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Three-Dimensional hydrodynamic and water-quality modelling of a CSO event in the Bubbly Creek, Chicago, IL

S. Sinha
Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana and Champaign, 205 N Mathews Avenue, Urbana IL 61801

X. Liu
Department of Civil and Environmental Engineering, University of Texas at San Antonio, One USTA Circle, San Antonio, TX 78249.

M. H. Garcia
Ven Te Chow Hydrosystems Labrotary, Department of Civil and Environmental Engineering,University of Illinois at Urbana and Champaign, 205 N Mathews Avenue, Urbana IL 61801

ABSTRACT: Bubbly Creek is a tributary of south branch of Chicago River, IL. It is mainly used for routing combined sewer overflow (CSO) through the Chicago River. In this work we numerically model a CSO event through the creek and study the flow structures for various flow conditions. The numerical model used for the aforementioned exercise is Environmental Fluid Dynamics code (EFDC). The model solves the three dimensional vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid. Model uses a stretched sigma or vertical coordinates and curvilinear orthogonal horizontal coordinates. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The flow features thus modeled are eventually used for modeling common water quality parameters. Bubbly creek is infamous for having less than desired water quality standards. The modeling exercise conducted helps us in understanding and isolating various reasons for the present state of the creek.

Keywords: EFDC, Mode-Splitting, Chicago River, Dissolved Oxygen, Biochemical Oxygen Demand

1 INTRODUCTION

1.1 *General background*

The study area for this modeling exercise comprises of the entire 2200 meters long channel of the South Fork of the South Branch of Chicago River, colloquially referred as “Bubbly Creek”, along with various slips at the mouth of the Creek. The extent of the domain becomes a little clearer in the Figure1. Bubbly creek was once a pristine wetland system that provided natural aquatic and terrestrial habitat for fish, bird and other species. Bubbly Creek has undergone major physical changes, which includes deepening and widening of the channel, creation of sheet pile banks, severe hydrologic alteration, and introduction of polluted sediments and runoff. A mix of land uses are found along the banks of Bubbly Creek including industrial plants, trucking terminals, rail yards and construction material yards which are giving way to new commercial and residential development. In olden days there were number of meat packing plants situated along the banks of the Bubbly Creek. The channel was systematically widened and deepened to allow for drainage and disposal of waste from the nearby meat packing industries. Biochemical reactions caused by the decomposing animal waste continuously produce methane and hydrogen sulphide bubbles. To this day these bubbles constantly float to and break at the water surface, for which the name, “Bubbly Creek” is colloquially given. Today, Bubbly creek is a relatively straight 2200 meters long channel that originates at the Racine Avenue Pumping Station (RAPS) and flows north during the over flow events to its confluence with the south branch of the Chicago River. Bubbly Creek is relatively shallow with depth varying from 2 meters near RAPS and around 5 meters at the mouth where it meets the south branch of the Chicago River. The width of the creek varies between 40 and 65 meters. The major physical alterations caused by the development has severely degraded the natural ecosystem and eliminated most of the natural aquatic and terrestrial habitat. Due to gigantic man made changes, hydrologic alterations, combined sewer overflow (CSO), Bubbly creek remains a severely impaired ecosystem with vast opportunities for restoration. Bubbly creek faces complex series of problems which requires a very keen and close examination, which hopefully would finally yield some pragmatic restoration procedures. Some of the challenges faces by the

Bubbly Creek are explained in little more detail here.

Stagnant flow condition: During dry weather periods Bubbly Creek is stagnant, except for the occasional movement of water caused by the passing boats or the slight surge from the south branch. Even during light to moderate rainfall the flows in Bubbly Creek is not severely affected as only a very small area adjacent to the channel directly drains into Bubbly Creek. It would not be a stretch to say that for most of the time Bubbly Creek behaves more like a lake system rather than a regular river. During the stagnant periods, severely degraded water quality in Bubbly Creek can be attributed to several factors, including biochemical activity between the sediment and the water column, residual water quality from CSOs and photosynthetic activity. Levels of dissolved oxygen (DO), which are indicators of water quality impairment in a stream, typically plummet during stagnant periods and often reaches zero.

Combined sewer overflow: During excessively heavy rainfall events, the combined sewer system that drains surface water runoff and sanitary waste by gravity to RAPS can become overwhelmed. During these times to avoid the problems of water accumulation in the related sewer shed, the pumps at RAPS are turned on which discharges directly into Bubbly Creek. As the quality of water coming into RAPS and getting discharges into Bubbly Creek is severely impaired it has an adverse effect on the overall water quality in Bubbly Creek. At maximum overflow capacity RAPS can discharge almost 170 cubic meters per second in Bubbly Creek. At such high discharge the water levels in Bubbly Creek can increase significantly, especially near the pumps the change in water levels has been observed to be as high as 1 meter. The flow velocity produced as a result of such massive discharge varies around 1 meter per second and some time even more. Such high velocities lead to increase bed shear stress which resuspends lot of undesired organic matter from the bed of Bubbly Creek, which again adversely affects the water quality.

In this paper we use a three dimensional numerical model to simulate a CSO events that happened during the month of September-2006. The overall aim is to examine the flow structures in Bubbly Creek resulting from the CSO events and study their affect on the crucial water quality parameters like BOD (Biochemical Oxygen Demand) and DO (Dissolved Oxygen). The numerical model chosen for the simulation of the aforementioned domain is Environmental Fluid Dynamics Code (EFDC) developed by Hamrick J.M. (1992).

Figure 1: Bubbly Creek from Google Earth

2 NUMERICAL MODEL

2.1 *Description*

The hydrodynamic component of EFDC is based on the three dimensional shallow water equations and includes dynamically coupled salinity and temperature transport. The basic physical process simulation in EFDC is similar to that of Princeton Ocean Model (POM) Blumberg & Mellor (1987), the US Army Corps of Engineer's CH3D-WES model, Johnson et al. (1983) and the TRIM model by Casualli and Cheng (1982).

The EFDC model has been applied to various water bodies and environmental engineering studies, of varied complexity. Some of the cases for example are as follows. Salinity intrusion studies in the Indian River Lagoon and Sebastian River, Florida Tetra Tech (1994), Sucsy et al. (1994). Large scale wetlands simulation in the

Everglades, Hamrick (1994b). Thermal simulation of Lake Okeechobee, Florida, Hamrick (1996).

As far as water quality model is concerned a simple DO – BOD (Dissolved Oxygen - Biochemical Oxygen Demand) was developed on the lines of Motta (2009). This was then linked with the hydrodynamic kernel of E.F.D.C which was used for the simulation exercise.

2.2 *Theoretical formulations*

The EFDC model solves the three dimensional vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid. Model uses a stretched sigma or vertical coordinates and curvilinear orthogonal horizontal coordinates. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The hydrodynamic equations that form the main kernel of the EFDC model are as follows.

$$\partial_t(mHu)+\partial_x(m_yHuu)+\partial_y(m_xHvu)+\partial_z(mwu)$$
$$-(mf+v\partial_x m_y-u\partial_y m_x)Hv=-m_yH\partial_x(g\zeta+p)$$
$$-m_y(\partial_x h-z\partial_x H)\partial_z p+\partial_z(mH^{-1}A_v\partial_z u)+Q_u$$
(1)

$$\partial_t(mHv)+\partial_x(m_yHuv)+\partial_y(m_xHvv)+\partial_z(mwv)$$
$$+(mf+v\partial_x m_y-u\partial_y m_x)Hu=-m_xH\partial_y(g\zeta+p)$$
$$-m_x(\partial_y h-z\partial_y H)\partial_z p+\partial_z(mH^{-1}A_v\partial_z v)+Q_v$$
(2)

$$\partial_z p=-gH(\rho-\rho_o)\rho_o^{-1}=-gHb \qquad (3)$$

$$\partial_t(m\zeta)+\partial_x(m_yHu)+\partial_y(m_xHv)+\partial_z(mw)=0 \quad (4)$$

$$\partial_t(m\zeta)+\partial_x\left(m_yH\int_0^1 udz\right)+\partial_y\left(m_xH\int_0^1 vdz\right)=0 \quad (5)$$

$$\rho=\rho(S,T) \qquad (6)$$

$$\partial_t(mHs)+\partial_x(m_yHuS)+\partial_y(mHvS)+\partial_z(mwS)$$
$$=\partial_z(mH^{-1}A_b\partial_z S)+Q_s$$
(7)

$$\partial_t(mHT)+\partial_x(m_yHuT)+\partial_y(m_xHvT)+\partial_z(mwT)$$
$$=\partial_z(mH^{-1}A_b\partial_z T)+Q_T$$
(8)

In these equations, u and v are the horizontal velocity components in the curvilinear, orthogonal coordinates x and y, m_x and m_y are the square roots of the diagonal components of the metric tensor, m = m_xm_y is the Jacobian or square root of the metric tensor determinant. The vertical velocity, with physical units in the stretched dimensionless vertical coordinate z is w, and is related to the physical vertical coordinate w^* by:

$$w=w^*-z\left(\partial_t\zeta+um_x^{-1}\partial_x\zeta+vm_y^{-1}\partial_y\zeta\right)+$$
$$(1-z)\left(um_x^{-1}\partial_x h+vm_y^{-1}\partial_y h\right)$$
(9)

The total depth, H = h + ζ, is the sum of the depth below and the free surface displacement relative to the undisturbed physical vertical coordinate origin, z^* = 0. The pressure p is the physical pressure in excess of reference density hydrostatic pressure, $\rho_o gH(1-z)$, divided by the reference density, ρ_o. In the momentum equations (1) and (2) f is the Coriolis parameter, which is switched off for the present simulations, A_v is the vertical turbulent or eddy viscosity, Q_u and Q_v are the momentum source-sink terms which is eventually modeled as the subgrid scale horizontal diffusion. The density of the water is modeled through a state equation and is a function of salinity S and temperature T. The continuity equation (4) has been integrated with respect to z over the interval (0,1) to produce the depth integrated continuity equation. In the transport equations for salinity (7) and temperature (8), Q_s and Q_T include subgrid scale horizontal diffusion and thermal sources and sink, while A_b is the vertical turbulent diffusivity. The system of equations from (1) to (8) forms a close set of equations provided the turbulent viscosity and diffusivity and source and sink terms are specified. The vertical turbulent viscosity and diffusivity are modeled in EFDC using Mellor and Yamada (1982) model modified by Galperin et al. (1988). The model relates the vertical turbulent viscosity and diffusivity to the turbulent intensity, qq, a turbulent length scale, l and a Richardson number R_q.

As far as the dissolved or suspended constituents are concerned the governing equation solved by the EFDC model for any water quality state variable can be given by the following equation.

$$\frac{\partial\left(m_x m_y HC\right)}{\partial t}+\frac{\partial\left(m_y HuC\right)}{\partial x}+\frac{\partial\left(m_x HvC\right)}{\partial y}+$$
$$\frac{\partial\left(m_x m_y HwC\right)}{\partial z}=\frac{\partial}{\partial x}\left(\frac{m_y HA_x}{m_x}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{m_x HA_y}{m_y}\frac{\partial C}{\partial x}\right)$$
$$+\frac{\partial}{\partial x}\left(m_x m_y\frac{A_z}{H}\frac{\partial C}{\partial x}\right)+m_x m_y HS_c$$
(10)

where C = concentration of water quality state variable, A_x, A_y, A_z = turbulent diffusivities in x, y and z directions respectively, S_c = internal and external sources and sinks per unit volume, H = water column depth.

EFDC model solves the advection-diffusion equation for a water quality state variable (10) by decoupling the physical transport and the kinetic terms. It should be mentioned that the computation of the kinetic step is made at a constant water depth at the end of the physical transport step. This allows the depth and the scale factors to be eliminated from the kinetic processes and which in turn can be further split into reactive and internal sources and sinks which can be presented by the following equation.

$$\frac{\partial C_k}{\partial t}=K\cdot C+R \qquad (11)$$

where K is the kinetic rate ($time^{-1}$) and R represent the internal source/sink term (mass $volume^{-1}$ $time^{-1}$). The solution scheme for both physical transport and the kinetic equations are second order accurate.

2.3 *Boundary conditions*

For solving the given set of partial differential equations from (1) to (8) numerically we need to specify the boundary conditions. For closed water bodies horizontal boundary condition is easy to implement as it only requires setting the boundary normal velocity and constituent flux to zero. In case of open horizontal boundaries, either the water depth or a combination of the normal velocity and water depth must be specified as well as influx of dissolved and suspended constituents must be specified. The vertical boundary condition for the solution of momentum equations (1) and (2) are based on the specification of kinematic shear stress. The vertical boundary condition as implemented in the model can be adequately represented by the following equations.

$$K_v H^{-1}\partial_z\left(u,v\right)_{z=0}=\left(\tau_{bx},\tau_{by}\right)=c_b\sqrt{u_1^2+v_1^2}\left(u_1,v_1\right)$$
(12)

$$K_v H^{-1}\partial_z\left(u,v\right)_{z=1}=\left(\tau_{sx},\tau_{sy}\right)=c_s\sqrt{u_w^2+v_w^2}\left(u_w,v_w\right)$$
(13)

The bottom of the river is denoted by z = 0, in normalized non-dimensional coordinates and the surface is denoted by z =1. U_w and V_w refers to the components of the wind velocity at 10 meters above the surface of the water surface. The subscript 1 denotes the velocity at the midpoint of the bottom layer. The bottom drag coefficient is given by:

$$c_b=\left(k^{-1}\ln\left(\frac{\Delta_1}{2z_o}\right)\right)^{-2} \qquad (14)$$

Where k, is the von Karman constant, Δ_1 is the dimensionless thickness of the bottom layer, and $z_o=z_o^*/H$ is the dimensionless roughness height. The wind stress coefficient is given by:

$$c_s=0.001\rho_a\rho_w{}^{-1}\left(0.8+0.065\sqrt{U_w^2+V_w^2}\right) \qquad (15)$$

for the wind velocities in meters per second with ρ_a and ρ_w denoting air and water densities respectively.

For water quality constituents the values at the inflow boundaries were specified, whereas at the open boundaries with water-surface elevation specified, zero gradient boundary condition was utilized for dissolved and suspended constituent.

2.4 *Numerical solution procedure*

The numerical solution of the EFDC model equations uses a finite volume-finite difference spatial discretization with a MAC or C grid staggering of the discrete variables. The velocity components are located on the faces of the primary control volume, where as the depth, buoyancy and concentration of transported constituents are located at the centroid of the control volume. The staggered arrangement of variables can be suitably presented in Figure 2.

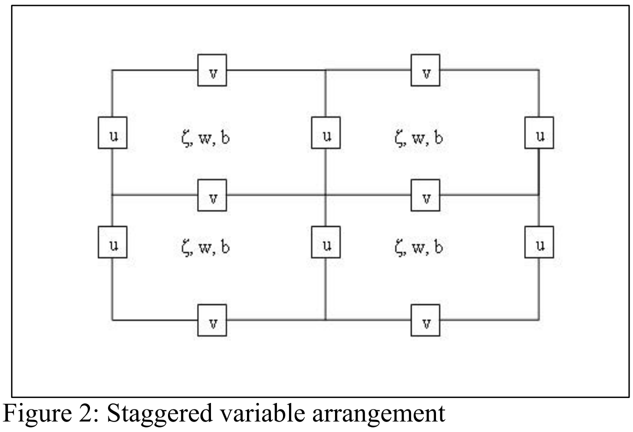

Figure 2: Staggered variable arrangement

The excess pressure presented in equation (3) is defined on the top faces of the continuity control volume. An additional set of control volume, staggered vertically are used for the transport equations of the turbulence parameters. The spatial integration is carried over different sets of staggered control volume, the horizontal depth and the excess pressure is determined by the finite difference operations, all the spatial discretization is carried out by the second order accurate central difference scheme.

The temporal integration of the momentum and continuity equation uses a second order accurate, semi-implicit, three time-level, leap frog trapezoidal scheme. The computational mode generated by a three time level scheme is suppressed by the periodic insertion of a two time level trapezoidal step. The mode splitting scheme which partially decouples the fast moving external or barotropic mode and slow moving internal or baroclinic mode is also used. The barotropic mode is implicit in horizontal and the baroclinic mode is implicit in the vertical direction.

3 CONFIGURATION OF EFDC MODEL FOR BUBBLY CREEK

3.1 *Grid generation*

The formulation and governing equation of EFDC model is based on orthogonal curvilinear coordinate system (OCCS), hence the first step before the model is used and simulations are conducted is the generation of the grid. The grid for the domain depicted in the Figure 1 was generated by using the grid generating tool gridgen. A portion of grid generated and used for the simulation is shown in Figure 3.

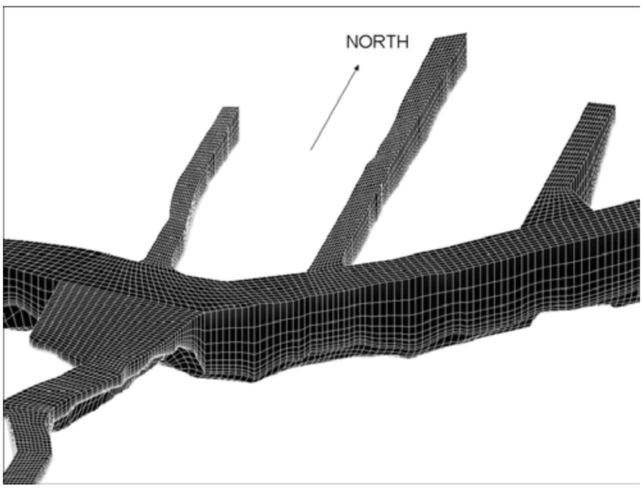

Figure 3: Portion of grid generated for the simulation

The grid generated has 7821 cells in horizontal and 8 layers in vertical which gives total 62568 control volumes or cells. It must be mentioned that while generating the grid it was tried to keep the mesh as orthogonal as possible, as it's a well known fact that a skewed mesh can lead to undesirable results and can also create problems in the convergence of the numerical solution. Sankarnarayanan and Spaulding (2003) conducted host of simulation to show the adverse effect of grid non-orthogonailty on the solution of shallow water equations in boundary-fitted coordinate system.

3.2 *Input data for simulation*

The numerical simulation conducted is based on the CSO event of September 13, 2006, the CSO volume was 19148813 cubic meters, corresponding for measured outflow duration of 7.66 hrs, which resulted in a mean flow discharge of 69.43 m^3/sec at the Racine avenue pumping station. The discharge coming from south branch in the direction of flow was of the order of 20 m^3/s. The initial water surface elevation for the whole domain was kept at -0.66 m. The water surface elevation at the west end of the domain was kept at a constant value of -0.66 meters with respect to the Chicago city datum (CCD), such a value was obtained by examining the various data set available at MWRD (metropolitan water reclamation district of Chicago) and USGS websites for various CSO events of the past. It has been observed that for a moderate CSO event, likes of one which has been simulated, the elevation at the west end near Cicero avenue doesn't change significantly. The general orientation of the flow in the Chicago River system can be suitably depicted by the Figure 4.

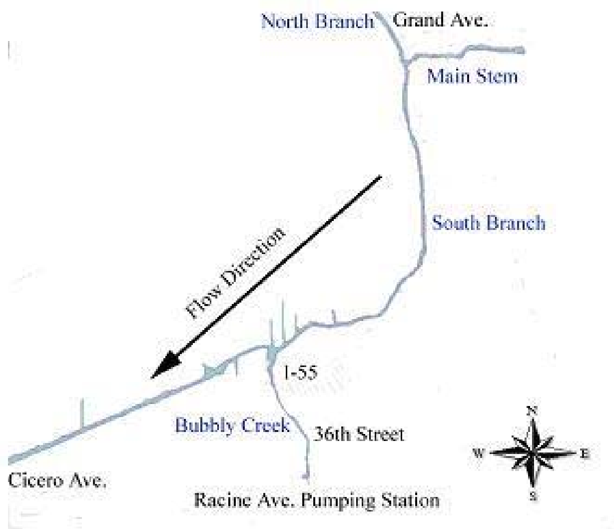

Figure 4: Segment of Chicago River System

It has been observed that the flow in the river system is generally oriented from North to South. When the Racine Avenue Pumping station starts pumping due to a CSO event, the upstream intrusion of the flow along the south branch of river has been observed. As mentioned in section-2, the boundary condition needed by the EFDC model at the open boundaries are, normal flow velocity or the depth, or some combination of both. In the simulation conducted the RAPS end and the portion on the grid extending towards the south branch, Figure 4, is taken as the open boundaries. The inflow at RAPS is set at 69.43 m^3/s for the first 7.66 hrs and then set to zero as the pumps are shut down. The flow from south branch entering the computational domain is set at 20 m^3/s.

As regards with water quality constituents, the incoming flow from the Racine avenue pumping station had saturated DO value of 9 mg/l, and BOD at 68.1 mg/l. The inflow from north in the main channel had incoming DO level of 6.86 mg/l and BOD of 5 mg/l. The SOD was taken constant at 3.3 $gm/mt^2/day$ for Bubbly Creek. The entire computational domain was initialized with DO value at 1.2 mg/l. This value was obtained by taking the average of the observed DO values at 36^{th} street and I-55 stations before the onset of the CSO event.

4 RESULTS AND DISCUSSION

As shown in Figure 1, Bubbly Creek has two observation stations at 36^{th} street near (RAPS) and at I55 close to the south branch of the Chicago River. These two monitoring stations take continuous hourly measurement of dissolved oxygen and temperature. It should also be mentioned that based on some historical data taken by USGS around 36^{th} street area in the Bubbly Creek, flow velocity has been found to be in the range of 1 meter/sec and above, when the amount of discharge from RAPS due to a CSO has been in the order of 60 m^3/sec. As mentioned in the previous section, the CSO event that was simulated lasted for 7.66 hrs but the actual simulation was carried out for 12 hrs to observe the after effects of the CSO event on pertinent water quality constituents.

4.1 *Hydrodynamic results*

The variation of flow velocity magnitude with time after the start of CSO at 36^{th} street and I-55 is presented here.

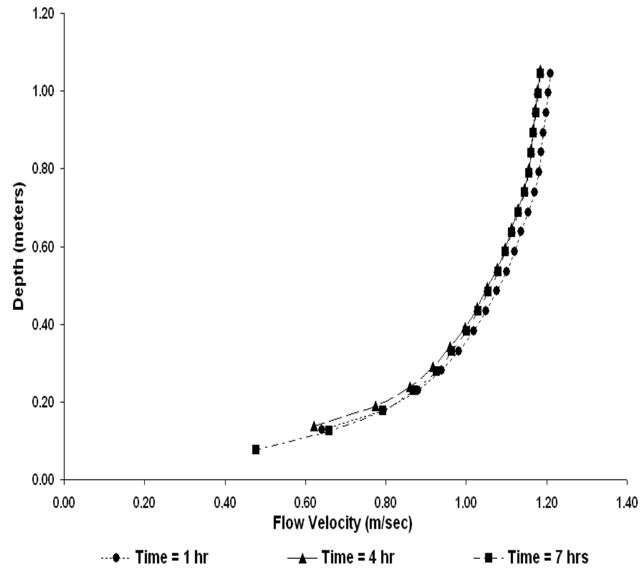

Figure 5: Veloc. variation at 36th street during CSO

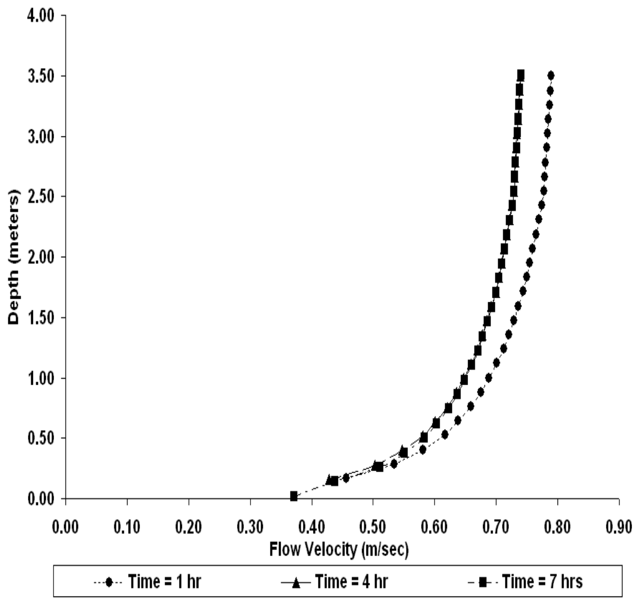

Figure 6: Veloc. variation at I-55 during CSO

It can be seen clearly from Figure 5 and Figure 6 respectively that the magnitude of flow velocity reaches nearly 1.2 and 0.80 meter/sec at the water surface at 36^{th} street and I-55 respectively. As mentioned before, this value is very much in the proximity of the flow velocity observed during; CSO events, with comparable discharges at Racine avenue pumping station (RAPS), as observed by USGS. The magnitude of flow velocity at I-55 is less than that at 36^{th} street, which can be attributed to the fact that the depth in the creek is shallower around 36^{th} street area. The same can be observed in the Figure 5 and Figure 6, the free surface at 36^{th} street is only at 1.1 meters, where as at I-55 which is near the turning basin the depth goes as high as 3.5 meters. As shown in Figure 4 the general direction of the flow in the Chicago River system is from north to south, the same is observed as a result of numerical simulation. The three dimensional plot for the flow velocity is presented here.

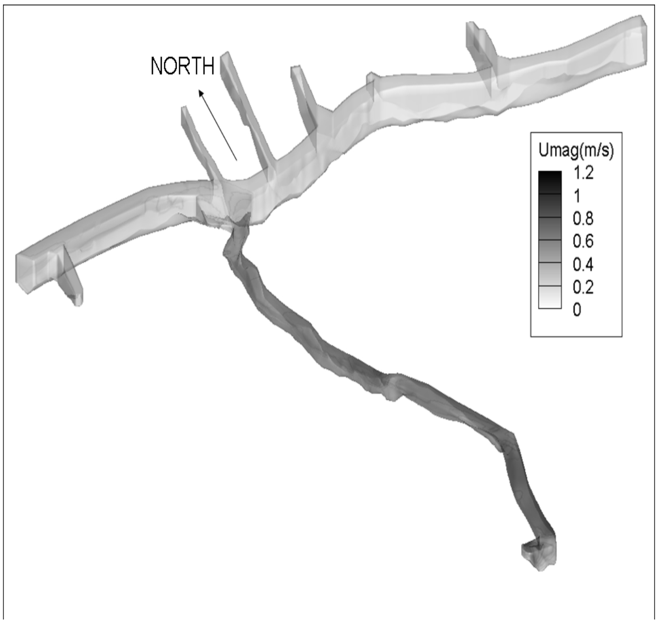

Figure 7: Flow Vel. Mag. in 3-dimension

It should also be noticed that once when the CSO event is over and the pumps at RAPS stop discharging, the flow velocity in the creek comes back to stagnant state, the same can be observed in the Figure 5 and Figure 6. The flow magnitude at 36th street and I-55 comes almost to zero value 9 hrs after the pump started, it should be kept in mind that the pumps were in action only during the first 7.66 hrs.

4.2 *Water quality results*

It is easy to speculate from the hydrodynamic results that, during a CSO event, for high discharges from RAPS any dissolved constituent in the Creek will be primarily driven by advection. The dissolved oxygen level at 36th street, I -55 and at any other place in the creek reaches to the level of DO that is coming in from the Racine avenue pumping station. For simulating the water quality constituents like DO, we make an assumption that the incoming water from RAPS is completely saturated. The water temperature for this simulation conducted here was taken constant at 20^0 centigrade. The saturated DO value at such a temperature comes out to be 9 mg/l, APHA (1992). The simulation conducted here started with very low dissolved oxygen value of 1.5 mg/l, which is not far from the value observed in the creek at various times of low flow condition. As the pumps starts to discharge during a CSO event they bring in huge amount of saturated water which increases the level of dissolved oxygen in the creek in a very short amount of time. The plot presented here shows the variation of dissolved oxygen with time for the CSO event simulated against the observed data.

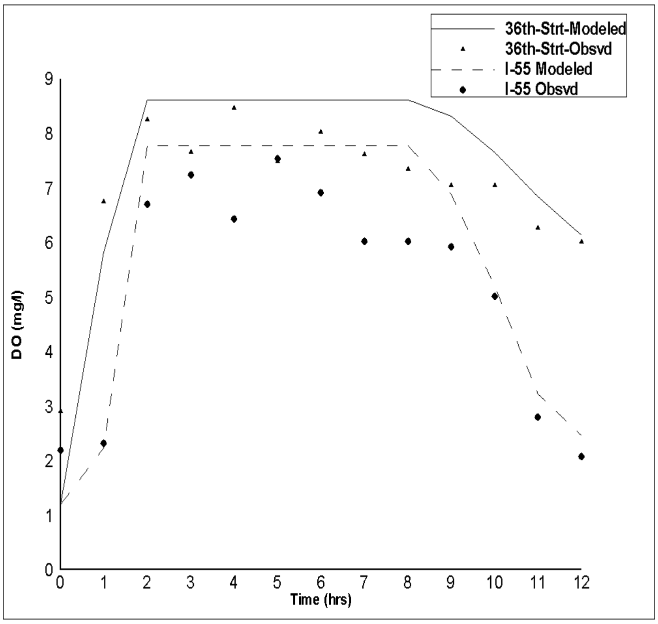

Figure 8: DO variation with time during CSO

It is clear from the plot in Figure 8 that the DO level at 36th street and I-55 shoots up to the level of saturation value in less than an hr. These values are almost same as the DO levels coming in from the Racine avenue pumping station. It is after the pump stops discharging that we see, the dissolved oxygen levels going down. As shown in the Figure 8 after 7.66 hrs, the duration of CSO when the pumps stops discharging we see a steady decline in the DO level, this can be attributed to the combine effect of sediment oxygen demand and because of high concentration of incoming BOD from the Racine avenue pumping station. Even, after the end of the CSO even there is enough BOD (biochemical oxygen demand) in the water to have an adverse impact on the water quality, primarily on the DO level. The plot for the variation of BOD with time is also presented here. As the name suggests the quality of water getting pumped into the system during a combine sever overflow is far from desirable, the amount of BOD in the water coming in from the Racine avenue pumping station was taken at 68.1 mg/l. Once again these values were carried through the whole system impairing the overall water quality of Bubbly creek and other segments of Chicago River.

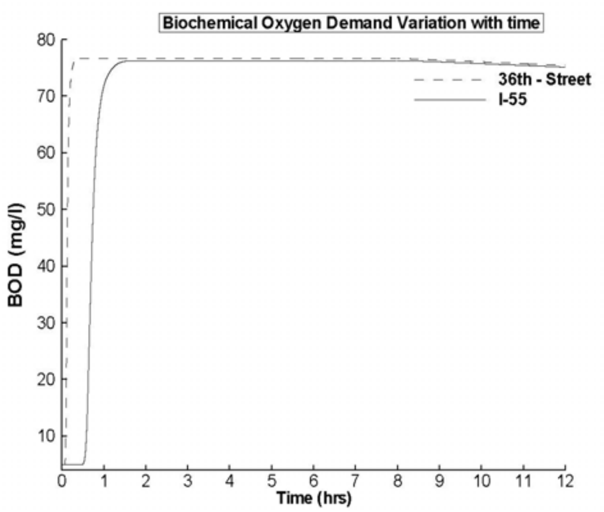

Figure 9: BOD variation with time during CSO

5 CONCLUSIONS

In conclusion it would not be a stretch to say that the DO levels in the creek during low flow condition is a balancing act between sediment oxygen demand and reaeartion. A simple DO-BOD model, which was used for the simulation was developed at integrated with the hydrodynamic kernel of EFDC as a part of this work. It is a well known fact that the kinetic portion of dissolved constituent is not only affected by BOD (biochemical oxygen demand) but also by other important constituents like phytoplankton, nitrogen, phosphorus etc. Hence, the future work will involve integrating all these mechanism in the simple DO-BOD model developed so far.

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