.3.2.7. Identify the sources of uncertainty in the measurements with Q-Track and adopt GUM standard for estimation of direct discharge measurement uncertainties.	Guide analysis with Over et al. (2017)
	5.3.2.8. Organize intensive data acquisition campaigns with Q-Track, ancillary equipment, and ADCP transect measurements for Q-Track evaluation as a primary standard for the Lemont gaging station.	Apply the USGS proposal presented in Workshop III.
	5.3.2.9. Complement the Q-Track data acquisition with records of known or observable large sources of perturbations in the CSSC system; i.e., draw downs, operations at the controlling structures, density currents, barge passages (see section 5.2.1).	
	5.3.2.10. Remove from the flow measurement reporting the flow events with large sources of perturbations. Compare daily, monthly, and annual flow budgets through the station for evaluation of alternative reporting approaches.	
	Index-velocity ratings using AVM and ADVM	
	5.3.2.11. Use the results of the activities recommended at items 5.3.2.5 through 5.3.2.10 to evaluate the index-velocity ratings performance subjected to large sources of perturbations in the system. Cluster the calibration data for the ratings according to the phase of the perturbations (i.e., distinguishing between the rising and falling limbs of inflow hydrographs produced by storms in the watershed) to differentiate the dynamic vs. quasi-steady state of the flow in the CSSC system).	Follow Jackson (2018) for clustering and Levesque and Oberg (2012) – for general evaluation.
	5.3.2.12. Evaluate if segmentation of the ratings based on the type of transients occurring in the CSSC is needed to accommodate for their impacts of the flow structure at Lemont.	Follow Ruhl and Simpson (2005) protocol.

	5.3.2.13. Evaluate the results at item 5.3.2.10 to conclude on the index-velocity performance in complex measurement environments. Decide on protocols and instrumentation to be used for the index-velocity based ratings as primary or secondary flow measurement standards at the Lemont gaging station.	
	5.3.2.14. Develop hybrid protocols for the index-velocity ratings using directly measured data with analytical models derived from Lemont-focused numerical modeling (Jackson et al. 2013).	Use Nihei and Kimizu (2008) and Hoitink et al. (2009).
Stream Flow Monitoring in CSSC	5.3.2.15. Continue to cooperate with USGS and other local stakeholders to ensure that an efficient and robust streamgaging network in the CSSC is maintained that meets LMDA mission requirements.	Requirements are detailed in the 8th LMDA TC letter to the Corps.
	5.3.2.16. The 8th TC feels that flow measurements for the Summit Conduit are of limited use for LMDA and should have a low priority.	
	5.3.2.17. Despite that the calibration of discharge measurements at Lockport Powerhouse and Controlling Works has been carried out over many years, it is still under evaluation and have never been used to estimate flows at Lemont. The 8th TC feels this should have an extremely low priority for the near future given the other more promising flow measuring methods currently under consideration (Q-Track).	
Precipitation network	5.3.2.18. Following the replacements of the old sensors, proceed with a thorough evaluation of the raingage networks.	
Overall LMDA process	5.3.2.19. Speed up the processing of the annual Water Year reports and make them available to the LMDA TCs with minimum backlog.	
	5.3.2.20. Improve the means to visualize the presentation of the LMDA budgets (i.e., inflows, outflows, and their locations) and their estimation procedures (i.e., direct measurements, numerical models) using contemporary interactive tools such as those enabled by web-based GIS platforms.	

6.0 Comments and Recommendations

6.1 General Comments

Early in its activity, the 8th TC was concerned to learn that key components of the Lake Michigan Diversion Accounting (LMDA) system might be in jeopardy for continued full operations (measurement of stage and discharge) as a result of budget cuts resulting in eliminating support for six of the streamflow gages currently used in the LMDA system (see location of the stations on the map in Figure 5.2):

1) Little Calumet River at Munster, Ind. (a key gage for determining the Indiana water supply reaching the State of Illinois, a subtraction from the flow measured at Lemont);
2) Grand Calumet River at Hohman Avenue in Hammond, Ind. (a key gage for determining the Indiana water supply reaching the State of Illinois, a subtraction from the flow measured at Lemont);
3) North Branch of the Chicago River at Niles, IL. (a major tributary to the Chicago Area Waterway System (CAWS) and key data for verification of the certified annual diversion);
4) Little Calumet River at South Holland, IL. (a major tributary to the CAWS, and key data for the verification of the certified annual diversion);
5) Midlothian Creek at Oak Forest, IL. (one of the few gaged tributaries in the diverted Lake Michigan watershed that can be used for model testing and verification); and

6) Thorn Creek at Thornton, IL. (one of the tributaries of the Little Calumet River whose data are used in a computational budget used to verify the certified annual diversion).

The members of the 8th TC have expressed their concerns about these funding cuts through a letter dated August 28, 2018 to Col. Reisinger, the Commander of the U.S. Army Corps of Engineers (USACE), Chicago District. The letter highlighted that the cuts come at a time when the CAWS stakeholders are aware about the difficulty to develop reliable ratings in the complex situations of CAWS. The USACE – Chicago District reply to the committee concerns was released on October 16, 2018 with the following favorable resolution "Chicago District senior leadership, in coordination with District project managers, collaborated with USGS and local stakeholders to identify alternative funding sources to mitigate any risks to the overall streamgaging program. Support for the streamgages noted in your letter will continue through FY 2019. The Corps will continue to cooperate with USGS and other local stakeholders to ensure that an efficient and robust streamgaging network is maintained that meets mission requirements."

The next major subject of detailed investigation for the flow measurement section is the analysis of the status and new developments at the Lemont gaging station. Given that the discharge of the Chicago Sanitary and Ship Canal (CSSC) monitored at Lemont represents the majority of the flow diverted from Lake Michigan and its watershed, the gaging station maintained by the USGS is considered the most important source of data used in the accounting system. This station is a central piece of the monitoring program and, consequently, has received continuous attention and upgrading since the implementation of the U.S. Supreme Court Decree for the Lake Michigan Diversion at Chicago, IL. Among the issues related to this station, special consideration is given to (a) the data collection protocol carried out at the Lemont gaging station and (b) the evaluation of the new developments on-going or planned to be deployed at this station.

Similar to other gaging stations in the system, this station is challenged by a complex measurement environment whereby the flow unsteadiness, gravity currents, non-uniform flows, and flow stratification can be present acting alone or in various combinations. Among them, the most prominent complexity is the flow unsteadiness that is triggered in the CAWS by multiple flow disturbances in the system. The unsteadiness problem was posed by the 6th TC (Espey et al., 2009) which recommended the investigation of the phenomenology of the unsteady flow process and evaluation of its implications on the flow monitoring. As the subject was extensively investigated through a series of dedicated projects, an evaluation of the previous findings and their implications for the discharge measurement is provided in this report. Finally, proposed solutions for addressing the flow unsteadiness effect are discussed.

1) The Committee fully concurs with the following recommendations of the 7th TC (Espey et al., 2014, p. 105):

> "6.1.6—Even though watersheds are not necessarily broken out in the accounting process, it would be useful to document inflows to and outflow from each watershed, as an intermediate product. A diagram for each watershed would be useful. These should identify the source of the input data. This would provide an important tool for future Technical Committee review.
>
> 6.1.7—Maps and GIS shape files should be developed that clearly delineate each watershed or sewershed that contributes to the diversion accounting. These should include Flow Diagrams that indicate the division of water at key locations. These diagrams should also include key features such as canals, rain gages, treatment plants, tunnels, etc."

Thus, the Committee recommends that the means to visualize the presentation of the LMDA budgets (i.e., inflows, outflows, and their locations) and their estimation procedures (i.e., direct measurements, numerical models) should be improved using contemporary interactive tools such as those enabled by web-based GIS platforms.

2) The 3rd TC (Espey et al., 1994, p. 122) was the first to recommend "Annual Lake Michigan diversion results should be published in a more timely manner." The slow certification and publication of Annual Lake Michigan diversion results at that time was the result of applying the first diversion accounting computer models (and then revising them in response to the comments of the 2nd TC (Espey et al., 1987) and obtaining completed and certified flow record from the relatively newly installed Acoustic Velocity Meter (AVM) gage on the CSSC at Romeoville. By the time the 4th TC met the problems causing delays in certification and publication of the Annual Lake Michigan diversion results had been rectified. The progress was recognized by the 4th TC (Espey et al., 2001) by concluding: "The Committee commends the USACE for the improved timeliness of the Water Year accounting reports since the Third Technical Committee. The timeliness of publication of water-year diversion accounting reports should be maintained." Unfortunately, 18 years after the 4th TC made this commendation and recommendation, the Committee must return to the recommendation of the 3rd TC that "Annual Lake Michigan diversion results should be published in a more timely manner." The Annual Diversion Accounting report for WY 2014 (USACE, 2019) was only published in January 2019, more than 4 years after WY 2014 ended. This is too big of a gap that impedes the TC review committee to conduct a thorough investigation. During the Second Workshop a representative of the Illinois Department of Natural Resources (IDNR) informed the Committee that it is difficult for IDNR to manage the diversion without getting timely information on the status of the LMDA.
Therefore, the Committee recommends "Annual Lake Michigan diversion results should be published in a more timely manner."

3) The partnership between the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (USACE) in developing improved methods of measuring flows in the CAWS and in improving the Hydrologic and Hydraulic (H&H) models used in the LMDA computations has been important since the early days of the development of the LMDA procedures. Former USGS staff have been members of the Technical Committees (TCs) for the Review of the Lake Michigan Diversion Flow Measurements and Accounting Procedures—Dr. Espey (all 8 TCs), Mr. Barnes (TCs 1 and 2), Mr. Lara (TC 3), Dr. Schmidt (TC 4), Mr. Mades (TC 5), and Dr. Melching (TCs 5, 6, and 8)—and have provided key input and guidance on the development of the LMDA procedures. Further, as TCs 5-8 have declared "The technology that has evolved with respect to acoustical flow measurements has not only met the standard of "best current engineering practice and scientific knowledge," but the USACE and USGS are establishing a higher, "state of the art" standard. The USGS leadership in this technical area is to be commended."
Thus, given the importance of the LMDA to the development of hydroacoustics, the important role that the USGS has played in the LMDA, and the importance of the LMDA as a U.S. Supreme Court mandated activity, the Committee was saddened that the leadership of the USGS Central Midwest Water Science Center did not feel that the TC workshops were important enough to attend in person to learn about this high priority project and its current status.

4) Recommendation 6.1.9 made by the 7th TC (Espey et al., 2014, p. 105) states:

"The Chicago District, Army Corps of Engineers, should explore the possibility of including the Lake Michigan Diversion Accounting (Col 11-13) referred to as the "Verification Method" with the current accounting method to provide a better estimate of Lake Michigan Diversions."

In cooperation with the USACE the USGS explored this possibility in an uncertainty analysis framework. Obtaining a better estimate may not be true for the case of LMDA because of the high and unknown uncertainties in the (A) modeling components of the LMDA and (B) the flows at the direct diversion points at the lakefront. In the Third Workshop, the USGS presented an uncertainty analysis Microsoft Excel worksheet to the Committee. Using crude estimates of the uncertainty in the modeled runoff (Columns 6 and 12) and direct diversion flow at the lakefront (Column 13) as well as more accurately known uncertainties in the water supply pumpage (Columns 4, 9, and 11) an uncertainty weighted average of the LMDA flow and the "Verification Method" flow was computed. This uncertainty weighted average indicated that the "better estimate" of the diversion flow was close to the LMDA flow because of the high uncertainty in the "Verification Method".

Thus, the Committee recommends that the USACE continue the traditional practice of reporting the LMDA flow as the diversion flow, and of using the "Verification Method" for verification.

6.2 *Hydrologic and Hydraulic Modeling Recommendations*

1) The 5th Technical Committee (TC) through the 8th TC agree with respect to the following conclusions.

   a) Proper application of HSPF in the diversion accounting would meet the Supreme Court's requirement that the diversion accounting be done according to the **"best current engineering practice and scientific knowledge".**
   b) Even though SCALP is not a "state of the art" model of sewer system hydraulics, it is adequate for the purpose of diversion accounting.
   c) Even though TNET is not "state of the art" and it has computational difficulties during rapidly varied flow, it is sufficient for its current use in the diversion accounting.
   d) The models used to compute aspects of the diversion accounting meet the Supreme Court's requirement that the diversion accounting be done according to the **"best current engineering practice and scientific knowledge"** if these models are properly applied to the Lake Michigan and Des Plaines River watersheds.

The 8th TC further concludes the following:

   e) "Regional" calibration of HSPF parameter sets and their application to nearby hydrologically similar watersheds is consistent with the **"best current engineering practice and scientific knowledge".**
   f) The pervious and impervious percentages by land use category used since Water Year (WY) 1997 meet the standard of the **"best current engineering practice".**
   g) The continued use of the land cover percentages in use since WY 1997 is reasonable and meets the standard of the **"best current engineering practice".**
   h) The results of the very extensive evaluation of regional HSPF parameter sets and parameter transfer in the Chicago area done by Soong and Over (2015) indicate that the various HSPF

parameter sets yield fairly similar overall levels of performance considering a number of quality-of-fit statistics. The currently used HSPF parameter set, derived by the USGS in 2008 by recalibrating the parameters for forest land and combining these with the CTE (2003a-c) parameters for grassland and impervious area, generally yields the best results for watersheds with higher amounts of forest land. This is important because the ungaged lower Des Plaines River and Summit Conduit watersheds that drain to the CSSC are key components of the LMDA determined by model simulation and these watersheds are 29.6% forest land. As discussed in Section 4.6.1 the USGS parameter set used since WY 2006 appears to be giving reasonable estimates of flows from the ungaged lower Des Plaines River and Summit Conduit watersheds when compared to neighboring gages using the area ratio method. **Therefore, given the generally good performance of the 2008 USGS parameters found by Soong and Over (2015) for various gaged watersheds in the Chicago area, and, especially, the good performance in estimating flows from the ungaged lower Des Plaines River and Summit Conduit watersheds, the Committee recommends that the USACE continue to use this parameter set in the LMDA computations.**

i) The Tunnel Network (TNET) model is a sophisticated hydraulic model of the TARP tunnels, but it assumes gradually varied flow, which is not always present in the tunnels leading to numerical instability and possible computational shut down. These numerical instabilities have been reduced by modifications the USACE has made to TNET in recent years as detailed in Section 4.3.2. Thus, the 8th TC concludes that the current version of TNET applied in the diversion accounting meets the standard of the **"best current engineering practice".**

As noted above, the 8th TC found that the improvements made in the calibration and application of these models since the time of the 5th and 6th TCs have been substantial and important. The 8th TC further concludes that these models are properly applied to the Lake Michigan and Des Plaines River watersheds. **Thus, the 8th TC concludes the models used to compute aspects of the diversion accounting meet the Supreme Court's requirement that the diversion accounting be done according to the "best current engineering practice and scientific knowledge".**

2) Unfortunately, now that all the major deficiencies in the H&H models used in the diversion accounting have been corrected, it is time to develop new models. Despite the fact that the models meet the requirement of "best current engineering practice and scientific knowledge" the 7th TC (Espey et al., 2014) pointed out some key practical short-comings of the models. Two of the 7th TC recommendations are particularly important for the continued high quality performance of the diversion accounting. These recommendations are as follows (Espey et al., 2014):

> "6.2.1.1—The versions of HSPF, SCALP and TNET currently used in LMDA are DOS-based; may have future hardware and computer operating system issues.
>
> 6.2.1.3—The numerical processes employed by the H&H models are still current and appropriate. There are numerous newer models currently available that have similar capabilities as the LMDA models currently in use. These newer models were developed for more modern computer technology, while older models are written in FORTRAN, which is increasingly difficult to support. Potential model replacements could be selected

that are similar, but the development of model input and calibration would require significant effort in order to match or exceed the existing model system. The Corps should consider developing a plan for the eventual replacement of these models."

These two issues have exacerbated over the last 5 years. The 8th TC's recommendations with respect to replacement of the Hydrological Simulation Program-Fortran (HSPF), Special Contributing Area Loading Program (SCALP), and TNET models in the near future are summarized in the following paragraphs.

HSPF

Since HSPF is fully supported by the U.S. Environmental Protection Agency (USEPA) it is regularly updated and can be easily run within USEPA's Better Assessment Science Integrating Point and Non-point Sources (BASINS) system, no alternative model is needed for HSPF.

SCALP

Whereas there are numerous models that perform similar modeling of combined sewer interceptor systems, the effort necessary to apply and "calibrate/test" a new model to the interceptor systems feeding to the Water Reclamation Plants (WRPs) and Tunnel and Reservoir Plan (TARP) system in the diversion watersheds would be more substantial than the effort to recode and test the SCALP model. Thus, the 8th TC supports the USACE's plan to recode and test the SCALP model for continued use in the LMDA.

TNET

As first noted in the 5th TC report (Espey et al., 2004) the University of Illinois (U of I) has been developing sophisticated hydraulic models for the TARP system since the early 2000s under contract with the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC). Three models developed by the U of I could potentially be useful to the USACE as they look to replace TNET, namely the (1) Illinois Transient Model (ITM), (2) Illinois Conveyance Analysis Program (ICAP), and (3) a USEPA Storm Water Management Model (SWMM) (Rossman, 2008) developed for the Calumet TARP system. Finally, the USACE also is considering developing new Hydrologic Engineering Center-River Analysis System (HEC-RAS) models of the TARP tunnels and reservoirs. In the following paragraphs the 8th TC offers its comments and recommendations with respect to these four options.

- The Committee concludes that the ITM computation time would be far too long for use in the annual diversion accounting.
- ICAP has been developed on the basis of extensive as-built information on the Calumet and Mainstream/Des Plaines TARP systems and has been extensively tested for simulation of water levels, volumes of pumping, and storage in reservoirs, especially for the Calumet TARP system. **Thus, the 8th TC recommends that the USACE work together with the U of I to modify ICAP to compute CSOs using actual pump operations, and evaluate the potential usefulness of ICAP for LMDA computations.**
- **The Committee recommends that the USACE work together with the U of I to evaluate the potential usefulness of the USEPA SWMM of the Calumet TARP system for LMDA computations.**
- The Committee feels that building and testing new HEC-RAS models of the Calumet and Mainstream/Des Plaines TARP systems from scratch will be a large undertaking. **Thus,**

the Committee feels that the LMDA funding might be more effectively spent if the existing, tested ICAP or SWMM models of the TARP system could be adapted for LMDA computations.

- **Whatever model is used to replace TNET—ICAP, SWMM, or HEC-RAS—it should be set up so that simulated water levels can be compared to measured water levels where available.**

3) **Given the importance of flow data at the Upper Des Plaines Pumping Station (UDPPS) to the LMDA, the USACE should do whatever it can to encourage the MWRDGC to make recording the UDPPS flow data a priority. Once more complete records of flow are available at the UDPPS the USACE should evaluate in detail the performance of the H&H models in estimating the flows reaching the UDPPS.**

4) The USACE has considered collecting more detailed and accurate topographic data on the pathway between the Des Plaines River and the CSSC through which spillovers can pass into the CSSC. **The 8th TC fully supports the USACE's attempts to better define the geometry of the lateral weir through which spillover events could pass.**

5) The 5th TC (Espey et al., 2004) recommended that since a recently revised TNET model (Burke, 1999) used a base groundwater inflow of 32.5 cfs at the Calumet TARP pump station and the average annual inflow shortfall in Calumet TARP flows was 14 cfs from 1989-1999. Thus, a review of groundwater inflow for the Calumet TARP system used in LMDA modeling was needed. In response to this recommendation, the USACE improved simulation of low flows in the Calumet TARP system by adjusting the simulation of overflow gate operations. **The 8th TC agrees that the changed gate operations have substantially improved the simulation quality, but still wonders if changed groundwater inflow could achieve the same or better improvements.** The U of I has developed detailed hydrologic and hydraulic models of the Calumet TARP system. As part of the model development the U of I compiled a detailed inventory of TARP drainage areas. The USACE should coordinate with the U of I to see if these service area delineations could aid in the definitive delineation of directly connected sanitary sewers. **This delineation would allow the sanitary flow and groundwater contributions to low flows to the Calumet TARP to be clearly determined.**

6) The high flows in the West Branch of the Grand Calumet River after dredging, the high water levels in Lake Michigan in recent years, and the possibility of flows from the East Branch reaching the West Branch indicate a complete re-evaluation of flows from Indiana reaching Illinois needs to be done using a new hydraulic model of the Grand Calumet River system. The 7th TC (Espey et al., 2014) recommended that "After dredging is complete, HEC-RAS model should be updated and recalibrated. Regression equations used for LMDA should be reviewed and revised as appropriate." The 8th TC fully concurs with the recommendation that a new HEC-RAS model should be developed for the post-dredging Grand Calumet River system. Further, the derivation of new equations should be completely detailed in a report for review by a future Technical Committee for Review of Lake Michigan Diversion Accounting. The U of I is developing a HEC-RAS model of the Grand Calumet River system for the MWRDGC. **Thus, the 8th TC suggests that the USACE could work together with the U of I in the development of the new HEC-RAS model to minimize duplication of effort. Then using the new HEC-**

RAS model new relations should be developed between Lake Michigan water levels and Indiana water supply reaching the Chicago Area Waterway System (CAWS) through the Grand Calumet river. The detailed water surface elevation data collected in the Grand Calumet iver system between late February 2017 and August 2018 may be sufficient to calibrate and verify the new HEC-RAS model for the Grand Calumet River system. However, the USACE should be aware that more data may be needed to fully calibrate and verify the model, and may want to have USGS re-establish the water-surface elevation data network for a limited period.

7) In October 2018, the USGS installed a new temporary gaging station at Columbia Avenue 1 mile upstream from Hohman Avenue. This gage is composed of a side-looking Acoustic Doppler Velocity Meter (ADVM, Sontek SL3000) mounted on a 2-in. diameter aluminum pipe on the left bank upstream culvert guidewall 20 ft upstream of Columbia Avenue. **The Committee commends the USGS on the establishment of this new gage, and it encourages the USACE to switch to using this gage in the development of new relations to determine Indiana water supply reaching the CAWS (to be used as a deduction in the LMDA). This recommendation is made because of the history of poor rating conditions at the Hohman Avenue gage discussed in Section 4.6.3.**

8) The 6th TC (Espey et al., 2009) recommended that the USACE should initiate a project to evaluate the position of the flow divide on the Little Calumet River. **The 8th TC reiterates this suggestion, and it notes that the U of I is developing new models of the Little Calumet River for the MWRDGC. Thus, the USACE could consult with the U of I on the issue of the flow divide in the Little Calumet River.** The USACE should be aware that more data on the Little Calumet River may be needed to verify the accuracy of the models of the Little Calumet River developed by the U of I so that accuracy of the determination of the flow divide can be assured.

6.3 *Flow Measurement Recommendations*

1) The 5th Technical Committee (TC) through the 8th TC agree with respect to the following conclusions and recommendations (for more details see Table 5.4):

   a) The aforementioned TCs agree that the flow measurement infrastructure and the protocols used in diversion accounting would meet the Supreme Court's requirement that the diversion accounting be done according to the **"best current engineering practice and scientific knowledge".** The flow monitoring at the Lemont gaging station, the key variable for the diversion accounting, exceeds through many aspects the best level of the current engineering practice and scientific knowledge, through innovation that advances hydrometric applications to new standards that are adopted in the worldwide community of practice.
   b) In the last decade, extensive efforts carried out by USACE and USGS led to a better substantiation of the impacts of the detrimental factors (e.g., flow perturbation due to operation of the controlling structures and navigation and formation of temperature and density gradients in the system) on the performance of the instruments and flow measurement methods used at CSSC streamflow gaging stations. Most of the studies were conducted at the Lemont station, the primary LMDA gaging station. These efforts led to the design and implementation of new measurement methods that are more capable to cope with flow complexity. Some of these efforts are still in incipient stages and should be continued with an accelerated pace to their validation (i.e., conduct of the full-fledged testing of the Q-Track method)

c) Similarly, extensive efforts have been dedicated to uniformly apply standardized methods for uncertainty analysis of key flow measurements for the diversion accounting. Given that more than 90% of the total annual diversion passes through the Lemont station, the uncertainty analysis started with this gaging station. The work is in full progress and should be continued until final assessments.
d) Assemble provisions for a comprehensive Flow Measurement Quality Assurance Plan to include CSSC-specific periodic verification procedures related to measurement of key variables for annual diversion accounting (e.g., precipitation, streamflow in the CSSC, and flow measurement at water intakes).

2) The 8th TC further makes the following conclusions and recommendations (for more details see Table 5.5):

Stream Flow Monitoring at the Lemont gaging station

a) Accelerate the implementation of the recently installed Q-Track instrumentation and ancillary protocols by rethinking the vertical traversing mechanism, finalizing the algorithm for discharge calculation, conducting intensive measurement campaigns for overall system performance, and identifying and assessing the sources of uncertainties involved in the measurement process. The assessment of the Q-Track performance should be made in an initial stages by eliminating from the analysis flow events and situations that were deemed as developing large sources of perturbations (temporal-spatial variations of the flow, density and temperature gradients, etc.). In subsequent stages, all the acquired flow measurements at the station should be analyzed through daily, monthly, and annual flow budgets.
b) Compare the data acquired with Q-Track to evaluate the level of performance of the index-velocity based discharge estimations obtained from index-velocity rating with raw data acquired with Acoustic Velocity Meter (AVM) and Horizontal Acoustic-Doppler Current Profilers (locally labelled as ADVMs). The evaluation should be made for long, continuous, time series of stream flow data and by clustering the calibration data for the ratings according to the phase of the perturbations (i.e., distinguishing between the rising and falling limbs of inflow hydrographs produced by storms in the watershed). The implications resulting from the comparison of the two approaches should guide the selection of the appropriate rating method and the identification of the primary and secondary flow measurement standard at the Lemont gaging station.
c) Expand the uncertainty analysis initiated for the direct measurements conducted with stage sensors, AVMs, and ADVMs to the assessment of the uncertainty of the Acoustic-Doppler Current Profiler (ADCP). This expansion is critically important as the measurements with ADCPS are used for the construction and calibration of the index-velocity ratings. Moreover, the assessment of the uncertainty in the construction of the ratings themselves is equally important for data quality ensurance. Continue using internationally-recognized standards for the conduct of uncertainty analysis (i.e., the Guide for Uncertainty in Measurements – GUM, 1993) for providing a uniform and robust analysis that can stand the rigors of legal challenges.

Stream Flow Monitoring in the CAWS

a) Continue to cooperate with USGS and other local stakeholders to ensure that an efficient and robust streamgaging network in the CAWS is maintained. The 8th TC expressed to USACE leadership its support for continuing the funding at current levels for meeting the LMDA Mission requirements for providing accurate flow measurement estimates in a highly, and possibly uniquely, complex measurement environment.

b) Given the secondary role of the monitoring at the Summit Conduit and the calibration of the discharge measurements at Lockport Powerhouse and Controlling for the annual diversion accounting, the 8th TC feels that the improvements previously recommended for the flow measurement should have lower priority for the present and near future.

Precipitation network

Following the replacements of the old sensors for estimation of the precipitation input from the 25 gages operated by the Illinois State Water Survey (ISWS) for the LMDA, proceed with a thorough evaluation of the raingage networks.

References

Ackers, P. and Harrison, A.J.M. 1964. Attenuation of flood waves in partfull pipes, *Proceedings, Institution of Civil Engineers*, London, 28, 361-382.

Antonie, L.H., 1964, Drainage and best use of urban land, *Public Works*, 95, 88-90.

Bicknell, B.R., Imhoff, J.C., Jobes, T.H., Donigian, A.S., Jr., Kittle, J.L., Jr., and Johanson, R.C., 1997, Hydrological Simulation Program – Fortran User's Manual for Release 12 (test release), U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Ga.

Brunner, G.W., 2016, *HEC-RAS River Analysis System User's Manual Version 5.0, U.S. Army Corps of Engineers Hydrologic Engineering Center Report No. CPD-68*, Davis, Cal.

Canotne, J.R., Seo, Y., Zimmer, A., Schmidt, A.R., and Garcia, M.H. 2009. Hydrologic Modeling of the Calumet TARP System, *Tunnel and Reservoir Plan Report No. 1*, University of Illinois at Urbana-Champaign.

Catano-Lopera, Y.A., Oberg, N., Choi, N.J., Schmidt, A.R., and Garcia, M.H., 2009, Hydraulic Conveyance Analysis of Calumet TARP System: *Tunnel and Reservoir Plan Report No. 3*, University of Illinois at Urbana-Champaign.

Chaudhry, M.H., Bhallamudi, S.M., Martin, C.S., and Naghash, M. 1990. Analysis of transient in bubbly homogeneous, gas-liquid mixtures, *Journal of Fluids Engineering*, 112, 225-231.

Cheng, Z., Lee, K., Kim, D., Muste, M., Vidmar, P., and Hulme, J., 2019, Experimental evidence on the performance of rating curves for continuous discharge estimation in complex flow Situations, *Journal of Hydrology*, 568, 959-971.https://doi.org/10.1016/j.jhydrol.2018.11.021

Christopher B. Burke Engineering, Ltd. (Burke), 1990, Infiltration and Inflow Study and Diversion Accounting Model Modification, report to the U.S. Army Corps of Engineers, Chicago District, A/E Contract No. DACW23-88-D-0013.

Christopher B. Burke Engineering, Ltd. (Burke), 1999, Hydrologic and Hydraulic Study of the Calumet Watershed, report to the U.S. Army Corps of Engineers, Chicago District, CBBEL Project No. 94-27A.

Chruscicki, J.B., Melching, C.S., Bicknell, B.R., Roy, S.D., Manoyan, S., Stewart, J.S., and Duncker, J.D., 2003, Simulation of Streamflow, Lake, and Wetland Water-Surface Elevations in the Swamp and Pickerel Creek Watersheds in the Wolf River Watershed, Near the Proposed Crandon Mine, Wisconsin, Final Report, U.S. Environmental Protection Agency, Region 5, Chicago, Ill.

Consoer Townsend Envirodyne (CTE) Engineers, 2003a, Initial Summary Memo, Subject: Lake Michigan Diversion Accounting for Water Years 2000 and 2001, Memo to U.S. Army Corps of Engineers, Chicago, District, October 30, 2003.

Consoer Townsend Envirodyne (CTE) Engineers, 2003b, Summary Memo – Calibration Run #1, Subject: Lake Michigan Diversion Accounting for Water Years 2000 and 2001, Memo to U.S. Army Corps of Engineers, Chicago, District, November 20, 2003.

Consoer Townsend Envirodyne (CTE) Engineers, 2003c, Summary Memo – Calibration Run #2, Subject: Lake Michigan Diversion Accounting for Water Years 2000 and 2001, Memo to U.S. Army Corps of Engineers, Chicago, District, December 9, 2003.

Demuynck, C. and Bauwens, W., 1996, Modelling of the Water Quality of the River Zenne in the Brussels Region, Laboratory of Hydrology, Vrije Universiteit Brussel.

Doherty, J. 2005. PEST, Model-Independent Parameter Estimation User Manual (5th Ed.), Watermark Numerical Computing, available online at http://www.pesthomepage.org/Home.php.

Doherty, J. 2013. Addendum to the PEST Manual, Watermark Numerical Computing, available online at http://www.pesthomepage.org/Home.php.

Donigian, A.S., Jr., Imhoff, J.C., Bicknell, B.R., and Kittle, J.L., Jr., 1984, Application Guide for Hydrological Simulation Program-Fortran, *EPA-600/3-84-065*, U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Ga.

Duncker, J.J., and Melching, C.S., 1998, Regional Rainfall-Runoff Relations for Simulation of Streamflow for Watersheds in Du Page County, Illinois, *U.S. Geological Survey Water-Resources Investigations Report 98-4035*.

Duncker, J.J., Vail, T.J., and Melching, C.S., 1995, Regional Rainfall-Runoff Relations for Simulation of Streamflow for Watersheds in Lake County, Illinois, *U.S. Geological Survey Water-Resources Investigations Report 95-4023*.

Duncker, J.J. and Johnson, K.K., 2015, Hydrology of and current monitoring issues for the Chicago Area Waterway System, northeastern Illinois, *U.S. Geological Survey Scientific Investigations Report 2015–5115*, 48 p., http://dx.doi. org/10.3133/sir20155115.

Du Page County, 1993, Proceedings of an Informational Seminar on "The Du Page County Hydrologic Information Program", April 29, 1993, presented by the Illinois Section of ASCE, Environmental Engineering and Water Resources Division and the Du Page County Department of Environmental Concerns, Stormwater Management Division.

Engel, B., Storm, D., White, M., Arnold, J., and Arabi, M., 2007, A hydrologic/water quality model application protocol. *Journal of the American Water Resources Association*, 43(5), 1223-1236.

Espey, W.H., Barnes, H.H., and Vigander, S., 1981, Lake Michigan Diversion Findings of the Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures, Prepared for the U.S. Army Corps of Engineers, Chicago District.

Espey, W.H., Barnes, H.H., and Westfall, D., 1987, Lake Michigan Diversion Findings of the Second Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures, Prepared for the U.S. Army Corps of Engineers, Chicago District.

Espey, W.H., Lara, O.G., and Barkau, R.L., 1994, Lake Michigan Diversion Findings of the Third Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures, Prepared for the U.S. Army Corps of Engineers, Chicago District.

Espey, W.H., Schmidt, A.R., and Barkau, R.L., 2001. Findings of the Fourth Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures, *in U.S. Army Corps of Engineers, 1998, Lake Michigan Diversion Accounting Water Year 1998 Annual Report*.

Espey, W.H., Melching, C.S., and Mades, D.M., 2004. Lake Michigan Diversion—Findings of the Fifth Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures, report prepared for the U.S. Army Corps of Engineers, Chicago District.

Espey, W.H., Melching, C.S., and Muste, M., 2009. Lake Michigan Diversion—Findings of the Sixth Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures, report prepared for the U.S. Army Corps of Engineers, Chicago District.

Espey, W.H., Clemmens, B., and Halverson, B., 2014. Lake Michigan Diversion—Findings of the Seventh Technical Committee for Review of Diversion Flow Measurements and Accounting Procedures, report prepared for the U.S. Army Corps of Engineers, Chicago District.

Franz, D.D. and Melching, C.S., 1997. Full Equations (FEQ) Model for the Solution of the Full, Dynamic Equations of Motion for One-Dimensional Unsteady Flow in Open Channels and Through Control Structures, *U.S. Geological Survey Water Resources Investigations Report 96-4240*.

García, C.M., Oberg, K.A., and García, M.H., 2007, ADCP measurements of gravity currents in the Chicago River, Illinois. *Journal of Hydraulic Engineering*, 133(12), 1356–1366.

Gonzalez-Castro, J.A., 2000, Applicability of the Hydraulic Performance Graph for Unsteady Flow Routing, Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign.

Harms, R. W. and Kenter, G., 1987, Mischwasserentlastungen, KOSIM V.3.0, Mikrocomputer in der Stadtenwasserung, Institut fur Technische-Wissenschaftliche Hydrologie, Hannover, Germany.

Harza Engineering, 1981, An Evaluation of Flow Measurement & Accounting Methods for Lake Michigan Diversion, Chicago, Ill.

Hart, E.D. and McGee, R., 1985. Lockport Power Plant sluice gate and control works discharge evaluation, USACE, Chicago District, Chicago, IL.

Henderson, F.M., 1966, *Open-Channel Flow*, Macmillan, New York.

Herschy, R., 2009, *Streamflow Measurement*. 3rd edition. Oxford, Taylor & Francis.

Hoitink, A., Buschman, F., and Vermeulen, B., 2009, Continuous measurements of discharge from a horizontal acoustic Doppler current profiler in a tidal river. *Water Resources Research*, 45, W11406. doi:10.1029/2009WR007791.

Hey, D.L., Dreher, D.L., and Trybus, T.W., 1980, NIPC Chicago Waterways Model: Verification/ Recalibration, Northeastern Illinois Planning Commission, Chicago, Ill.

Hoy, M.A., Schmidt, A.R., and Garcia, M.H., 2009, Unsteady Flow Routing Using Predetermined Solutions to the Equations for Conservation of Mass and Momentum, *Hydraulic Engineering Series Report No. 86*, Department of Civil Engineering, University of Illinois at Urbana-Champaign.

Hydrocomp, 1977a, Des Plaines River Hydrologic Calibration, Volume V, Number 2, report to the Northeastern Illinois Planning Commission, Chicago, Ill., Areawide Clean Water Planning, Water Quality Evaluation.

Hydrocomp, 1977b, Hickory Creek Hydrologic Calibration, Volume VII, Number 2, report to the Northeastern Illinois Planning Commission, Chicago, Ill., Areawide Clean Water Planning, Water Quality Evaluation.

Hydrocomp, 1977c, Little Calumet River Hydrologic Calibration, Volume 8, Number 2, report to the Northeastern Illinois Planning Commission, Chicago, Ill., Areawide Clean Water Planning, Water Quality Evaluation.

Hydrocomp, 1977d, North Branch Chicago River Hydrologic Calibration, Volume VI, Number 2, report to the Northeastern Illinois Planning Commission, Chicago, Ill., Areawide Clean Water Planning, Water Quality Evaluation.

Hydrocomp, 1979, Chicago Sanitary and Ship Canal Hydrologic Calibration, report to the Northeastern Illinois Planning Commission, Chicago, Ill., Areawide Clean Water Planning, Water Quality Evaluation.

Hydrologic Engineering Center, 1986, Lake Michigan Diversion Accounting – Evaluation of Hydrologic Simulation Procedures, *Project Report 86-7*, Davis, Calif.

GUM, 1993, *Guide to the Expression of Uncertainty in Measurement*, ISBN 92-67-10188-9, BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, International Organization for Standardization, Geneva, Switzerland.

Jackson, P.R., Garcia, C.M., Oberg, K.A., Johnson, K.K., and Garcia, M.H., 2008, Density currents in the Chicago River: Characterization, effects on water quality, and potential sources, *Science of the Total Environment*, 401, 130-143

Jackson, P.R., Johnson, K.K., and Duncker, J.J., 2012, Comparison of index velocity measurements made with a horizontal acoustic Doppler current profiler and a three-path acoustic velocity meter for computation of discharge in the Chicago Sanitary and Ship Canal near Lemont, Illinois, *U.S. Geological Survey Scientific Investigations Report 2011–5205*, 42 p.

Jackson, P.R., Sinha, S., Dutta, S., Johnson, K.K., Duncker, J.J., and Garcia, M.H., 2013, Evaluation of the potential for hysteresis in index-velocity ratings for the Chicago Sanitary and Ship Canal near Lemont, Illinois, *U.S. Geological Survey Scientific Investigations Report 2013–5095*, 33 p., http://pubs.usgs.gov/sir/2013/5095/

Jackson, P.R., 2016, Acoustic Doppler current profiler velocity data collected in the Chicago Sanitary and Ship Canal in 2010 and 2011 in support of the interbasin transport study for invasive Asian carp: U.S. Geological Survey data release, accessed January 2017 at https://doi.org/10.5066/F7S180KR

Jackson, P.R., 2018, Characterizing variability in vertical profiles of streamwise velocity and implications for streamgaging practices in the Chicago Sanitary and Ship Canal near Lemont, Illinois, January 2014 to July 2017, *U.S. Geological Survey Scientific Investigations Report 2018–5128*, 73 p., https://doi.org/10.3133/sir20185128.

Joint Committee for Guides in Metrology (JCGM), 2008, *Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement*., Report 100:2008.

James, L.D., 1972, Hydrologic modeling, parameter estimation, and watershed characteristics: *Journal of Hydrology*, 17, 283-307.

Jarrett, G.L., Downs A.C., and Grace-Jarrett, P.A., 1998, Continuous Hydrologic Simulation of Runoff for the Middle Fork and South Fork of the Beargrass Creek Basin in Jefferson County, Kentucky: *U.S. Geological Survey Water-Resources Investigations Report 98-4182*.

Johnson, K.K., and Goodwin, G.E., 2012, Monitoring of Stage and Velocity, for Computation of Discharge in the Summit Conduit near Summit, Illinois, 2010-2012: *U.S. Geological Survey Open-File Report 2012-1244*.

Jones, P.M., and Winterstein, T.A., 2000, Characterization of Rainfall-Runoff Response and Estimation of the Effect of Wetland Restoration on Runoff, Heron Lake Basin, Southwestern Minnesota, 1991-97, *U.S. Geological Survey Water-Resources Investigations Report 00-4095*.

Lanyon, R., and Yourell, A., 2003, Comparison of Raingages in Two Networks 1990-2002, Draft Report, Metropolitan Water Reclamation District of Greater Chicago, Chicago, Ill.

Le Coz, J., Pierrefeu, G., and Paquier, A., 2008, Evaluation of river discharges monitored by a fixed side-looking Doppler profiler, *Water Resources Research*, 44, W00D09, doi: 10.1029/2008SF006967, 13 p.

Le Coz, J., Renard, B., Bonnifait, L., Branger, F., Le Boursicaud, R., 2014, Combining hydraulic knowledge and uncertain gaugings in the estimation of hydrometric rating curves: A Bayesian approach, *Journal of Hydrology*, 509, 573-587.

Levesque, V.A. and Oberg, K.A., 2012, Computing discharge using the index velocity method. *Report on Techniques and Methods 3-A23*. US Geological Survey, 148. [Online] Available from http://pubs.usgs.gov/tm/3a23

León, A.S., Christensen, D.R., Schmidt, A.R., and García, M.H., 2007, Illinois Transient Model User's Manual: A model for the analysis of unsteady free surface, pressurized and mixed flows in storm-

sewer systems, Draft Report, Ven Te Chow Hydrosystems Laboratory, University of Illinois at Urbana-Champaign.

León, A.S., Ghidaoui, M.S., Schmidt, A.R., and García, M.H., 2006, Godunov-type solutions for transient flows in sewers, *Journal of Hydraulic Engineering*, 132(8), 800-813.

León, A.S., Ghidaoui, M.S., Schmidt, A.R., and García, M.H., 2008, Efficient second-order accurate shock-capturing scheme for modeling one- and two-phase water hammer flows, *Journal of Hydraulic Engineering*, 134(7), 970-983.

León, A.S., Ghidaoui, M.S., Schmidt, A.R., and García, M.H., 2009a, Application of Godunov-type schemes to transient mixed flows, *Journal of Hydraulic Research*, 47(2), 147-156.

León, A.S., Oberg, N., Choi, N.J., Schmidt, A., and Garcia, M.H., 2009b, Transient Analysis of the Calumet TARP System, Report prepared for the Metropolitan Water Reclamation District of Greater Chicago, University of Illinois at Urbana-Champaign.

León, A.S., Ghidaoui, M.S., Schmidt, A.R., and Garcia, M.H., 2010, A robust two-equation model for transient-mixed flows, *Journal of Hydraulic Research*, 48(1), 44-56.

Lumb, A.M., and James, L.D., 1976, Runoff files for flood hydrograph simulation: *Journal of the Hydraulics Division*, ASCE, 102(HY10), 1515-1531.

Lumb, A.M., McCammon, R.B., and Kittle, J.L., Jr., 1994, Users Manual for an Expert System (HSPEXP) for Calibration of the Hydrological Simulation Program-Fortran, *U.S. Geological Survey Water-Resources Investigations Report 94-4168.*

Luo, H., Schmidt, A.R., Robertson, A., Morales, V., Oberg, N., Garcia, M.H., 2014, Hydrologic/Hydraulic Analysis of Mainstream/Des Plaines TARP systems, *Tunnel and Reservoir Plan Report No. M29*, University of Illinois at Urbana-Champaign.

Magette, W.L., Shanholtz, V.O., and Carr, J.C., 1976, Estimating selected parameters for the Kentucky Watershed Model from Watershed Characteristics: *Water Resources Research*, 12(3), 472-476.

Mead and Hunt, 2002, Hydrologic and Hydraulic Analysis for Diversion Accounting – Water Year 1998, report to the U.S. Army Corps of Engineers, Chicago District.

Melching, C.S. and Meno, M.W., 1998, Intercomparison of principle hydrometric instruments – Third phase: Evaluation of ultrasonic velocity meters for flow measurement in streams, canals, and estuaries, World Meteorological Organization, *Technical Reports in Hydrology and Water Resources No. 69*, WMO/TD-No. 931, Geneva, Switzerland.

Melching, C.S. and Oberg, K.A., 1993, Comparison, analysis, and estimation of discharge data from two acoustic velocity meters on the Chicago Sanitary and Ship Canal at Romeoville, Illinois, *U.S. Geological Survey Water-Resources Investigations Report 93-4048*.

Melching, C.S., 2006, Sewer flow measurement, Chapter 2.2, *Wastewater Quality Monitoring and Treatment*, P. Quevauviller, O. Thomas, and A. Van der Beken, eds., John Wiley and Sons, London, p. 119-144.

Mills, P.C., Duncker, J.J., Over, T.M., Domanski, M.M., and Engel, F.L., 2014, Evaluation of a Mass-Balance Approach to Determine Consumptive Water Use in northeastern Illinois, *U.S. Geological Survey Scientific Investigations Report 2014-5176*.

Morales, V.M., Mier, J.M., and Garcia, M.H., 2017, Innovative modeling framework for combined sewer overflow prediction, *Urban Water Journal*, 14(1), 97-111.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., and Veith, T.L., 2007, Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3), 885-900.

Morlock, S.E., Nguyen, H.T., and Ross, J.H., 2002, Feasibility of acoustic Doppler velocity meters for the production of discharge records from U.S. Geological Survey streamflow-gaging stations. *U.S. Geological Survey Water-Resources Investigations Report 01-4157*.

Mueller, D.S., Wagner, C.R., Rehmel, M.S., Oberg, K.A., and Rainville, F., 2013, Measuring discharge with acoustic Doppler current profilers from a moving boat. (ver. 2.0, December 2013) *Report on Techniques and Methods* 3-A22, U.S. Geological Survey, 95. [Online] Available from: http://pubs.water.usgs.gov/tm3a22

Muste, M. and Lee, K., 2013, Hysteresis in index-velocity rating curves, Report submitted for US Corps of Engineers, Chicago District, Chicago, IL.

Muste, M., Cheng, Z., Vidmar, P., and Hulme, J., 2015, Considerations on discharge estimation using index-velocity rating curves, In: *Proceedings of the 36th IAHR World Congress*, 28 June – 3 July, The Hague, The Netherlands.

Muste, M. (Ed.), 2017, Guidelines for the Assessment of Uncertainty for Hydrometric Measurement, *WMO-No. 1097*, World Meteorological Organization, Geneva, Switzerland.

Nash, J.E. and Sutcliffe, J.V., 1970, River flow forecasting through conceptual models, Part 1—A discussion of principles, *Journal of Hydrology*, 10, 282-290.

Nihei, Y. and Kimizu, A., 2008, A new monitoring system for river discharge with horizontal acoustic Doppler current profiler measurements and river flow simulation. *Water Resources Research*, 44, W00D20. doi:10.1029/2008WR006970.

Northeastern Illinois Planning Commission (NIPC), 1985, *Lake Michigan Diversion Accounting Manual of Procedures*, prepared for the Illinois Division of Water Resources, Chicago, Ill.

Oberg, N., Schmidt, A.R., Landry, B.J., Leon, A.S., Waratuke, A.R., Mier, J.M., and Garcia, M.H., 2017, Improved understanding of combined sewer systems using the Illinois Conveyance Analysis Program (ICAP), *Urban Water Journal*, 14(8), 811-819.

Over, T. M., Muste, M., Duncker, J.J., Tsai, H-W., Jackson, P.R., Johnson, K.K., Engel, F.E. and Prater, C.M., 2017, Uncertainty analysis of an index velocity meter and discharge computations at the Chicago Sanitary and Ship Canal near Lemont, Illinois, *Proceedings of the Hydraulic Measurement and Experimental Methods Conference*, University of New Hampshire, Durham, NH.

Price, T. H., 1994, Hydrologic Calibration of HSPF Model for DuPage County. West Branch DuPage River at West Chicago, West Branch DuPage River at Warrenville, East Branch DuPage River at Maple Avenue, Salt Creek at Western Springs. Including Hydraulic Evaluation at Salt Creek at Western Springs, Salt Creek at Rolling Meadows: Northeastern Illinois Planning Commission, Chicago, Ill., 92 p.

Rantz, S.E. and others, 1982a, Measurement and Computation of Streamflow. Volume 1. Measurement of Stage and Discharge, *U.S. Geological Survey Water-Supply Paper No. 2175.*

Rantz, S.E. and others, 1982b, Measurement and Computation of Streamflow: Volume 2. Computation of Discharge, *U.S. Geological Survey Water Supply Paper 2175*.

Rennie, C., Hoitink, A.J.F., and Muste, M., 2017, Discharge measurements, Sections 7.4 to 7.6 in Experimental Hydraulics, Volume II; J. Aberle, C.D. Rennie, D.M. Admiraal, and M. Muste (Eds.); Taylor & Francis, New York, NY.

Riggins, R.B. and Yen, B.C., 1995, Detection of Effect of Urbanization on Storm Runoff, in *Watershed Management*, T.J. Ward, ed., Proceedings of Symposium on Watershed Management, ASCE, San Antonio, p. 408-418.

Rossman, L.A., 2008, Storm Water Management Model User's Manual Version 5.0, Water Supply and Water Resources Division, National Risk Management Research Laboratory, *U.S. Environmental Protection Agency Report EPA/600/R-05/040*.

Ruhl, C.A. and Simpson, M.R., 2005, Computation of discharge using the index-velocity method in tidally affected areas, *U.S. Geological Survey Scientific Investigations Report 2005-5004*.

Rust Environment and Infrastructure, 1993a, Diversion Accounting Update for the New 25-Gage Precipitation Network, submitted to the U.S. Army Corps of Engineers, Chicago District, October 1993.

Rust Environment and Infrastructure, 1993b, Technical Memorandum on HSPF Parameter Assignments Used in the Lake Michigan Diversion Accounting Program, U.S. Army Corps of Engineers – Chicago District, submitted to the U.S. Army Corps of Engineers, Chicago District, October 1993.

Scharffenberg, B., Bartles, M., Brauer, T., Fleming, M., and Karlovits, G., 2018, *Hydrologic Modeling System HEC-HMS User's Manual, U.S. Army Corps of Engineers Hydrologic Engineering Center Report No. CPD-74A*, Davis, Cal.

Schmidt, A.R., 2002, Analysis of stage-discharge relations for open channel flows and their associated uncertainties. *Ph.D. Thesis*, University of Illinois at Urbana-Champaign, Urbana, Ill.

Sharpe, J.B., and Soong, D.T., 2015, Lake Michigan Diversion Accounting Land Cover Change Estimation by Use of the National Land Cover Dataset and Raingage Network Partitioning Analysis: *U.S. Geological Survey Open-File Report 2014-1258*.

Shrestha, R.L., and Melching, C.S., 2003, Hydraulic Calibration of an Unsteady Flow Model for the Chicago Waterway System, *Technical Report 14*, Institute of Urban Environmental Risk Management, Marquette University, Milwaukee, Wis. and *Report 03-18*, Research and Development Department, Metropolitan Water Reclamation District of Greater Chicago.

Soil Conservation Service, 1986, Urban Hydrology for Small Watershed, *Technical Release 55*, U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C.

Song, T. and Graf, W.H., 1996, Velocity and turbulence distribution in unsteady open-channel flows, Journal of Hydraulic Engineering, 122(3), 141–154.

Straub, T.D., Johnson, K.K., Hortness, J.E., and Duncker, J.J., 2012, Control structure ratings on the Chicago Sanitary and Ship Canal near Lockport. *U.S. Geological Survey Scientific Investigations Report 2012-5131*.

Soong, D.T., Ishii, A.I., and Su, T.Y., 2007, Evaluation of flows simulated with regional parameters at Tinley Creek watershed, Illinois, *Proceedings, World Water and Environmental Resources Congress, ASCE, 2007 – Restoring Our Natural Habitat*, May 14-19, 2007, Tampa, Fla., CD-ROM

Soong, D.T., and Over, T.M., 2015, Analysis of regional rainfall-runoff parameters for the Lake Michigan diversion hydrological modeling: *U.S. Geological Survey Scientific Investigations Report 2015-5053*.

Soong, D.T., and Su, T.Y., 2008, Methodology for evaluating hydrologic model parameters in an urban setting: Case study using transferred HSPF parameters in Midlothian and Tinley Creek watersheds, Illinois, *Proceedings, International Symposium of Flood Defence*, May 6-8, 2008, Toronto, Canada, CD-ROM.

TARP Research Group, 2014, *MetroFlow – Coupled Models for the Calumet and Mainstream Des Plaines TARP System, User Manual*, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign.

Teledyne/RDI, 2013, Teledyne RD Instruments; web site: http://www.rdinstruments.com/wr_main.aspx;
Channel Master: http://www.rdinstruments.com/channelmaster.aspx ;
Stream Pro: http://www.rdinstruments.com/streampro.aspx;
Rio Grande: http://www.rdinstruments.com/rio.aspx

Trajkovic, B., Ivetic, M., Calomino, R., and D'Ippolito, A., 1999, Investigation of transition from free surface to pressurized flow in a circular pipe, *Water Science and Technology*, 39(9), 105-112.

Vasconcelos, J.G., Wright, S.J., and Roe, P.L., 2006, Improved simulation of flow regime transition in sewers: Two-component pressure approach, *Journal of Hydraulic Engineering*, ASCE, 132(6), 553-562.

U.S. Army Corps of Engineers (USACE), 1990, Lake Michigan Diversion Accounting 1989 Annual Report – Including WY84 & WY85 Accounting, Chicago District.

U.S. Army Corps of Engineers (USACE), 1994, Lake Michigan Diversion Accounting Annual Report Water Years 1990-92, Chicago District.

U.S. Army Corps of Engineers (USACE), 1996, Lake Michigan Diversion Accounting Lakefront Accounting Technical Analysis, Draft Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 1997a, Grand Cal River-Indiana Harbor Canal Sediment Cleanup and Restoration Alternatives Project Draft Report, Appendix A, Hydrologic and Hydraulic Analysis, Chicago District.

U.S. Army Corps of Engineers (USACE), 1997b, Lake Michigan Diversion Accounting Annual Report Water Year 1995, Chicago District.

U.S. Army Corps of Engineers (USACE), 2001, Lake Michigan Diversion Accounting Water Year 1998 Annual Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2004a, Lake Michigan Diversion Accounting Water Year 1999 Annual Report. Contains Lake Michigan Diversion Accounting Water Year 1998 Report and Water Year 1999 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2004b, Lake Michigan Diversion Accounting Water Year 2000 Annual Report. Contains Lake Michigan Diversion Accounting Water Year 2000 Report and Water Year 2001 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2007a, Lake Michigan Diversion Accounting Water Year 2002 Annual Report. Contains Lake Michigan Diversion Accounting Water Year 2002, Chicago District.

U.S. Army Corps of Engineers (USACE), 2007b, Lake Michigan Diversion Accounting Water Year 2003 Annual Report. Contains Lake Michigan Diversion Accounting Water Year 2003, Chicago District.

U.S. Army Corps of Engineers (USACE), 2011a, Lake Michigan Diversion Accounting Water Year 2006 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2011b, Lake Michigan Diversion Accounting Water Year 2007 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2012, Lake Michigan Diversion Accounting Water Year 2008 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2013a, Lake Michigan Diversion Accounting Water Year 2010 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2013b, Lake Michigan Diversion Accounting Water Year 2011 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2015, Lake Michigan Diversion Accounting Water Year 2012 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2016, Lake Michigan Diversion Accounting Water Year 2013 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2018, Lake Michigan Diversion Accounting Manual of Procedures, Chicago District.

U.S. Army Corps of Engineers (USACE), 2019a, Lake Michigan Diversion Accounting Water Year 2014 Report, Chicago District.

U.S. Army Corps of Engineers (USACE), 2019b, Lake Michigan Diversion Accounting Water Year 2015 Report, Chicago District.

Vanrolleghem, P.A., Benedetti, L., and Meirlaen, J., 2005, Modelling and real-time control of the integrated urban wastewater system, *Environmental Modelling & Software*, 20, 427-442.

Vougioukas, S., Papamichail, D., Georgiou, P., and Papadimos, D., 2011, River discharge monitoring using a vertically moving side-looking acoustic Doppler profiler, *Computer and Electronics in Agriculture*, 79, 137-141

Waite, A.M., Hornewer, N.J., and Johnson, G.P., 2002, Monitoring and Analysis of Combined Sewer Overflows, Riverside and Evanston, Illinois, 1997-99, *U.S. Geological Survey Water-Resources Investigations Report 01-4121*.

Wallingford Software Ltd., 2006, *Infoworks-CS*, Wallingford, U.K.: Wallingford Software Ltd.

Wang, F. and Huang, H., 2005, Horizontal acoustic Doppler current profiler (H-ADCP) for real-time open channel flow measurement: Flow calculation model and field validation. *Proceedings 31st Congress of the International Association of Hydraulic Engineering and Research*. Seoul, Korea, p. 319–328.

Westcott, N.E., 2014, Continued Operation of a 25-Raingage Network for Collection, Reduction, and Analysis of Precipitation Data for Lake Michigan Diversion Accounting: Water Year 2013, *Illinois State Water Survey Contract Report 2014-01*, Champaign, Ill.

Wicklein, S.M. and Schiffer, D.M., 2002, Simulation of Runoff and Water Quality for 1990 and 2008 Land-Use Conditions in the Reedy Creek Watershed, East-Central Florida, *U.S. Geological Survey Water-Resources Investigations Report 02-4018*.

World Meteorological Organization (WMO), 2010, *Manual on Stream Gauging, Volume II, Computation of Discharge*. *WMO No. 1044*. [Online] Available from: http://www.wmo.int/pages/prog/hwrp/publications/stream_gauging/1044._Vol_II_en.pdf

Yang, S.Q., Tan, S.K., and Lim, S.Y., 2004, Velocity distribution and dip phenomenon in smooth uniform open channel flow, *Journal of Hydraulic Engineering*, 130(12), 1179–1186.

Yen, B.C., 1973, Open-channel flow equations revisited, *Journal of the Engineering Mechanics Division, ASCE*, 99(EM5), 979-1009.

Yen, B.C., 1986, Hydraulics of sewers, in *Advances in Hydroscience*, London, Academic Press, Vol. 14, p. 1-115.

Yen, B.C., and Gonzalez, J.A., 1994, Determination of Boneyard Creek flow capacity by hydraulic performance graph, *University of Illinois at Urbana-Champaign Water Resources Center Research Report 219*, Urbana, IL.

Yen, B.C., and Gonzalez-Castro, J.A., 2000, Open-channel capacity determination using hydraulic performance graph, *Journal of Hydraulic Engineering*, 126(2), 112-122.

Zhou, F., 2000, Effects of trapped air on flow transients in rapidly filling sewers, Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada.

Zimmer, A., Schmidt, A., Ostfeld, A., and Minsker, B., 2013, New method for the offline solution of pressurized and supercritical flows, *Journal of Hydraulic Engineering*, 139(9), 935-948.