Computationally Implicit Hydraulics for Real-Time Combined Sewer Overflow Modeling and Decision Support

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ABSTRACT

Large-scale combined sewer systems necessitate accurate hydraulic models with a low computational requirements to depict combined sewer overflows (CSOs) in real-time. A hydraulic model is proposed that incorporates the mass and momentum equations into a series of look-up tables. Flow that enters the interceptors is routed downstream based on a hydraulic performance graph (HPG) which conserves momentum, and a volumetric performance graph (VPG) which conserves mass, established for each conduit. Weirs and sluice gates that control water distribution throughout the combined sewer system are also represented by look-up tables created off-line. During real-time computations, referencing the look-up tables is faster than computing the full equations. The model includes accurate sewer and deep tunnel components imported from Arc-GIS, and is shown to emulate EPA SWMM 5.0 dynamic wave results on a faster time scale. Calibration and timing results show that the model may be successfully applied to evaluate potential operating scenarios more quickly than SWMM.

INTRODUCTION

Combined Sewer Overflows (CSOs) are prevalent in many older urban areas (EIP, 2005; EPA NPDES) during high intensity and long duration rainfall events. CSOs are a significant source of water contamination in urban rivers and lakes (EPA) and can be very difficult and expensive to ameliorate by separating the existing sewer system (EIP, 2005). As a result, many municipalities have resorted to real-time control of the existing combined sewer system (Pleau et al. 2005), or have installed deep tunnels that collect potential CSOs (Razak and Christensen, 2001; Dalton and Rimkus, 1985). Overflows are usually controlled by sluice gates that restrict water flow to the tunnel, as well as pumping to the wastewater treatment plant(s) at the downstream end of interceptor and tunnel conduits. The watersheds and combined sewer pipelines near the ground surface drain to interceptor lines that convey wastewater to treatment plants under normal flow conditions. Under high flow conditions when the treatment plants reach capacity, excess wastewater would originally flow through tide gates to the nearby river. The deep tunnel is designed to catch potential overflows; dropshaft and sluice gate structures control water flow to the deep tunnel.

Real-time control of the existing sewer system requires an accurate hydraulic model of the combined sewer system to depict when and where CSOs might occur, but necessitates fast
computation (Schutze et al. 2004). Reduction in computational intensity for real-time sewer system modeling can be achieved by removing non-critical sewer system elements through network skeletonization (Shamir and Salomons, 2008; Vanrolleghem et al., 2005.) The computational requirements of models that utilize network skeletonization may be further reduced by approximating the hydraulic system response. In addition to boundary relocation, Vanrolleghem et al. (2005) utilize a KOSIM (linear reservoir) representation of the reduced network in combination with a river model comprised of a series of completely stirred tank reactors. Butler and Schutze (2005) also use the KOSIM model. Cembrano et al. (2004) use a similar transfer function, or linear reservoir model, for offline optimization. Meta-models commonly apply moving averages; Pleau et al. (2005) minimize overflow and maximize sewer storage and conveyance through an online moving average model. Dynamic neural networks can also serve as approximations to the actual computational model (Darsono and Labadie, 2007).

Extension of the linear reservoir model to pipe flow does not adequately account for backwater effects or pressurized flow (Rauch et al, 2002); Cardle (1991) notes that an accurate model of pressurized and free surface flow is necessary for effective real-time control. In an effort to enhance the model type used for real-time control, this work incorporates the mass and momentum equations into a series of look-up tables that are extended for surcharged and supercritical flow. The model does not require the online definition of flow type proposed by Duchense et al. (2001). This paper first introduces the case study to which the work is applied. The model algorithms are then discussed in the methodology section, followed by the calibration results. Conclusions and future work on the model are addressed in the last two sections.

CASE STUDY

The model utilized in this study is based on the portion of the deep tunnel system that flows directly under the North Branch of the Chicago River. This tunnel belongs to the Chicago Deep Tunnel Project (TARP) of the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) and spans approximately eight miles. The tunnel in this area has a constant 30 foot diameter and reaches a junction with the Mainstream tunnel, at which point it flows south. North Branch interceptor flows connect to the Mainstream interceptors and flow north to a treatment plant. Combined sewer overflow monitoring is done by the MWRDGC, and CSO data as well as sluice gate positions for recent years are available. The North Branch system (Figure 1) is an attractive place to initialize the study because of the high number of CSOs along the river, the simple interceptor structure of the North Branch system, and the records of operation available.
Boundary conditions must be defined at the upstream ends of the system (flow coming from upstream) as well as water levels in the deep tunnel and downstream of the North Branch interceptor. Upstream flow into the deep tunnel and the deep tunnel level at the Mainstream intersection are determined by simulating an EPA-SWMM model of the entire TARP system. The downstream end of the interceptor is controlled by a stage-outflow relationship that reflects the pumping rate at the water treatment plant. Rainfall over the sewersheds is routed to the interceptors where it flows to a treatment plant. When interceptor flows exceed capacity, water may flow over weirs to connecting structures and tunnel dropshafts (denoted as yellow circles in Figure 1). System decision variables to minimize CSOs in real-time consist of sluice gate positions that control whether water enters the deep tunnel or flows into the river, as well as a treatment plant pumping rate that controls flows and water levels in the interceptor lines.

Rainfall for this project is estimated using NEXRAD Level-II data for the Chicago area. A Linux tool (Hill, 2008) is used to extract a rainfall hyetograph (rainfall rate as a function of duration) for each sewershed from NOAA reflectivity. The rainfall used consists of three events in different seasons of record. The first is a rainfall event on July 24, 2010, the second is an event on April 25, 2007, and the third is a winter event on January 9, 2008.

**METHODOLOGY**

This section provides a description of the different hydrologic and hydraulic components used in the model. The sub-sections below explain the model implementation of the main sewer system components: watershed hydrology, interceptor hydraulics, connecting structure flow, and deep tunnel hydraulics.

Watersheds and local sewers provide inflow to the interceptors. Excess overland and sanitary flows are portrayed through the cell model, a linear reservoir model which has proven successful for watershed routing (Diskin et al., 1984) and is used in this case to reduce detailed
hydrologic computations. The cell model was introduced by Diskin et al. (1984), and further utilized by Karnieli et al. (1994) and Ostfeld and Pries (2003).

Interceptor hydraulics will be based on the methodology proposed by Hoy (2005). Flow that enters the interceptors is routed downstream based on a hydraulic performance graph (HPG) and a volumetric performance graph (VPG) established for each conduit. The HPG describes the flow capacity of an open channel as a function of downstream water surface elevation (Yen and Gonzalez-Castro; 1994, 2000; Schmidt, 2002). The HPG ensures conservation of momentum for the reach and is a collection of the backwater profiles created through the gradually varied flow equation (Chow, 1959). Mass balance in the St. Venant equations is maintained through the VPG which describes the volume stored in the reach for each flow condition described by the HPG. The HPG and VPG files are created offline for a range of flow rates and downstream boundary conditions for each sub-conduit through tools scripted in C++ (Oberg, 2008). The graphs are used for interpolation during optimization; step-wise steady flow is assumed for HPG and VPG lookup. Water levels at the interceptor weirs determine whether water flows toward the CSO and deep tunnel; a lookup table is assembled which indexes flow over the interceptor weir as a function of interceptor water elevation, and is combined with the HPG-VPG approach for interceptor flow calculations.

If interceptor water levels (as computed with the HPG) get sufficiently high, water flows over weirs toward connecting structures. Flow over the interceptor weir is partitioned between the sluice gate and the overflow. Flow through the sluice gates is based on mass and momentum conservation as established in the USGS FEQ model (Franz and Melching, 1997). Increasingly closed sluice gate positions cause upstream water levels to increase, resulting in a higher risk of CSOs. A lookup table is used to quantify sluice gate flow and CSO flow as a function of flow into the connecting structure. The water determined to flow through the sluice gates is used to establish deep tunnel water levels. Tunnel hydraulics may be computed using only the HPG to route water upstream and establish water elevations at each dropshaft and sluice gate structure, or applying the HPG-VPG combination.

**SOLUTION METHOD**

Optimization within an implicit-in-time numerical formulation conserves both mass and momentum (Hoy, 2005). Martin (2010) expanded the original work by Hoy (2005) by introducing ghost nodes to resolve continuity problems at the junctions, and by accelerating the convergence time by using Newton-Raphson iteration. At each time step, a system of equations and its Jacobian (a matrix of the partial derivatives) are built; the system of equations includes one equation for each unknown water elevation and flow rate throughout the system. The code is implemented in Matlab.
This work extends the HPG-VPG approach by adapting the HPG and VPG graphs to include pressurized and supercritical flow in addition to open channel and subcritical flow. These aspects are discussed below.

The HPG and VPG curves are extended to include pressurized flow. Original HPG and VPG curves portray Manning’s open channel flow, at water elevations equal to 80 percent of conduit diameter, as the maximum flow rate. HPGs and VPGs must frequently account for a higher range of water elevations and flow rates to ensure storage balance for high intensity storm events in closed conduits. Pressurized flow values within the HPG are derived through application of the Darcy-Weisbach equation and connected to the open-channel hydraulic performance curves by computing the pressurized water elevation at the conduit full flow, and connecting this point to the flow when the conduit is 80 percent full. This connection eliminates potential discontinuities during interpolation.

Conduits experiencing supercritical flows are also incorporated within HPG and VPG iteration. Water surface profiles in steep sloped conduits are controlled by a critical depth upstream for a wide range of downstream water elevations. Flow lines comprising a typical subcritical HPG define a single upstream water surface elevation for a downstream water elevation and conduit flow rate. The change in upstream elevation given a change in downstream elevation or flow rate can be calculated from interpolation. Introducing an additional possible upstream depth (for a constant flow rate) for a variety of downstream water surface elevations implies that a change in the downstream water surface or the flow yields two different upstream water surface elevations. No single derivative exists with which to compose the Jacobian matrix. A recursion implements Newton-Raphson optimization separately upstream and downstream of the critical depth location, thereby eliminating iteration between two derivative values.

RESULTS

Calibration results are shown for scenarios in which the sluice gates are 10 percent open. A SWMM interceptor model that includes all sluice gates, weirs, and connection tunnels is compared to the proposed HPG-VPG approach. The legend used for the three comparison figures (2 through 4) is the same; the HPG-VPG model results use the solid lines to represent interceptor characteristics and circles to show the interceptor (weir) outflows; SWMM with all components uses smaller dotted lines to show the water profiles and triangles to denote the flow volumes out of the interceptors. Interceptor outflows comprise water that has the potential either to cause overflows or to enter the deep tunnel.

The July 2010 storm is the most severe of those examined; the interceptor system is pressurized for most of the twenty 15 minute intervals simulated. As a result, the initial time intervals witness the system going from almost dry bed conditions to pressurized flow, and require an increased time step for convergence. Water surface elevations and flow rates are
shown in Figure 2; the y axis in Figure 2a plots the water surface elevation in meters, and 2b plots the flow rate in cubic meters per second. Both graphs plot the upstream distance from the interceptor junction with the Mainstream system on the x axis. The black solid lines delineate the conduit inverts and diameter, the darker lines show the water profiles at interval 10, and the lighter gray lines represent the water surface at time interval 20. The two abrupt changes to the slope of the solid line representing the conduit inverts (at 2914 and 5057 meters upstream) are steep sloped conduits. The circles and triangles plotted for each model and time interval display the overflow to the weir and connecting structure that could be potential CSO flow. The water surface elevations at time interval 1, shown in Figure 2a, are low enough that the corresponding flows are not plotted in Figure 2b.

![Figure 2a: July 2010 Water Surface Profiles and Flow](image1)

![Figure 2b: July 2010 Water Surface Profiles and Flow](image2)

Figure 2: July 2010 Water Surface Profiles and Flow

Figure 2a shows that upstream of the most upstream steep sloped conduit (at 5057 meters) the conduits are pressurized for the later time intervals. The water profiles fall below the top of the conduit diameter downstream of the steep conduit, demonstrating that this conduit acts as a bottleneck to restrict downstream flows. Figure 2b shows that the largest overflows occur at time interval 10 at the most upstream weir (5057 meters), validating the bottleneck. At interval
20, weir overflows are also largest at the most upstream location, resulting in negative conduit flows from the downstream portion of the system to replace the high outflows. The HPG-VPG interceptor model flows closely emulate the SWMM results. The water surface elevation results are also comparable for all conduits.

Water surface elevations and flows for the April 2007 event (Figures 3a and 3b) also show close matches between the HPG approach and SWMM.

![Figure 3: April 2007 Water Surface Profiles and Flow](image)

Figure 3a shows that at the upstream end of the steep sloped conduit (5057 meters upstream) SWMM simulates high water elevations that approach pressurized conditions. Figure 3b shows that at the location of the disparity between pressurized and free-surface water elevations, SWMM simulates lower flows for both intervals 10 and 20 than the other model. The weir flows are negative for this model, indicating instability.

The January 2008 water surface elevations and flows are show in Figures 4a and 4b.
The January storm is not large enough to pressurize the system, and the water surface profiles shown in 4a for the HPG-VPG approach and SWMM are very similar. SWMM closely emulates the HPG-VPG determined flow rates for the upstream conduits, however, the HPG computation underestimates flows at time interval 10 for downstream and centrally located conduits. For the January storm event, interceptor flows are under-predicted by the HPG-VPG approach. This may be a result of different flow depth calculations upstream of the supercritical conduit between the two models.

The results for the three storm events show that the coupled HPG-VPG approach yields water profiles and flow rates similar to the dynamic wave approach in EPA SWMM.

CONCLUSIONS

A computationally implicit, stepwise steady model is proposed for use in real-time decision support of combined sewer systems. The model compiles hydraulic performance graphs (HPGs) and volumetric performance graphs (VPGs) offline to represent the St. Venant mass and
momentum equations for all conduits. Newton-Raphson iteration allows water elevations and flow rates to converge at each time step. The USGS FEQ equations solve for sluice gate flows. Extensions to the HPG-VPG system shown allow computations of pressurized and super critical flow. The resulting model applied to interceptor hydraulics is shown to represent the system well when the system is pressurizing or depressurizing. The HPG-VPG model has identified flow bottlenecks and discrepancies between overflow volumes that may influence optimization results. The Matlab code is used to simulate a variety of design storm events, and results in as much as a 200 percent reduction in computational time over SWMM simulations for the same storm events and conduit layouts. The convergence speed in Matlab may be improved by using methods other than Newton-Raphson, and variations to the Biconjugate Gradient Method will be examined.

REFERENCES


