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HYDROLOGIC AND HYDRAULIC MODELING OF THE TUNNEL AND RESERVOIR PLAN SYSTEM IN NORTHEASTERN ILLINOIS

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ABSTRACT

The Tunnel and Reservoir Plan (TARP) was adopted by the Metropolitan Sanitary District of Greater Chicago in 1972 to address combined sewer overflow (CSO) pollution and flooding problems in 970 km² of the Chicago metropolitan area served by combined sewers. TARP consists of about 175 km of tunnels, three reservoirs, 256 drop shafts, and over 600 connecting structures, pumping stations, and other appurtenances for the capture and storage of CSOs and for conveying the stored CSOs to water reclamation plants for treatment. The TARP system is comprised of three independent systems: the Calumet system serving the south suburbs and a portion of the south side of Chicago, the Upper Des Plaines system serving the northwest suburbs, and the Mainstream/ Des Plaines system serving the remainder of Chicago and the north, west and southwest suburbs.

The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) desires to develop new, updated and enhanced computer models to allow for simulation of the TARP systems. The new models will be used to optimize operation of the system as actually constructed, to determine constraints in the system, identify physical changes that may be needed to improve performance, and allow what-if analyses to be performed for potential storm scenarios and facility revisions. The modeling includes development of a Physical Inventory system, Hydraulic Modeling of the TARP systems, and Hydrologic Modeling of the TARP service areas. The Physical Inventory provides a digital description of the physical geometry of the TARP system and the related hydraulic performance of system components. Hydrologic Modeling uses data for each dropshafts service area to determine hydrographs describing the inflows to the TARP systems. A major component of the Hydrologic Modeling is to develop tools and methods that allow robust simulation of the extreme heterogeneity of highly urbanized systems and that provide guidance for data compilation needed to improve the accuracy of such simulations. Hydraulic Modeling uses the information from the Physical Inventory and the Hydrologic Modeling to simulate hydraulic response of the TARP system to different inputs. The Hydraulic Modeling tools developed are capable of simulating the range of possible flows in the system, from gravity flows over a dry bed to mixed gravity/surcharged flows to shocks and hydraulic transients.

INTRODUCTION

The Tunnel and Reservoir Plan (TARP) was adopted by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) in 1972 to address the combined sewer overflow (CSO) pollution and flooding problems in the Chicagoland area. TARP consists of tunnels, reservoirs, drop shafts, connecting structures, pumping stations, and other appurtenances for the capture and

storage of CSOs and for conveying the stored CSOs to water reclamation plants for treatment.

TARP, as shown in Figure 1, is split into four systems, namely: O'Hare, Des Plaines, Mainstream and Calumet. The Calumet TARP system has 59.0 km of deep tunnels and 63 drop shafts that will eventually feed the 4.8 billion gallon Thornton reservoir. The Mainstream/Des Plaines TARP system has 106.4 km of deep tunnels and 190 drop shafts that will eventually feed the 10.5 billion gallon McCook Reservoir. The O'Hare TARP system, which is outside the scope of this work, has 10.6 miles of tunnels that feed the 0.35 billion gallon O'Hare Reservoir. Approximately 971 km² of combined sewer area are captured by the TARP systems.

Prior to the development of TARP, the study area was subject to frequent combined sewer overflows during storm events. These events had detrimental effects on connecting waterways, including the Little Calumet River, Lake Michigan and Cal Sag Channel. In the 1970's, a team of engineers from MWRDGC, the City of Chicago, Cook County and State agencies considered various plans to solve the problem of flooding and water pollution. The tunnel and reservoir was selected as the best and most cost-effective plan and has since received awards for its innovation and engineering (e.g., Robison, 1986). The primary objective of TARP is to capture and treat all or practically all of the combined sewer overflows and thereby greatly reduce flooding and waterway pollution in the Calumet area (Kiefer and Associates 1976).

The District has engaged the University of Illinois at Urbana-Champaign (UIUC) to develop advanced computer model for each TARP system. The new flow models will be used to optimize operation of the system as actually constructed, determine constraints in the system, identify physical changes that may be needed to improve performance, and allow "what-if" analyses to be performed for potential storm scenarios and facility revisions.

In the initial phase of the research a Physical Inventory, providing a digital description of the hydraulic performance and related physical geometry of the TARP systems, was developed. This inventory provides a framework for the modeling that can facilitate all the 'bookkeeping' needed to develop and apply the models and to update the models to reflect changes to components of the system or to reflect improved hydraulic or hydrologic descriptions of components of the system.

In addition to developing the Physical Inventory, the initial phase of this research involved development of hydraulic models for the TARP system. The models developed include a conveyance model and an unsteady, mixed-flow model. Research into the hydraulic behavior of the TARP systems also includes development of 3-dimensional computational fluid dynamics (CFD) models of selected structures to quantify their behavior under hydraulic conditions that are infeasible to measure.

Once the hydraulic tools necessary to model the TARP system were developed it became apparent that a better understanding of the hydrologic inputs to the system was required. Uncertainty in the inflows to the system is the most significant factor limiting the accuracy, and thus usefulness, of the hydraulic simulations.

One of the primary objectives of the present phase of this research is to improve the understanding of the hydrology of the TARP service areas. This includes developing operational models of the service areas for the TARP systems and research to develop improved hydrologic models for highly urbanized watersheds.

The initial operational model, which is presently limited to the Calumet TARP system, adopted

a lumped modeling approach because of the complexity and size of the TARP service areas. The collection system comprises streets and roadways, combined sewers, and interceptor sewers that number in the hundreds of thousands. It is impractical to attempt to simulate every pipe, junction, inlet etc. in the system. Although lumping the non-linear hydrologic processes introduces significant errors and uncertainty into the model, development of these service-area models in the consistent manner described will provide an operational tool to allow planning level analyses (e.g. what reduction in CSO volume could be expected for a 10-year average return interval (ARI) storm once Thornton Reservoir is operational). Improvements to the operational model will be made over time as the developmental and research model is developed and tested.

PHYSICAL INVENTORY

The *Physical Inventory* provides a digital description of the hydraulic performance and related physical geometry of the TARP systems. This provides a framework for the modeling that can facilitate all the ‘bookkeeping’ needed to develop and apply the models and to update the models to reflect changes to components of the system or to reflect improved hydraulic or hydrologic descriptions of components of the system.

Tunnels

Data describing the geometric characteristics have been entered for 214 km of tunnels in and feeding the Calumet and Mainstream/Des Plaines TARP systems. These characteristics include the topology (which tunnels, structures, etc. connect to the downstream and upstream end of each tunnel segment), length, diameter, upstream and downstream invert elevations, roughness coefficient, slope, and state-plane coordinates for each tunnel segment.

In addition hydraulic performance graphs (HPGs) and volumetric performance graphs (VPGs) summarizing the discharge and storage characteristics of each tunnel segment for the range of possible flow conditions were developed and checked for each tunnel segment. The HPGs are stored in the *Physical Inventory* system in both a graphical and tabular formats. The graphical format is useful to engineers to understand the conveyance of the system—particularly in locations that limit the conveyance of the system. The tabular format will be used with models of the unsteady-flow hydraulics of the system.

Because flow in either direction is possible in much of the system and likely in a portion of the system, the HPG’s need to reflect both “downstream” (with the pipe gradient) and “upstream” (against the pipe gradient) flows.

Structures

Data describing geometric characteristics of one thousand and twelve structures for the Calumet Mainstream/Des Plaines TARP systems have been entered to the *Physical Inventory* system. These include 253 drop shafts, 132 sluice gates, 228 air chamber/exit conduits, 34 tide and backflow gates, 166 connecting structures, 54 junction chambers, and 145 other structures. These characteristics include the topology (which tunnels, structures, etc. connect to the structure) and physical characteristics such as length, diameter, upstream and downstream invert and inlet/outlet elevations, type of structure, roughness coefficient, slope, and state-plane coordinates for each structure.

HYDRAULIC ASSESSMENT

The *Hydraulic Assessment* includes HPGs and VPGs for the tunnels, an assessment of the

hydraulic capacity of individual components of the TARP systems, and assessment of the capacity of the system considering interactions among different components. The assessment of the hydraulic capacity summarizes the capacity of each component/structure for the range of possible operating conditions and can be used to determine the controlling feature at each location in a manner that reflects interactions among the components of the system. The hydraulic assessment utilizes several modeling tools that range from a steady-state conveyance model to an unsteady, mixed-flow model, to 3-dimensional CFD models of selected structures.

Hydraulic Models

The hydraulic assessment commenced with a review of the literature pertaining to simulation of hydraulic transients in sewers. Transient flows in sewers are multi-regime, multi-component and multi-phase and involve rapid spatial and temporal variations. The regimes include open channel, waterhammer and unsteady gas flows. Transitions from one flow regime to another are governed by flow instabilities that are generally not well understood. The instabilities that could arise in sewer flows include transitions between flow regimes (e.g., dry-bed to flowing; subcritical to supercritical flow; gravity to pressurized flow), effects of natural harmonic frequencies in the system, and effects of multi-phase flows.

As part of the evaluation of modeling approaches for the Chicago TARP system, two prototype second-order explicit Finite-Volume Godunov-Type Schemes (FV-GTS) were developed and evaluated for unsteady gravity and surcharged flows in sewers. Traditionally, hydraulic transients have been modeled using the Method of Characteristics, which is noted for its ability to handle complex boundary conditions. The two FV-GTS described herein incorporate boundary conditions in a similar manner to the Method of Characteristics. Results show that these schemes are significantly faster to execute than the fixed-grid Method of Characteristics scheme with space-line interpolation, and in some cases, the accuracy produced by these two schemes can not be matched by the accuracy of the Method of Characteristics scheme, even when a Courant number close to one and a large number of grids is used. Furthermore, unlike the Method of Characteristics solutions, which exhibit increasing numerical dissipation with decreasing Courant numbers, the resolution of the shock fronts was maintained by the FV-GTS schemes even for very low Courant numbers (0.0001). For two-phase water hammer flows, the two schemes tested show good agreement between experimental data and the results of numerical simulations (Leon et al, 2006a).

Steady Flow Conveyance Model

The Illinois Hydraulic Conveyance Analysis Program (ICAP) (Oberger, et al, 2009) is a steady-flow model that allows simulation of steady gravity (free-surface), pressurized (surcharged), and mixed gravity and surcharged flows. This provides a tool that allows examination of the conveyance capacity and resulting hydraulic grade line for any set of inflow and downstream boundary conditions. This tool displays the heads in an entire tunnel system using an on-line map and color codes to indicate different ranges of heads. Heads that exceed a specified head (e.g., -2.5 ft CCD, which is the average water level in the canal receiving CSOs from the Calumet TARP service area) are displayed in red to allow for easy identification of conditions that will result in overflows to the canal system. This tool also allows for easy display of the conditions in any pipe of the system.

The steady flow model was applied to determine the conveyance capacity of the Indiana Avenue

leg of the Calumet TARP system to provide guidance for the design of the proposed gate to isolate the Thornton Reservoir from the tunnel system. Results indicated that the maximum conveyance while maintaining free-surface flow was 241 m³/sec and that the maximum capacity, with the reservoir empty and the tunnel pending overtopping at the junction is 886 m³/sec. It should be noted that this analysis was limited in scope to the Indiana Ave. leg; at the maximum conditions overtopping would occur at other parts of the system.

The ICAP model can be run in a step-wise steady mode to examine the conveyance of the TARP system for a time-varying rainfall as the downstream boundary conditions change due to filling and/or pumping of the reservoir.

Unsteady, Mixed-Flow Model

A model to simulate unsteady free-surface and pressurized (mixed) flows has been developed based on the Finite Volume Goudonov-Type scheme that has been shown to conserve mass and momentum and provide sharp resolution of discontinuities without spurious oscillations (Leon et al. This model has been successfully tested for a variety of flow conditions in simple tunnels by comparing simulation results to published laboratory data.

This model has now been expanded to incorporate the different types of internal and external boundary conditions found in the TARP system, including reservoirs, dropshafts, and junctions with different geometries. These boundary conditions can address both subcritical and supercritical flow conditions in any of the links connected to the boundary. The model can simulate transitions to/from dry-bed conditions, transitions between sub- and super-critical flow and between gravity and pressurized flow (Leon et al, 2006, 2007, 2008).

The unsteady mixed-flow model has been successfully used to simulate the Calumet TARP system for a variety of hypothetical and real storms. This model can simulate the hydraulics of the system with or without a reservoir. The model successfully simulates the formation and propagation of shocks in the system.

The unsteady, mixed-flow model was applied to determine the conveyance capacity of the Indiana Avenue leg of the Calumet TARP system to provide guidance for the design of the proposed gate to isolate the Thornton Reservoir from the tunnel system. This simulation allowed consideration of how the reservoir filled for different flow conditions. This simulation also showed potential transient effects that result from the shape of the inflow hydrograph. Depending on these effects, the conveyance capacity of this tunnel may be smaller than indicated by the steady-state model. The magnitude of this cannot be determined without a defined inflow hydrograph that represents the hydrology and hydraulic behavior of the area and system contributing flow to the Indiana Ave. tunnel.

HYDROLOGIC MODELING TO ESTIMATE DROPSHAFT INPUTS

Fundamental to understanding the hydraulics of Chicago's Tunnel and Reservoir Plan (TARP) is derivation of the hydrologic inputs necessary to drive the hydraulic modeling. Having compiled a detailed physical inventory of the Calumet and Mainstream TARP systems, and developed both steady and unsteady flow hydraulic models capable of simulating these systems, focus has now been placed on gaining a better understanding of the hydrology of the service areas contributing to TARP. The TARP systems are designed to intercept combined stormwater and wastewater flows that would otherwise overflow into adjacent rivers or waterways during large storm events.

As a consequence of this interception, the TARP systems collect storm and sanitary flows from the combined, sanitary and interceptor sewers. Combined sewers collect sanitary flows from residential, commercial and industrial properties and stormwater runoff from these properties and adjacent roadways. This process is depicted in Figure 1. In order to accurately account for the flow contributing to the TARP system four hydraulic networks must be considered:

1. Overland flow network: this network represents the flow path from when rain falls until it enters an inlet to the combined sewer system. The predominant hydraulic network here will be the curb and gutter street network.
2. Combined sewer or sanitary sewer network: local municipality controlled sewer networks that capture and convey storm and or sanitary flows.
3. Interceptor network: this network, which is maintained by MWRDGC, intercepts flows from the combined and sanitary sewer networks and transports flow to treatment plants.
4. TARP system: network of deep tunnels that receive intercepted flow from combined, sanitary, and interceptor networks through MWRDGC controlled drop shafts and control structures.

The combined sewer network contributing to each dropshaft will consist of hundreds of inlets, manholes and conduits. As an example consider the combined sewer network that services dropshaft CDS-51 in the Village of Dolton, a southern suburb ~~in~~ of Chicago. This catchment captures storm and sanitary flows for the 341 ha service area contributing to drop shaft CDS-51, which feeds the Calumet TARP system. This catchment has been divided into 773 subcatchments collecting inflow from in excess of 800 inlets and feeding a pipe network of 775 pipes ranging in size from 15 cm to 214 cm. The combined sewer network contributing to CDS-51 is typical of the combined sewer networks servicing the Calumet TARP system. As such the combined sewer network contributing to the TARP systems is one that contains hundreds of thousands of pipes, manholes and inlets.

In order to providing accurate estimates of flows into TARP dropshafts in a timely manner, a three-tiered approach to modeling the hydrology of the TARP system has been initiated. At this stage the primary focus is on determining inflows in the Calumet TARP system but this will expand to the entire TARP system in time.

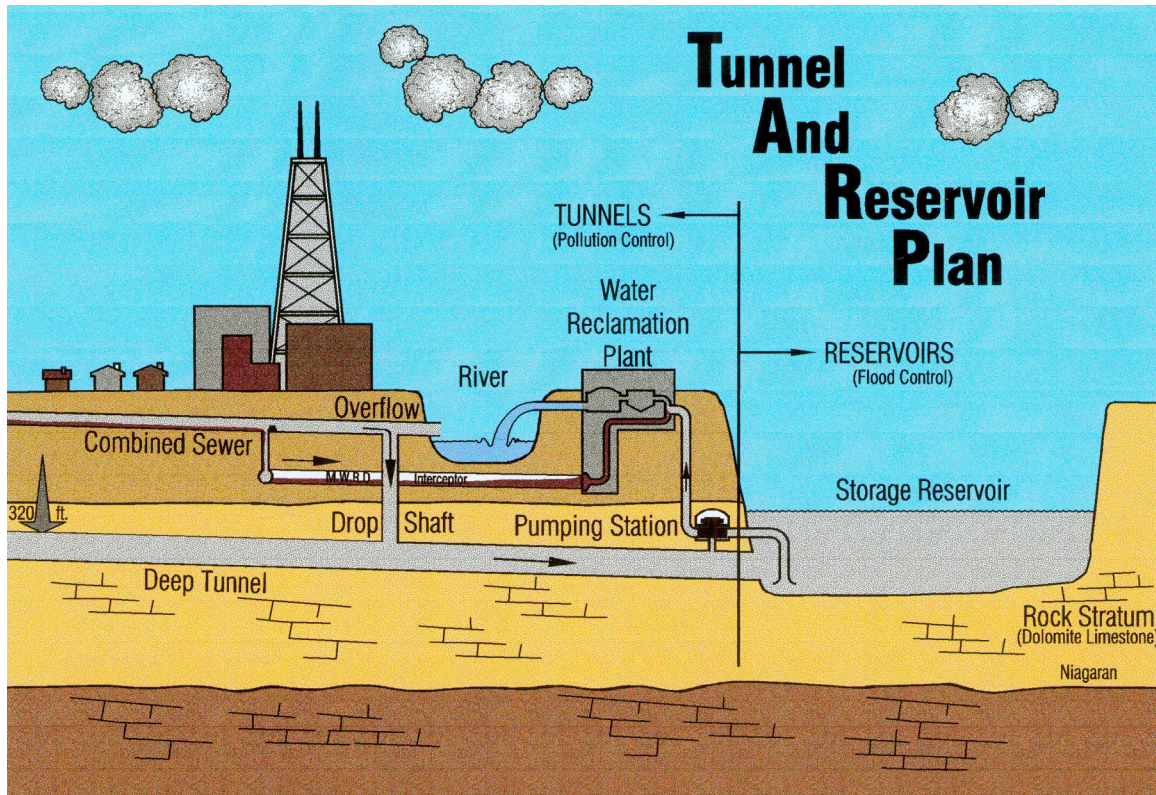


Figure 1—Conceptual basis for Tunnel and Reservoir Plan (courtesy of MWRDGC).

At the grossest scale a lumped model treating the entire Calumet TARP system as a single catchment was developed. A HEC-HMS model (Feldman, 2000) was created using the service area delineated by Kiefer & Associates Inc. (1976), and publicly available Geographic Information System (GIS) databases for land use, soils and topography. The Green and Ampt method was selected as the loss method and the Clark Unit Hydrograph method was used for surface runoff routing. This model no more than a rough estimate of the flow from a given design storm that will reach the Calumet TARP system. The model lumps a service area of almost 90 square miles into a single catchment resulting in a high level of uncertainty.

The second tier of the hydrologic modeling involves estimating inflows into the system on a dropshaft by dropshaft basis by creating a lumped hydrologic model for each dropshaft. A protocol for the creation of a lumped hydrologic InfoSWMM (MWHSoft, 2005) model for each drop shaft has been developed. This protocol describes the methodology adopted for the lumped modeling and guides the modeler through the steps required for creating the model. Before this modeling can begin it is imperative that the service area for each dropshaft be delineated.

Once the service area for each drop shaft has been delineated an ArcGIS database is created for each drop shaft. This database is used to extract some of the information (catchment area, catchment slope, longest flow path, soil properties etc.) required for the development of the lumped model.

Utilizing the lumped hydrologic modeling guidelines, together with the ArcGIS databases, lumped InfoSWMM models have been created for all dropshafts in the Calumet TARP system. Lumped models for dropshaft CDS51 in the Calumet TARP service area have been compared

with field data collected by the USGS for CDS51. Precipitation data (hourly) from a USGS gage located in the southwest corner of the CDS51 service area were used to run a long term simulation of the lumped model for CDS51 in InfoSWMM. The results of this simulation were subsequently compared to the field data collected by the USGS for the period spanning April 24th to September 30th 2007.

A comparison was made between the inflows predicted by the lumped InfoSWMM model and the inflow into CDS51 measured by the USGS. Figures 2 shows the results for a storm where InfoSWMM does a good job of predicting the observed inflow. However, other events show results ranging from trace rainfall recordings at the USGS gage producing significant inflow at CDS51 to instances where InfoSWMM significantly overestimates the inflow observed at CDS51 (Fig. 3). The lack of one definite trend between the predicted and observed inflows tends to indicate that the assumption that the rainfall measured at the nearby gauge is homogenous over the catchment may lead significant errors in the predicted flows.

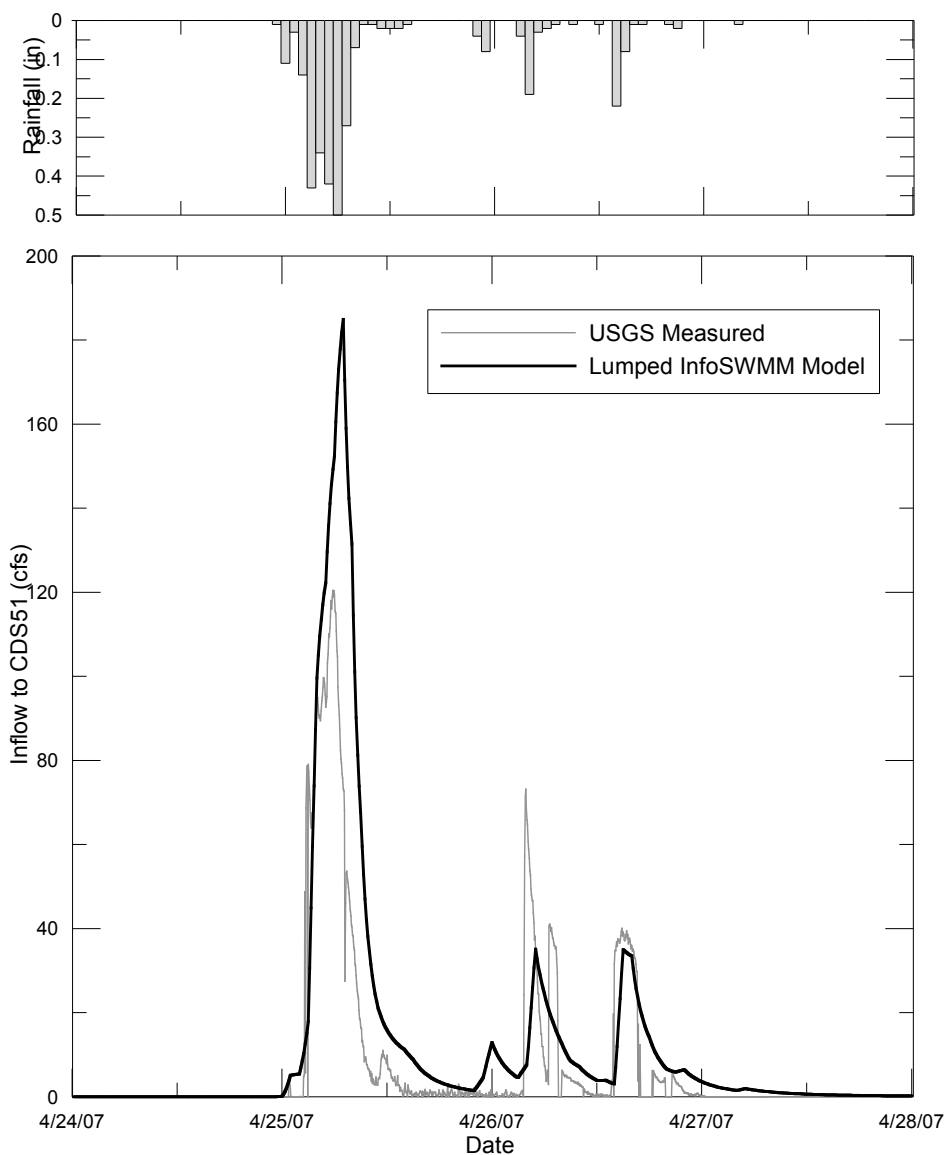


Figure 2.—Simulation results for storm of April 25-27, 2007 at CDS-51.

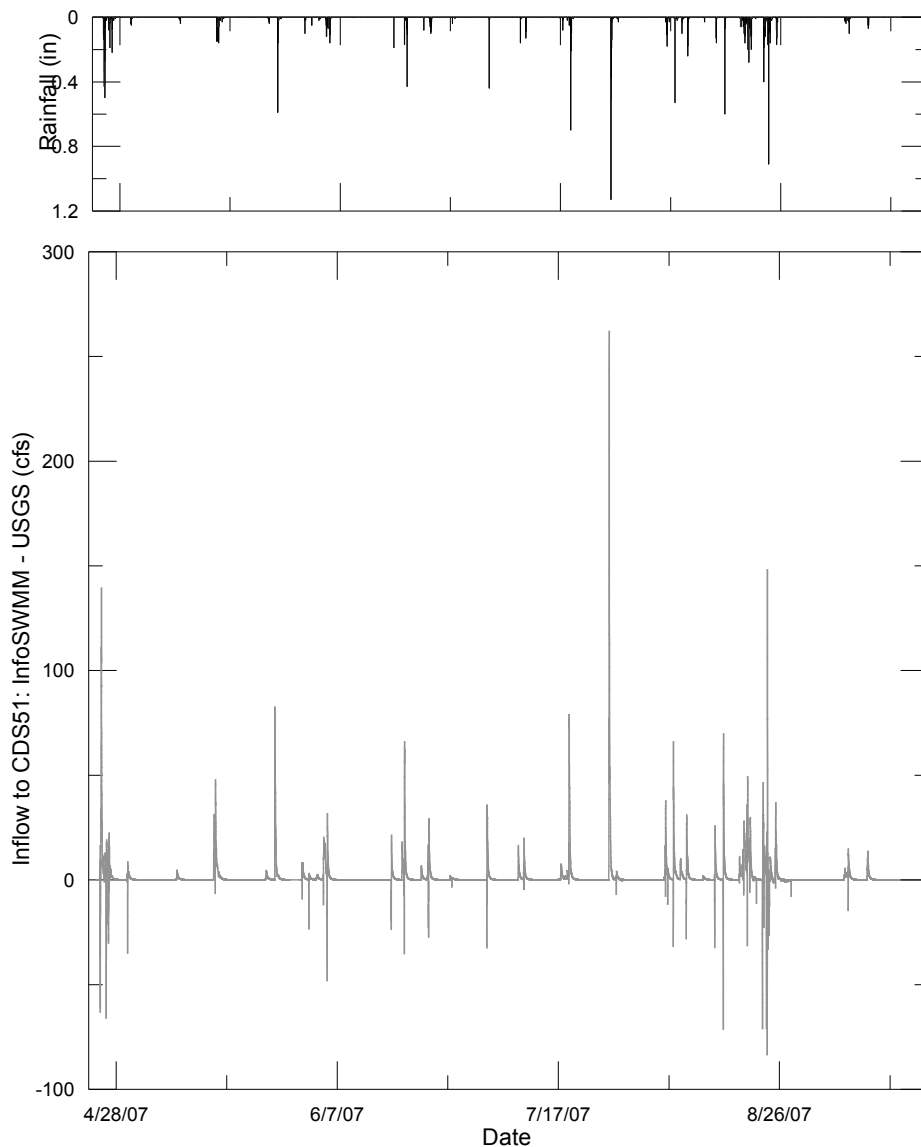


Figure 3.—Simulation of April through August, 2007 at CDS-51.

The third tier of the modeling is developing a novel approach to simulate complex urban watersheds without resorting to conduit skeletonization and subcatchment aggregation methods to reduce the network complexity to a tractable level. Cantone and Schmidt (2008) have shown that these simplification techniques may introduce bias into the predicted hydrographs. Furthermore, the majority of the urban hydrologic models require significant amounts of data describing the system and calibration to field data because of the simplifying assumptions inherent in the models. In many cases the assessment of existing urban hydrologic systems is hindered by the absence of input and/or calibration data. In order to address these issues, an innovative approach to modeling large urban hydrologic systems has been developed. This approach builds on the fundamentals of the geomorphologic instantaneous unit hydrograph (GIUH) that was developed by Rodriguez-Iturbe and Valdes in 1979. The approach described

by Cantone and Schmidt (2009), uses the morphology of the sewer system to route flow through the network and generate a network impulse response function. Excess rainfall is determined using the Green and Ampt method based on the physical characteristics of the underlying soils. The Kinematic Wave approach is used, in conjunction with relevant subcatchment and sewer parameters generated stochastically, to establish probability distribution functions (PDF) for overland and sewer travel times. The PDF's of the travel time are convoluted to generate the network impulse response function. This approach maintains the non-linearity of the physical processes in highly urbanized catchments allowing an improved understanding of the physical process.

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