



# Integrated urban hydrologic and hydraulic modelling in Chicago, Illinois



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## ABSTRACT

With rapidly growing urbanization, urban flooding and water quality control are becoming a vital component of sustainable urban infrastructure. Integrated urban hydrologic and hydraulic modelling represents a potential framework for capturing system interactivity and optimizing the design, operation, and engineering of urban systems. This work describes how a widely-used hydrodynamic model, the Environmental Fluid Dynamics Code (EFDC), was made compliant with the Open Modelling Interface (OpenMI) standard. The new version of the EFDC has potential to be coupled with any OpenMI-compliant model for various studies. As an example, this paper presents an application of the OpenMI version of EFDC coupled with InfoWorks-CS for a representative highly urbanized area in the city of Chicago, Illinois, United States. The integrated modelling simulates the two-way linkage between the sewer network and the Chicago Area Waterway System (CAWS). This interaction between the river and sewer pipe systems can not be described by decoupled models. By coupling the models, it is possible to observe the interaction between the sewer system overflow discharge and the hydraulic head in the pipe network. This is particularly important since higher water levels in the pipe system increase the potential for flooding.

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## Software availability

Software: I-EFDC

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Programming languages: FORTRAN, C#

Hardware requirements: Intel i7/Xeon Workstation, 8 GB RAM

Operating system: Linux, Windows 7+

## 1. Introduction

With growing urbanization, water related environmental problems in cities have become more important. Sustainable urban drainage (the reduction of urban flooding) and water quality (the safety of drinking water and recreational water) are primary concerns for all major cities. The assessment of complex problems such

as those that are present in urban areas requires inter-disciplinary research that allows for a more holistic understanding of these systems (Hamilton et al., 2015; Vanrolleghem et al., 2005). In particular, numerical modelling has been accepted as an important alternative to describe and understand different hydrologic processes in urban areas. In past years, many calibrated and validated urban hydrological and/or hydraulic models have been developed to solve specific problems with a focus on individual sub-systems. However, these models usually used different platforms or software, such as HEC models of U.S. Army Corps of Engineers, SWMM of U.S. Environmental Protection Agency, and so on. A main drawback of these individual models is that they are unable to capture the exchange of mass, energy, and other information between sub-systems. Therefore, it is very important and useful to link existing models with integrated modelling approach which provides an opportunity to better elucidate the interaction and feedback of these sub-systems and capture in more detail the complexities associated with large urban areas.

Previous research efforts on model-linking have developed several different frameworks and standard such as OMS (David et al., 2002), TIME (Rahman et al., 2003), MODCOM (Hillyer et al.,

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2003), KEPLER (Altintas et al., 2004), FRAMES (Babendreier and Castleton, 2005), and OpenMI (Moore and Tindall, 2005; Gregersen, 2007). The comparisons of some core characteristics between these frameworks are shown in (Knäpen et al., 2013). The Open Modelling Interface (OpenMI) is one of such frameworks and a software standard that supports dynamically linking models at runtime. A model is OpenMI compliant when it implements the OpenMI standard which defines an interface for different models to exchange data. All models which are OpenMI compliant are allowed to exchange information on one integrated system. An incomplete list of current OpenMI compliant models can be found on the OpenMI website (OpenMI, 2015). OpenMI has been successfully used in many integrated urban water models. For instance, OpenMI was used to analyze the water quality of the river Zenne (Belgium) by successfully coupling both SWAT and SWMM models with a sediment transport model, a stream water temperature model and a fecal bacteria model (Shrestha et al., 2013, 2014). In addition, OpenMI has been implemented to couple InfoWorks-CS and InfoWorks-RS for studying sewer-river linking (Smolders et al., 2008).

et al., 1992). In this study the coupled interaction between the sewer and river model includes only the hydrodynamics, which is a foundation for subsequent studies that examine the effect of this coupling in the dynamics of water quality and sediment transport. It must be noted that EFDC is able to simulate both the water quality (based on CE-QUAL-ICM (Cercio and Cole, 1994)), and the sediment transport (Liu and Huang, 2009; Elçi et al., 2007). In addition, EFDC also can provide hydrodynamic results to other advanced receiving water quality models, such as WASP (Di Toro et al., 1983; Ambrose and Wool, 2009).

### 2.1. Governing equations

The governing equations for continuity and horizontal momentum conservation are as follows:

$$\frac{\partial(m\zeta)}{\partial t} + \frac{\partial(m_y Hu)}{\partial x} + \frac{\partial(m_x H v)}{\partial y} + \frac{\partial(mw)}{\partial z} = 0 \quad (1)$$

where  $\zeta$  is the surface elevation above or below datum; the total

$$\begin{aligned} \frac{\partial(mHu)}{\partial t} + \frac{\partial(m_y Huu)}{\partial x} + \frac{\partial(m_x Hvu)}{\partial y} + \frac{\partial(mwu)}{\partial z} - \left( mf + v \frac{\partial m_y}{\partial x} - u \frac{\partial m_x}{\partial y} \right) H v = & -m_y H \frac{\partial(g\zeta + p)}{\partial x} - m_y \left( \frac{\partial h}{\partial x} - z \frac{\partial H}{\partial x} \right) \frac{\partial p}{\partial z} \\ & + \frac{\partial(mH^{-1} A_v \frac{\partial u}{\partial z})}{\partial z} + Q_u \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial(mHv)}{\partial t} + \frac{\partial(m_y Huv)}{\partial x} + \frac{\partial(m_x Hvv)}{\partial y} + \frac{\partial(mwv)}{\partial z} - \left( mf + v \frac{\partial m_y}{\partial x} - u \frac{\partial m_x}{\partial y} \right) H u = & -m_x H \frac{\partial(g\zeta + p)}{\partial y} - m_y \left( \frac{\partial h}{\partial y} - z \frac{\partial H}{\partial y} \right) \frac{\partial p}{\partial z} + \frac{\partial(mH^{-1} A_v \frac{\partial v}{\partial z})}{\partial z} + Q_v \end{aligned} \quad (3)$$

In this work, the widely-used three-dimensional surface water hydrodynamic model, Environmental Fluid Dynamics Code (EFDC), was made OpenMI-compliant for the purpose of coupling it with any other OpenMI-compliant model to facilitate integrated catchment research and modelling. A case study of a highly urbanized area of Chicago, Illinois (Fig. 1) is presented. An existing urban hydrological and hydraulic model, CS-TARP model, was already developed for the drainage system in Chicago using InfoWorks-CS by the University of Illinois (Luo et al., 2014). With the platform of OpenMI, a three-dimensional EFDC river model was able to be integrated with the developed CS-TARP model. The main goals of the case study were: (i) to develop a model that is capable of capturing the feedback between the sewer systems and the waterways, (ii) and to analyze the major implications of having a model that considers the coupled feedback for different rainfall events.

## 2. The three-dimensional EFDC

The Environmental Fluid Dynamics Code (EFDC) is a widely used open source code which can model both the hydrodynamics and water quality for free surface water systems such as rivers, lakes, and estuaries (Ji, 2008; Liu and Huang, 2009; Sinha et al., 2012, 2013). EFDC uses sigma vertical coordinates and curvilinear orthogonal horizontal coordinates. The model solves the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations with the assumption of a vertically hydrostatic pressure distribution and the Boussinesq approximation (Hamrick

et al., 1992). In this study the coupled interaction between the sewer and river model includes only the hydrodynamics, which is a foundation for subsequent studies that examine the effect of this coupling in the dynamics of water quality and sediment transport. It must be noted that EFDC is able to simulate both the water quality (based on CE-QUAL-ICM (Cercio and Cole, 1994)), and the sediment transport (Liu and Huang, 2009; Elçi et al., 2007). In addition, EFDC also can provide hydrodynamic results to other advanced receiving water quality models, such as WASP (Di Toro et al., 1983; Ambrose and Wool, 2009).

## 3. OpenMI-compliant EFDC

The Open Model Integration (OpenMI) framework provides an interface, *OpenMI.Standards.ILinkableComponent*, that compliant components must implement in order to be linked together. Each modeller can implement the *ILinkableComponent* according to development needs. This allows modellers to abstract the actual implementation of the model from other models using the OpenMI framework, or in the case of EFDC, which was written in FORTRAN, to make minimal adjustments to an existing model by the

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