

ILLINOIS TRANSIENT MODEL TWO-EQUATION MODEL V. 1.1

User's Manual (May 2009)

BY

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Abstract

The Illinois Transient Model (ITM) is a multipurpose Finite Volume (FV) shock-capturing model to analyze transient flows in closed-conduit systems ranging from dry-bed flows, to gravity flows, to partly gravity-partly surcharged flows (mixed flows) to fully pressurized flows (waterhammer flows). The ITM model can handle complex boundary conditions such as dropshafts, reservoirs and junctions with any number of connecting pipes and any type of horizontal and vertical alignment.

The current version of the ITM model (V. 1.1 May, 2009) has features that make this model superior with respect to other models for analyzing transient flows in complex closed-conduit systems. The first feature is that the ITM model can simulate all possible flow regimes in complex closed-conduit systems. In particular, the ITM model can accurately describe positive and negative open channel-pressurized flow interfaces, interface reversals, and it can simulate sub-atmospheric pressures in the pressurized flow region. The second feature is that the ITM model can simulate transient mixed flows when large pressure wave celerities (~ 1000 m/s) are used. The latter is very important when pressurized transient flows are of interest. If transients are of no interest, a small pressure wave celerity may be used to speed up the computations.

The numerical code for the hydraulics of the ITM model was written from scratch by Dr. Arturo León at the University of Illinois at Urbana-Champaign. The graphical user interface of the ITM model was modified from the graphical interface of the SWMM model originally developed by the U.S. Environmental Protection Agency (EPA). The SWMM model has a powerful graphical user-interface but a simplified hydraulic model that can not be used for analyzing hydraulic transients. To take advantage of the tools of the SWMM graphical user interface, the graphical user interface of the ITM Model was adapted from the graphical user interface of the SWMM model by Engineer Nils Oberg.

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Chapter 1

Introduction

1.1 What is the Illinois Transient Model (ITM) and what are the modeling capabilities

The Illinois Transient Model (ITM) is a multipurpose Finite Volume (FV) shock-capturing model to analyze transient flows in closed-conduit systems ranging from dry-bed flows to gravity flows, to partly gravity-partly surcharged flows (mixed flows) to fully pressurized flows (waterhammer flows). The ITM model can handle complex boundary conditions such as dropshafts, reservoirs and junctions with any number of connecting pipes and any type of horizontal and vertical alignment.

Historically, the ITM model was first developed in 2004 using a modified Preissmann slot approach (one-governing equation) for simulating mixed flows. The 2004 version of the ITM model, as other Preissmann-slot based models have the inability of simulating negative pressures. Because negative pressures are very common in pressurized transient flows, it was decided to change the approach for handling mixed flows. The second version of the ITM model was completed in 2006. In the 2006 version of the ITM model, the free surface region is modeled using the 1D Saint-Venant equations, the pressurized region is modeled using the 1D compressible waterhammer equations and open channel-pressurized flow interfaces are modeled by enforcing mass, momentum and energy relations across the interfaces together with Riemann solvers at the sides of the mixed flow interfaces. This version of the ITM model is referred as the two-equation model. The current version of the ITM model (V. 1.1 May, 2009) is an improved version of the 2006 ITM model.

The current version of the ITM model has features that make this model superior with respect to other models for analyzing transient flows in complex closed-conduit systems. The first feature is that the ITM model can simulate all possible flow regimes in complex closed-conduit systems. In particular, the ITM model can accurately describe positive and negative open channel-pressurized flow interfaces, interface reversals, and it can simulate sub-atmospheric pressures in the pressurized flow region. The second feature

is that the ITM model can simulate transient mixed flows when large pressure wave celerities (~ 1000 m/s) are used. The latter is very important when pressurized transient flows are of interest. If transients are of no interest, a small pressure wave celerity may be used to speed up the computations.

The graphical user interface of the ITM model was modified from the graphical user interface of the SWMM model originally developed by the U.S. EPA. The SWMM model has a powerful graphical user-interface but a simplified hydraulic model that can not be used for analyzing hydraulic transients. To take advantage of the tools of the SWMM graphical user interface, the graphical user interface of the ITM Model was adapted from the graphical user interface of the SWMM model.

1.2 Common applications of the ITM model

The ITM model has been used in several studies such as: (1) to assess the impact of gate closures in the generation of transients in the Tunnel and Reservoir Plan (TARP) Calumet system in Chicago; (2) to study transient phenomena in the TARP systems associated to heavy rainfall events, (3) to study the conveyance capacity of the TARP systems. The ITM model can be used in transient and no transient conditions. If transients are of no interest, a small pressure wave celerity may be used in the user interface to speed up the computations.

Overall, the ITM model can be used for simulating all possible flow regimes in complex closed-conduit systems ranging from dry-bed flows to gravity flows, to partly gravity-partly surcharged flows (mixed flows) to fully pressurized flows. Currently, the ITM model supports four types of boundary conditions, namely, dropshaft boundary, junction boundary, constant flow or pressure boundary and reservoir boundary.

1.3 Installing the ITM model

The ITM model version 1.1 is designed to run under the Windows 2000/XP operating system of a personal computer. It is distributed as a single file, ITM.exe. (Nils please complete this). To install The ITM model:

1. Select Run from the Windows Start menu.
2. Enter the full path and name of the ITM.exe file or click the Browse button to locate it on your computer.
3. Click the OK button type to begin the setup process.

The setup program will ask you to choose a folder (directory) where the ITM program files will be placed. The default folder is *c:\ProgramFiles\ITM*.

After the files are installed your Start Menu will have a new item named ITM. To launch ITM, simply select this item off of the Start Menu, and then select ITM from the submenu that appears. The name of the executable file that runs ITM under Windows is ITM.exe. Under Windows 2000, XP for running ITM are stored in a folder named ITM under the users Application Data directory. If you need to save these settings to a different location, you can install a shortcut to ITM on the desktop whose target entry includes the name of the ITM executable followed by /s %userfolder%, where %userfolder% is the name of the folder where the personal settings will be stored. An example might be: Enter example

To remove ITM from your computer, please do the following:

1. Select Settings from the Windows Start menu.
2. Select Control Panel from the Settings menu.
3. Double-click on the Add/Remove Programs item.
4. Select ITM from the list of programs that appears.
5. Click the Add/Remove button.

1.4 Steps in using the ITM model

The user should carry out the following steps when using the ITM model (for details see Chapters 3 and 4):

1. Draw a network representation of the physical components of the closed-conduit system.
2. Add inflow hydrographs.
3. Edit the properties of the objects that make up the system.
4. Specify the set of options for the simulation.
5. Run the simulation.
6. View the results of the simulation.

1.5 About this manual

Chapter 1: Introduction.

Chapter 2: Governing equations, numerical techniques and validation of the ITM model. This chapter presents a brief description of the governing equations and the numerical techniques used for implementing the

ITM model. This chapter also presents a description of various test cases used for the validation of the ITM model.

Chapter 3 Working with the ITM model. This chapter presents a brief description of new attributes unique to the ITM model to help get started using ITM.

Chapter 4: ITM Examples. This chapter presents two examples for familiarizing the ITM user in setting input data, running and visualizing results. The first example is a simple hypothetical three-way merging flow and the second one is an actual combined storm-sewer system (Calumet TARP system, Chicago).

The manual also contains two appendixes: Appendix A -lists the input file for the first example in Chapter 4. Appendix B -lists the input file for the second example in Chapter 4.

Chapter 2

Governing equations, numerical techniques and validation of the ITM model

The ITM model was built upon our earlier work and the work of others for simulating free surface flows, pressurized flows and mixed flows (simultaneous occurrence of free surface and pressurized flows). In the ITM model the free surface region is simulated using the 1D Saint-Venant equations, the pressurized region is simulated using the classical 1D compressible waterhammer equations and open channel-pressurized flow interfaces are simulated by enforcing mass, momentum and energy relations across open channel-pressurized flow interfaces.

The ITM model can accurately describe complex flow features, such as positive and negative mixed flow interfaces, interface reversals and open channel bores. In particular, the ITM model can simulate negative interfaces in mixed flow conditions having supercritical flow in the free surface region. The authors are not aware of any existing mixed flow model that was formulated for negative interfaces when the flow in the free surface region is supercritical. The ITM model can also simulate negative pressures in pressurized flow regime.

Furthermore, the ITM model can simulate mixed flow conditions for a large range of pressure wave celerities (~ 1000 m/s) compared to current models. Current mixed flow models use small values of the pressure wave celerity in order to avoid numerical instabilities (e.g., Trajkovic et al. 1999, Vasconcelos et al. 2006). Even so, good results are obtained when simulating mixed flows in a single pipe, in which the pressurized flow region is isolated and there is no interaction of pressurized waves (e.g., Trajkovic et al. 1999, Vasconcelos et al. 2006, León et al. 2009a). However, as is shown in León et al. 2009b, when there is interaction of pressurized waves, such as in the case of multiple pipes, the results are dependent on the selection of the pressure wave celerity. Overall, the ITM model is capable of simulating transient flows ranging from

dry-bed flows, to free surface flows, to partly free surface-partly pressurized flows (mixed flows), to fully pressurized flows.

2.1 Governing equations

The one-dimensional open-channel and compressible water hammer flow continuity and momentum equations for prismatic conduits are written in their vector conservative form as follows (e.g. Guinot 2003, León 2006, León et al. 2006, 2008):

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} = \mathbf{S} \quad (2.1)$$

where the vector variable \mathbf{U} , the flux vector \mathbf{F} and the source term vector \mathbf{S} for open-channel flows may be written as (e.g., León 2006, León et al. 2006):

$$\mathbf{U} = \begin{bmatrix} \rho A \\ \rho Q \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \rho Q \\ \rho \frac{Q^2}{A} + A\bar{p} \end{bmatrix} \text{ and } \mathbf{S} = \begin{bmatrix} 0 \\ (S_o - S_e)\rho g A \end{bmatrix} \quad (2.2)$$

and for compressible water hammer flows as (e.g., Guinot 2003, León 2006, León et al. 2008):

$$\mathbf{U} = \begin{bmatrix} \rho_f A_f \\ \rho_f Q \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \rho_f Q \\ \rho_f \frac{Q^2}{A_f} + A_f p \end{bmatrix} \text{ and } \mathbf{S} = \begin{bmatrix} 0 \\ (S_o - S_e)\rho_f g A_f \end{bmatrix} \quad (2.3)$$

where the variables for free surface flows are: A = cross-sectional area of the flow; Q = flow discharge; \bar{p} = average pressure of the water column over the cross sectional area; ρ = liquid density (assumed constant for free surface flows but not for pressurized flows); g = gravitational acceleration; S_o = slope of the bottom channel; and S_e = slope of the energy line. The variables for compressible water hammer flows (pressurized flows) are: A_f = full cross-sectional area of the conduit, p = pressure acting on the center of gravity of A_f , and ρ_f = fluid density for compressible water hammer flows.

The Eq. (2.1) for compressible waterhammer flows does not form a closed system in that the flow is described using three variables: ρ_f , p and Q . However, it is possible to eliminate the pressure variable by using the general definition of the pressure wave celerity (a_g), which relates p and ρ_f (e.g., Guinot 2003)

$$a_g = \left[\frac{d(A_f p)}{d(A_f \rho_f)} \right]^{1/2} \quad (2.4)$$

The wave celerity in single-phase (pure liquid) pressurized flows (a) is assumed to be constant (e.g., Wylie and Streeter 1983) and can be estimated using

the following relation that is derived from classical structural mechanics (e.g., Wylie and Streeter 1983):

$$a = \left[\frac{k_f / \rho_{ref}}{1 + \frac{k_f d}{E e}} \right]^{1/2} \quad (2.5)$$

where ρ_{ref} is a reference density, d is the pipe diameter, e is its thickness, E is Young's modulus of elasticity of the pipe material and k_f is the compressibility of the fluid in the pipe. Assuming an infinitely rigid pipe (e.g., A_f is assumed to be constant) and substituting a_g by a in Eq. (2.4), the integration of the differentials $d\rho_f$ and dp in Eq. (2.4) gives the following equation that relates p and ρ_f (León et al. 2007, 2008)

$$p = p_{ref} + a^2(\rho_f - \rho_{ref}) \quad (2.6)$$

where p_{ref} is a reference pressure. In free surface flows, the gravity wavespeed c is given by $c = \sqrt{gA/T}$ where T is the topwidth of the flow. According to this relation, the gravity wavespeed is unbounded as the water depth approaches the crown of the conduit. When the water depth approaches the crown of the conduit; the pressure wave and not the gravity wave should become the primary mode of propagation of a disturbance. In fact, experiments in circular pipes (e.g., Hamam and McCorquodale 1982) showed that flow instabilities occur for water depths greater than $0.8d$, causing oscillations that will lead to a sudden jump to pressurized flow. In the ITM model, the phase change from free surface to pressurized flow (not from pressurized to free surface flow) is assumed to occur when the water depth exceeds $y = y_{ref}$, where y is the water depth and y_{ref} is a reference depth. At this threshold condition ($y = y_{ref}$), all the flow parameters (e.g., fluid density, hydraulic area and average pressure) in both open-channel and pressurized flow regime have to be the same. Herein, y_{ref} is set equal to $0.95d$. It is pointed out that the results are not highly sensitive to y_{ref} . However, when using a small value of y_{ref} , large mass conservation errors may be attained. The reference area (A_{ref}) is the hydraulic area below $y_{ref} = 0.95d$ and A_f in the previous equations is replaced with A_{ref} . This results in a reduction of the hydraulic area for pressurized flows of less than 2%. When using the present model to simulate pure pressurized flows, A_{ref} can be set equal to A_f . In this way, the reduction in hydraulic area for pressurized flows (less than 2%) assumed when simulating mixed flows is eliminated. The assumed reference density (ρ_{ref}) is 1000 kg/m^3 that corresponds to clean water at a temperature of 4 degrees Celsius. For the phase change from pressurized to free surface flow (depressurization) the criteria given in Yuan (1984) is used.

Although the free surface and pressurized flow governing equations are mathematically similar (i.e., both hyperbolic), the physics of these flows have

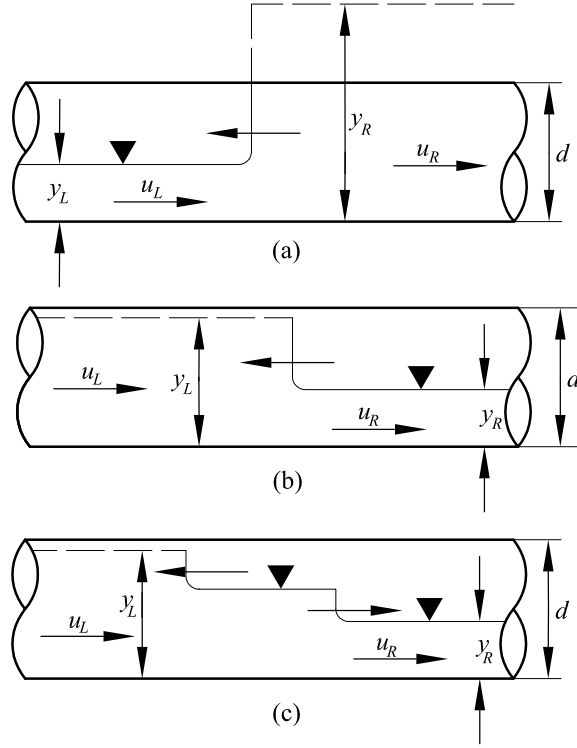


Figure 2.1: (a) Positive interface moving in the upstream direction (e.g., generated by sudden closure of a downstream gate) (b) Negative interface moving in the upstream direction (e.g., generated by depressurization at the downstream end of the system) (c) Interface reversal.

marked differences. One important distinction between these flows is the ability of pressurized flows to sustain sub-atmospheric pressures. Another important difference is that in pressurized flows a disturbance is propagated at a speed that is two orders of magnitude faster than in free surface flows. A moving interfacial boundary separates the two flow regimes. Song et al. (1983), Cardle (1984) among other authors defined an open channel-pressurized (mixed) flow interface as positive if it is moving towards the open-channel flow (Fig. 2.1 (a)), and negative or retreating if it is moving towards the region of pressurized flow (Fig. 2.1 (b)). The change in direction of the interface from positive to negative is called interface reversal (Fig. 2.1 (c)). The direction and speed magnitude of a mixed flow interface can be determined using the following relation (e.g., Song et al. 1983)

$$w(t^n) = \frac{Q_R - Q_L}{A_R - A_L} \quad (2.7)$$

where a positive sign indicates that the interface is moving downstream and upstream otherwise.

The flow variables used in this manual are (ρA) and (ρQ) for free surface

flows, and $(\rho_f A_f)$ and $(\rho_f Q_f)$ for pressurized flows. However, the engineering community prefers to use the piezometric head h and flow discharge Q . The latter variables can be determined from the flow variables used as follows:

- Free surface flow

$$\begin{aligned} h &= y & (\text{where } y \text{ is a geometric function of } A) \\ Q &= (\rho Q)/\rho_{ref} & (\rho = \rho_{ref} \text{ for free surface flow}) \end{aligned} \quad (2.8)$$

- Pressurized flow

$$\begin{aligned} h &= y_{ref} + \frac{a^2}{g} \left(\frac{\rho_f A_f}{\rho_{ref} A_{ref}} - 1 \right) \\ Q &= \frac{(\rho_f Q_f)}{(\rho_f A_f)} A_f \end{aligned} \quad (2.9)$$

where h is measured over the conduit bottom.

Following the criteria for determining if the flow is in free surface or pressurized flow regime is given. After a given node has been pressurized, free surface flow is not necessarily generated at this node when its head drops below the pipe crown. As is reported by several researchers (e.g., Cardle 1984, Yuan 1984, Cardle et al. 1989), in negative interfaces there is a negative pressure on the pressurized side of the interface. In the latter case, the conditions given in Yuan (1984) for negative interfaces are used for the depressurization of the node. Furthermore, when a pipe system has been fully pressurized, the only way to start the depressurization process is through ventilated boundaries (e.g., dropshafts, reservoirs, etc).

2.2 Numerical solution of governing equations

The numerical scheme used in the ITM model is an explicit Finite Volume (FV) Godunov-type method. FV methods have the ability to capture discontinuities (e.g., shocks) in the solution automatically, without explicitly tracking them (e.g., Toro 2001). The FV method is based on writing the governing equations in integral form over an elementary control volume or cell, hence the general term of Finite Volume (FV) method. The computational grid or cell involves discretization of the spatial domain x into cells of length Δx_i and the temporal domain t into intervals of duration Δt . The i th cell is centered at node i and extends from $i - 1/2$ to $i + 1/2$. The flow variables (A and Q) are defined at the cell centers i and represent their average value within each cell. Fluxes, on the other hand are evaluated at the interfaces between cells ($i - 1/2$ and $i + 1/2$). For the i th cell, the updating FV formula for the left side of Eq. (2.1) is given by (e.g., Toro 2001, LeVeque 2002):

$$\mathbf{U}_i^{n+1} = \mathbf{U}_i^n - \frac{\Delta t}{\Delta x_i} (\mathbf{F}_{i+1/2}^n - \mathbf{F}_{i-1/2}^n) \quad (2.10)$$

where the superscripts n and $n + 1$ reflect the t and $t + \Delta t$ time levels respectively. In Eq. (2.10), the determination of \mathbf{U} at the new time step $n + 1$ requires computation of the numerical flux (\mathbf{F}) at the cell interfaces at the old time n . To introduce the source terms (right side of Eq. 2.1) into the solution, a first-order time splitting method is used which takes into account an algorithm for ensuring that stationary flows don't produce unphysical flows. In the Godunov approach (Godunov 1959), the flux $\mathbf{F}_{i+1/2}^n$ is obtained by solving the Riemann problem with constant states \mathbf{U}_i^n and \mathbf{U}_{i+1}^n . This way of computing the flux leads to first-order accuracy of the numerical solution. To achieve second-order accuracy in space and time in the ITM model, the MUSCL - Hancock method (e.g., Toro 2001) was used. Second or higher order schemes are prone to spurious oscillations in the vicinity of discontinuities. To preserve the second-order accuracy of the solution away from discontinuities, while ensuring that the solution is oscillation-free near shock waves and other sharp flow features, a Total Variation Diminishing (TVD) method was used in the ITM model. The TVD property of the MUSCL - Hancock method is ensured by applying the MINMOD pre-processing slope limiter (see Toro 2001). For a comprehensive description of the numerical method used in the ITM model for free surface, pressurized and mixed flows, the reader is referred to León (2006), León et al. (2006, 2008, 2009c).

With regard to the boundary conditions used in the ITM model the reader is referred to León et al. (2009b). León et al. (2009b) presented a general boundary condition for transient flows in a drop-shaft connected to an arbitrary number of pipes. This BC is general in the sense that it handles all possible flow regimes and their combinations at a junction.

2.3 Validation of the ITM model

The purpose of this section is to evaluate the accuracy and robustness of the ITM model for simulating transient free surface flows, pressurized flows and mixed flows in storm-sewers. Because of the lack of experimental data for complex test cases (e.g., complex boundaries), some of the test cases presented herein consider hypothetical storm-sewer systems (e.g., a three-way merging flow system and a three-way dividing flow system). A three-way merging flow consists of two inflowing pipes and one outflowing pipe and a three-way dividing flow boundary consists of one inflowing pipe and two outflowing pipes. For evaluating the hypothetical tests, Computational Fluid Dynamics (CFD) modeling results were used as frame of comparison. Two state-of-the-art CFD codes were used, namely FLOW-3D (Flow Science, Inc. 2005). and OpenFOAM (OpenCFD, Ltd. 2007). Unlike OpenFOAM, FLOW-3D has a module that allows modeling acoustic waves in pressurized flow conditions. The propagation of acoustic waves is associated with the compressibility of the flow;

however not all CFD compressible models can simulate acoustic waves. It is acknowledged that the ITM model has been validated with more test cases than those presented in this section. The reader is referred to León (2006), León et al. (2006, 2008, 2009a, 2009b, 2009c) for a description of all test cases used for validating the ITM model. Five test cases are considered in this section. These are:

1. Experiments type A of Trajkovic et al. (1999) [Mixed flow].
2. Experiment of Vasconcelos et al. (2006). [Fully-pressurized flow].
3. Hypothetical three-way merging flow [Mixed flow].
4. Hypothetical Three-way dividing flow [Mixed flow].
5. Experiments of León et al. (2009b) [Fully-pressurized flow].

2.3.1 Experiments type A of Trajkovic et al. (1999)

In this test case, the ITM model is used to reproduce a set of experiments conducted at the Hydraulics Laboratory of University of Calabria by Trajkovic et al. (1999). In this test case, the ability of the ITM model to simulate a positive mixed flow interface reversing its direction and becoming a negative interface is tested. The experimental setup consisted of a perspex pipe ($n_m = 0.008 \text{ m}^{1/6}$) about 10 m long, having an inner diameter of 10 cm. Upstream and downstream tanks were connected to the pipe with automatic sluice gates. The experimental investigations evaluated the effect of rapid changes in the opening or closing of the sluice gates. Acknowledging the possible interference of the air phase in case the pipe became pressurized, several vents were placed at the top of the pipe.

In this test case, the type A set of experiments in Trajkovic et al. (1999) is considered. The initial conditions for this set of experiments were inflow rate constant at $0.0013 \text{ m}^3/\text{s}$, the bed slope at 2.7% (supercritical flow with an initial Froude number equal to 2.9), the upstream sluice gate opened $e_1 = 0.014 \text{ m}$, and the downstream sluice gate totally opened. The transient flow was generated after a rapid (but not instantaneous) closure of the downstream sluice gate that caused the formation of an open channel surge moving upstream. This surge was continuously strengthened by the inflow and after few seconds became a positive mixed flow interface that moved upstream. After 30 seconds of the gate closure, the gate was partially reopened. When the area of reopening was small, the positive interface continued to move upstream without retreating back downstream. When the area of reopening was about 10% or higher than the cross-sectional area of the pipe, the positive interface continued to move upstream propelled by its own inertia but after a short time the positive interface reversed its direction becoming a negative interface. Different values for the reopening (e_2) were tested. In this test case, three values

for the reopening are considered: $e_2 = 0.008$ m, $e_2 = 0.015$ m, and $e_2 = 0.028$ m.

Simulated (ITM and Trajkovic et al. (1999) model) and measured pressure traces at 0.6 m from downstream gate for the three reopenings are shown in Fig. 2.2. The results shown in this figure for the ITM model were generated using 400 cells, a Courant number (Cr) of 0.80 and a pressure wave celerity of 500 m/s (estimated using Eq. 2.5). The results presented in Fig. 2.2 labeled Trajkovic et al. were obtained from Trajkovic et al. (1999). The results of the model of Trajkovic et al. were generated using a pressure wave celerity of about 4 m/s. Even though the comparison of results between our model and that of Trajkovic et al. (1999) may not seem relevant because different pressure wave celerities were used, the results may help to point out that our model is robust for large pressure wave celerities.

As can be observed in Fig. 2.2, the simulated pressure head (h) traces for both numerical models have a good agreement with the corresponding experimental measurements. In particular, the formation of the filling bore and its velocity of propagation are accurately predicted by both models. However, all the computed shock fronts are steeper than the measured ones. This is because in the experiments the closing of the gate was rapid, but not instantaneous, as was assumed in the simulations.

Fig. 2.2 also shows a drop in the pressure head after the partial reopening of the downstream gate ($t = 30$ s). In the simulations (both models), an instantaneous partial reopening was assumed which caused a steeper front of the pressure drop compared to the experimental results. The smaller pressure drop in the simulations (both models) may be in part due to the inaccuracies in representing the partial opening at the downstream boundary. At this boundary, the orifice equation of Trajkovic et al. (1999) was used.

For a reopening of 0.008 m [Fig. 2.2(a)], after a small drop in the pressure head, the pressure head continuously increased in all sections (both models and experiment). This is because the outflow from the pipe was smaller than the inflow. For a reopening of 0.015 m [Fig. 2.2(b)], a stationary mixed flow interface was observed and computed (experiment and ITM model only) in the pipe after the drop in the pressure head. For a reopening of 0.028 m [Fig. 2.2(c)], the mixed flow interface traveled downstream (experiment and ITM model only), because the outflow was greater than the inflow. It is acknowledged that in Trajkovic et al. (1999) the numerical results for a reopening of 0.015 and 0.028 m [Figs. 2.2(b) and 2.2(c)] are not shown after about $t = 32$ s (shortly after gate is partially reopened). These authors reported numerical instabilities, even when a small wave celerity was used (~ 4 m/s).

As is pointed out by several authors (e.g., Trajkovic et al. 1999, Vasconcelos et al. 2006, León et al. 2009a), the results are almost independent of the pressure wave celerity when simulating mixed flows in a single pipe, in which the pressurized flow region is isolated and when there is no interaction of pressurized waves. This explains why researchers using very low pressure wave

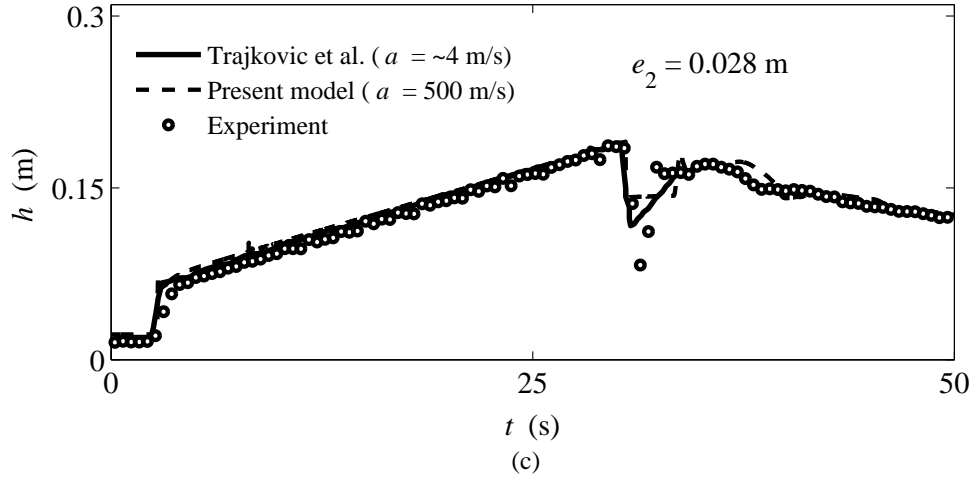
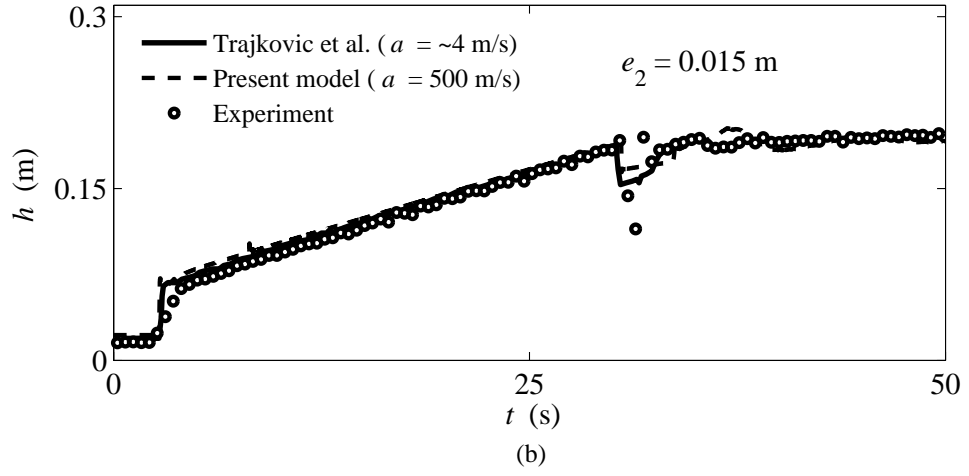
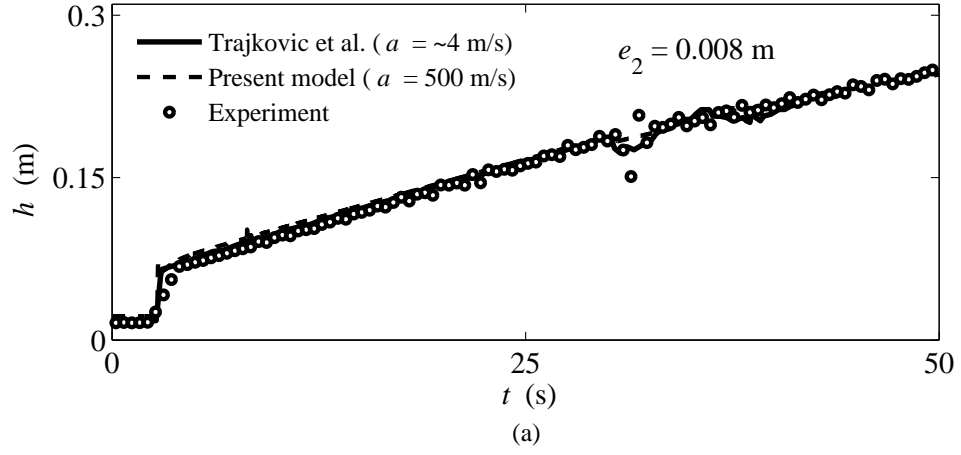


Figure 2.2: Measured and computed pressure heads at 0.6 m from downstream gate for type A experiments of Trajkovic et al. (1999).

celerities obtained good agreement with experiments when simulating mixed flows. However, as is shown in León et al. 2009b, when there is interaction of pressurized waves such as in the case of multiple pipes; the results are highly dependent on the selection of the pressure wave celerity. In the latter case only a pressure wave celerity equal to the water hammer wavespeed gives accurate results on the propagation speed and magnitude of pressurized transients.

From Figs. 2.2(b) and 2.2(c), the reader can notice that shortly after the gate was reopened 0.015 m or 0.028 m, the positive interface reversed its direction becoming a negative interface. This is particularly clear for a reopening of 0.028 m [Fig. 2.2(c)]. Also, the initial Froude number of the flow was about 2.9 that corresponds to supercritical flow. As we mentioned earlier, the ITM model can simulate mixed flows without restriction of the type of flow in the free surface region. Figs. 2.2(b) and 2.2(c) show that our model can simulate a negative interface when the flow in the free surface region is supercritical.

2.3.2 Experiments of Vasconcelos et al. (2006)

The purpose of this section is to test the ability of the ITM model in simulating sub-atmospheric pressures in pressurized flow regime. The experiment used in this section was conducted at the University of Michigan and is reported in Vasconcelos et al. (2006). The experimental setup consisted of an acrylic pipeline 14.33 m long, having an inner diameter of 9.4 cm. The center portion of this pipe was raised about 15 cm with respect to both ends in order to create conditions for the occurrence of sub-atmospheric pressures. The pipeline was connected at its upstream end by a box tank and by a cylindrical tank at its downstream end. The experiment considered was obtained by filling the system to a level of 0.30 m at the box tank and the system allowed to come to rest. Then a syphon outflow was suddenly initiated at the box tank ($t = 0$). After some time, the water level in the box tank decreased to a level that created sub-atmospheric pressures at the center portion of the pipe. When the water level at the box tank dropped below the pipe crown just downstream of this tank, a complex flow pattern was developed. In this case, the flow just downstream of the box tank was in sub-atmospheric conditions, and under these conditions, air flow flowed from the tank into the pipe. This constitutes a two-phase flow problem that is outside of the scope of this work. The intrusion of air flow in the experiment occurred at about $t = 42.5$ s, and in the model about 1.7 seconds earlier. Since our work is limited to single-phase flows, the comparison between model prediction and experimental results are presented until right before the occurrence of air intrusion only ($t < \approx 40.8$ s).

To show the sequence of the formation of sub-atmospheric pressures, simulated pressure head snapshots at different times are presented in Fig. 2.3. When using the present model to simulate fully pressurized flows, as in this test case, A_{ref} can be set equal to A_f (full cross-sectional area of the conduit).

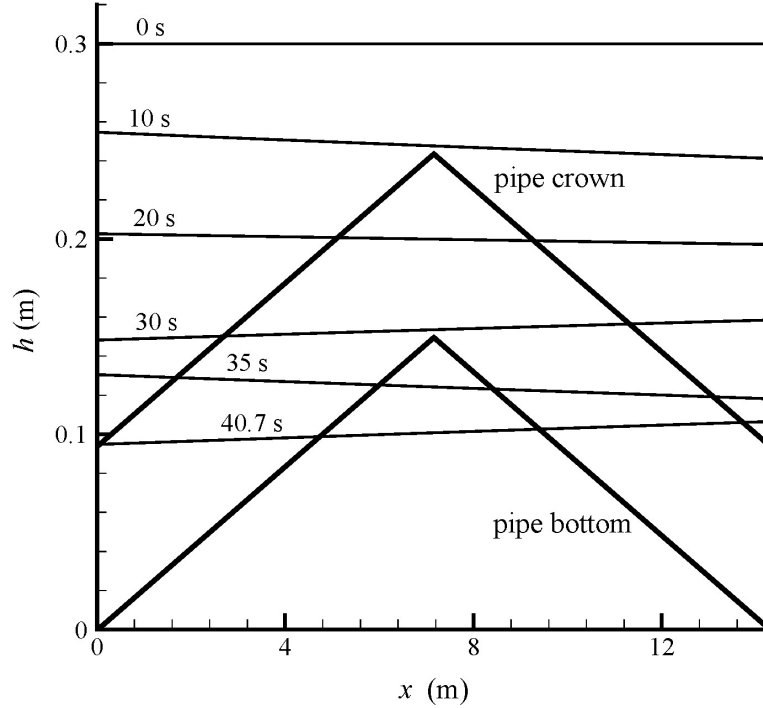


Figure 2.3: Simulated pressure head snapshots for experiments of Vasconcelos et al. (2006).

In this way, the about 2% reduction in hydraulic area for pressurized flows assumed when simulating mixed flows is eliminated. The pressure wave celerity used in the simulations was 300 m/s based on experimental measurements of pressure pulse propagation. The outflow was assumed constant and a value of 0.45 L/s was estimated by observing the change in water volume over time. For estimating energy losses, Vasconcelos et al. (2006) used a Manning roughness of $0.012 \text{ m}^{1/6}$. However the Manning's equation is applicable to fully rough flows only. Since the experiments were performed in laminar and transitional flow conditions ($Re < 4300$), the Darcy-Weisbach equation, which is applicable to laminar, transitional and fully rough flows would be a better estimate for the energy losses. For comparison, the numerical simulations were performed using the equations of Manning and Darcy-Weisbach.

The simulated and experimental velocities at 9.9 m downstream of the box tank are presented in Fig. 2.4. The model predictions and experiments for the pressure head at 14.1 m downstream of the box tank are presented in Fig. 2.5. The simulated results were generated using 400 cells and a Cr of 0.80. The results for the velocities (Fig. 2.4) show a good agreement between model and experiments for the frequency of oscillations. However, the velocity amplitudes are overestimated by the model. As suggested by Vasconcelos et al. (2006), this may be in part because the outflow uniformity assumption which may not be accurate. The differences between model prediction and experiments may be associated also to neglecting unsteady friction in the model. As can be seen

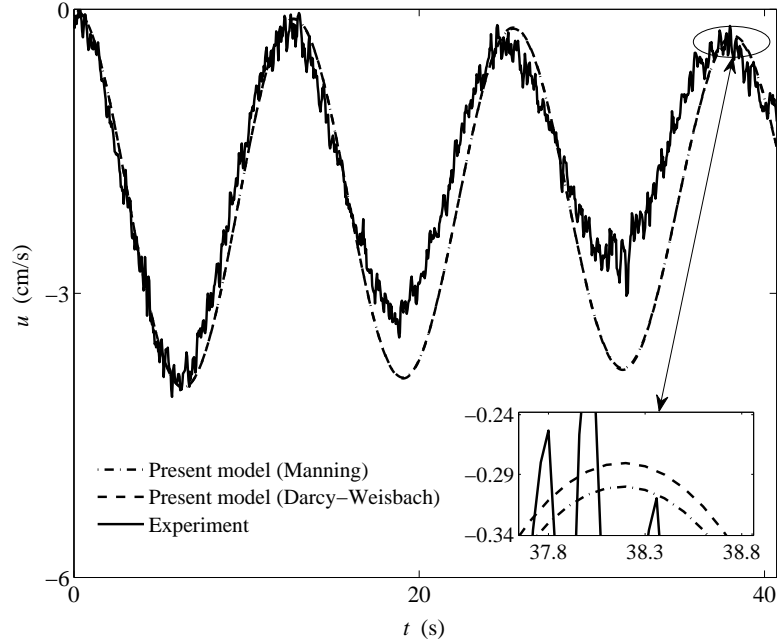


Figure 2.4: Measured and computed velocities at 9.9 m from the upstream end for experiments of Vasconcelos et al. (2006).

in Fig. 2.4, the simulated results using the Manning’s and Darcy-Weisbach equation are almost the same, the former being slightly more dissipative. The results for the pressure head (Fig. 2.5) show a good agreement between model predictions and experiments. The differences between the simulated and experimental pressure heads may be explained using the same reasons given for the velocities.

The reason for the oscillations in the velocity (Fig. 2.4) may not be clear at first examination. However, by taking a look at the pressure head plot (Fig. 2.5), the aforementioned oscillations start to make sense. The velocity at a given section is associated with the local difference in pressure head at both sides of the section. In the experiment, the outflow from the upstream tank creates a variation of the pressure head in the whole pipeline. Since both tanks are relatively small and as the system tries to reach steady state, oscillations in the pressure head are produced (Fig. 2.5). The oscillations in the pressure head in turn cause oscillations in the flow velocity.

2.3.3 Hypothetical three-way merging flow

The hypothetical test presented in this section considers a three-way merging flow system that is depicted in Fig. 2.6(a). As shown in Fig. 2.6(a), all pipes have a length of 5 m, the junction pond has a diameter of 1 m, the inflowing pipes (pipes 1 and 2) have both a diameter of 0.5 m and the outflowing pipe (pipe 3) has a diameter of 0.8 m. The Manning’s roughness coefficient used in the 1D simulation is $n_m = 0.015 \text{ m}^{1/6}$, the waterhammer wave speed

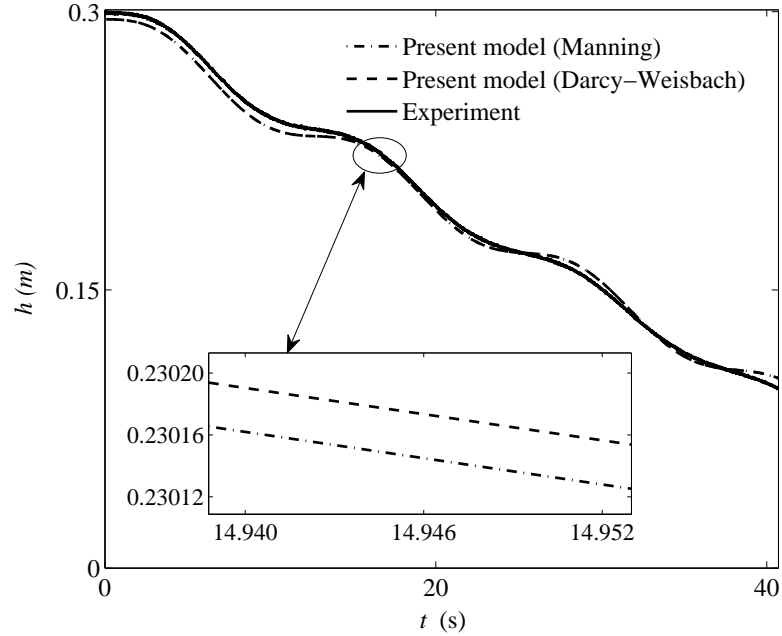


Figure 2.5: Measured and computed pressure heads at 14.1 m from the upstream end for the experiments of Vasconcelos et al. (2006).

considered is 100 m/s and the initial flow velocity in all pipes is 0 m/s. A waterhammer wave speed of 100 m/s was used because of PC hard disk storage limitations (200 GB) when running FLOW-3D. For instance when using a mesh of 6,000,000 cells, a pressure wave celerity of 100 m/s, an output time of 0.001 s (to be able to capture the pressure head traces associated with a pressure wave celerity of 100 m/s) and a simulation time of 0.2 seconds, the storage required in the PC was about 150 GB. Given the PC hard disk storage limitations, it was decided to use a maximum pressure wave celerity of 100 m/s in this and the next test case.

It is pointed out that the pressure wave celerity is not a limitation for the ITM model. In fact this model was used for simulating the test case under consideration for pressure wave celerities of 500 and 1000 m/s (results not shown). When using the ITM model, the solutions for free surface flows were identical to those obtained using a celerity of 100 m/s. For pressurized flows, as expected, the amplitude of the pressure peaks were all different from each other, where the largest amplitude was obtained using the highest pressure wave celerity used (1000 m/s).

To ensure that the CFD results (Flow-3D model) are mesh independent a mesh convergence study was performed. This study was performed for the pressure traces at midway of pipe 3 using three mesh sizes, which results are shown in Fig. 2.7. The mesh size used in the study from the smallest to the largest were 797400, 2694465 and 6,000,000 cells, respectively. As can be observed in Fig. 2.7, mesh convergence is approximately achieved using the intermediate mesh size (2694465 cells). The CFD results presented in this

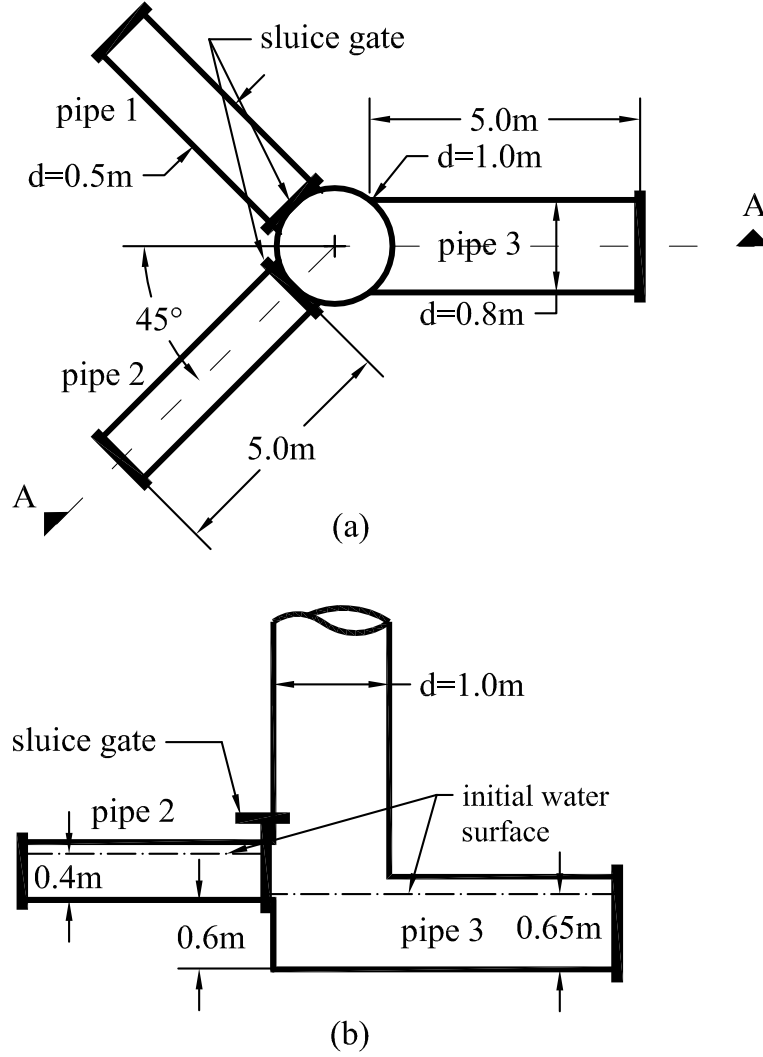


Figure 2.6: (a) Plan and (b) section A-A view for three-way merging flow hypothetical case.

section and the next one (similar to the present test case) were obtained using a mesh of 6,000,000 cells.

The initial water surface levels for this test are presented in Fig. 2.6(b). As can be observed in Figs. 2.6(a) and 2.6(b), the initial zero-velocity water pools in each pipe are separated by two sluice gates located at the downstream end of each inflowing pipe. The boundary conditions at the upstream end of the inflowing pipes (pipes 1 and 2) and at the downstream end of the outflowing pipe (pipe 3) were assumed to be zero-flux boundaries, which represent a dead-end pipe. The transient flow is obtained after an instantaneous and simultaneous opening of the sluice gates at time $t = 0$.

The opening of the sluice gates generated a free surface flow surge at the upstream end of pipe 3 that moved in the downstream direction. The continuous

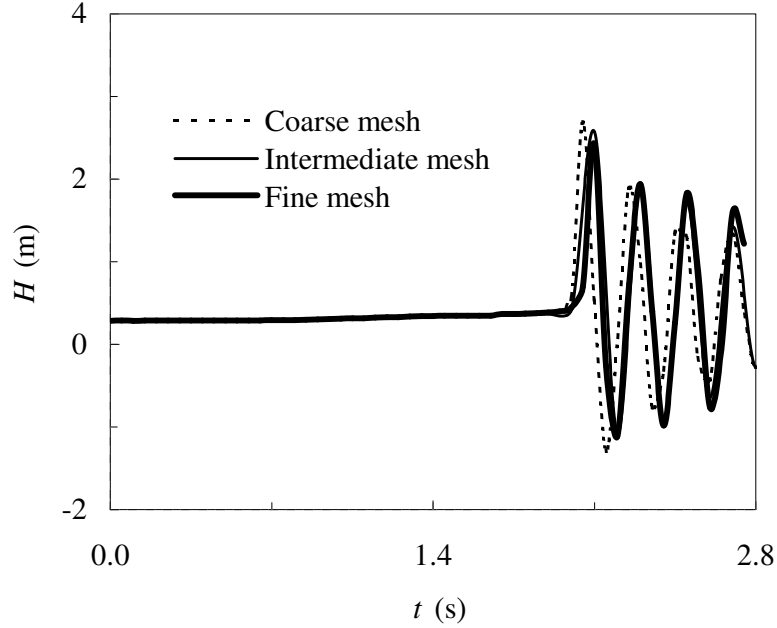


Figure 2.7: CFD mesh convergence for three-way merging flow test case (Pressure head traces at mid-way of pipe 3).

supply from the inflowing pipes into the outflowing pipe (pipe 3) pressurized the upstream end of pipe 3 making the free surface flow surge become an open channel-pressurized flow positive interface that moved in the downstream direction. Once this positive interface reached the downstream end (dead-end) the whole pipe 3 was pressurized and remained that way during the entire simulation. At the inflowing pipes (pipes 1 and 2), the flow remained fully free surface during the entire simulation, although some wave reflections originated at their boundaries (dead-end and junction pond) were observed during the visualization of the simulations. The simulated pressure head traces mid-way of pipes 2 (results for pipe 1 are the same as pipe 2 because of symmetry) and 3 are presented in Figs. 2.8 and 2.9, respectively. The simulation time for this test case was 12 seconds, however for pipe 3 (Fig. 2.9) that involves pressurized flows (high frequency of oscillations) the results are shown only for the first 2.8 seconds for better visualization. The simulated results using the ITM model were obtained using 200 cells in each pipe and a maximum Courant number of $Cr = 0.8$.

The results of pressure head traces for pipe 2 (Fig. 2.8) obtained using the ITM model agree well with the results obtained using the FLOW-3D model, although the slightly earlier pressurization of the upstream end of pipe 3 when using the ITM model made the free surface flow surge generated at the junction pond arrive earlier at mid way of pipe 2. Fully free surface flow was achieved in pipes 1 and 2 during the entire simulation. The results for pipe 3 (Fig. 2.9), which undergoes a flow type change from free surface flow to mixed flow to pressurized flow, also show good agreement between the ITM model

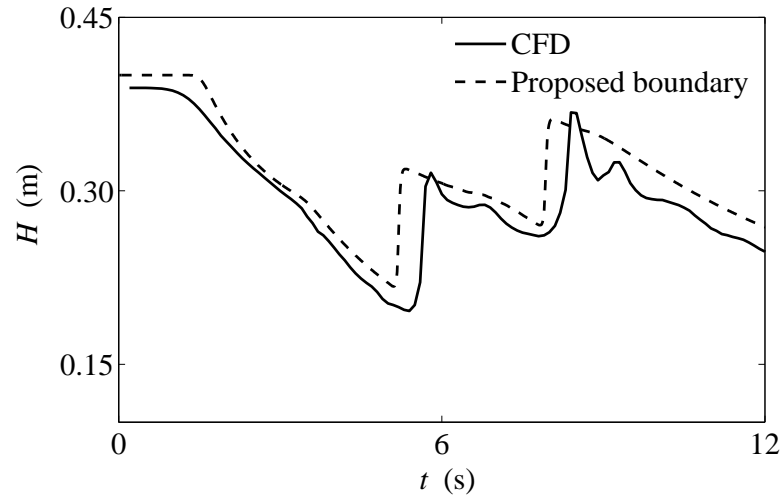


Figure 2.8: Pressure head trace at mid-way of pipe 2.

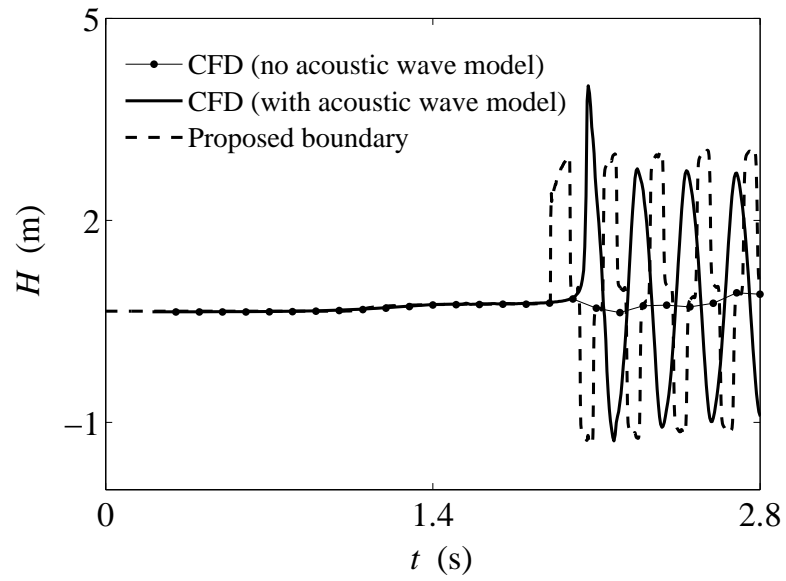


Figure 2.9: .
] Pressure head trace at mid-way of pipe 3.

and FLOW-3D (using the acoustic wave model), although this pipe is fully pressurized earlier when using the ITM model. Fig. 2.9 also shows the results of FLOW-3D without using the acoustic wave model. These results show that for pressurized transient flows, the pressure heads obtained without using the acoustic wave model are much smaller than when using this model. The latter results show that the compressibility of the flow (associated with the propagation of acoustic waves) is very important when simulating pressurized transient flows. For simulating free surface flows, considering compressibility of the flow is not important as they produce identical results.

2.3.4 Hypothetical three-way dividing flow

The hypothetical test presented in this section considers a three-way dividing flow system which is depicted in Fig. 2.10(a). As shown in Fig. 2.10(a), all pipes have a length of 5 m, the junction pond has a diameter of 1 m, the inflowing pipe (pipe 1) has a diameter of 0.6 m and the outflowing pipes (pipes 2 and 3) have both a diameter of 0.5 m. The Manning's roughness coefficient used in the 1D simulation is $n_m = 0.015 \text{ m}^{1/6}$, the waterhammer wave speed considered is 100 m/s and the initial flow velocity in all pipes is 0 m/s. A waterhammer wave speed of 100 m/s rather than 1000 m/s was used because of the same reasons as explained in the previous test case. The number of cells used in the CFD simulation was about 6,000,000 and the output time was 0.001 seconds.

The initial water levels for this test are presented in Fig. 2.10(b). As can be seen in Figs. 2.10(a) and 2.10(b), initially the upstream water pool (pipe 1) is separated from the downstream water pools (pipes 2 and 3) by a sluice gate located immediately upstream of the junction pond. The boundary conditions at the upstream end of pipe 1 and at the downstream end of pipes 2 and 3 were assumed to be zero-flux boundaries. The transient flow was produced after an instantaneous opening of the sluice gate at time $t = 0$.

The opening of the sluice gate generated two free surface flow bores at the upstream end of pipes 2 and 3 that moved downstream in the respective pipes. Shortly thereafter, the water supply from the inflowing pipe (pipe 1) into the outflowing pipes (pipes 2 and 3) pressurized and depressurized intermittently the upstream end of pipes 2 and 3 creating positive and negative open channel-pressurized flow interfaces at the upstream end of these pipes. Shortly after, the upstream end of pipes 2 and 3 were fully pressurized, which created positive open channel-pressurized flow interfaces that moved downstream in the respective pipes. Once these positive interfaces reached the downstream end (dead-end) the entire pipes 2 and 3 were pressurized and remained that way during the entire simulation. At the inflowing pipe, the flow remained fully free surface during the entire simulation, although some wave reflections originating at its boundaries (dead-end and junction pond) were observed during the visualization of the simulations. The simulated pressure head traces mid-

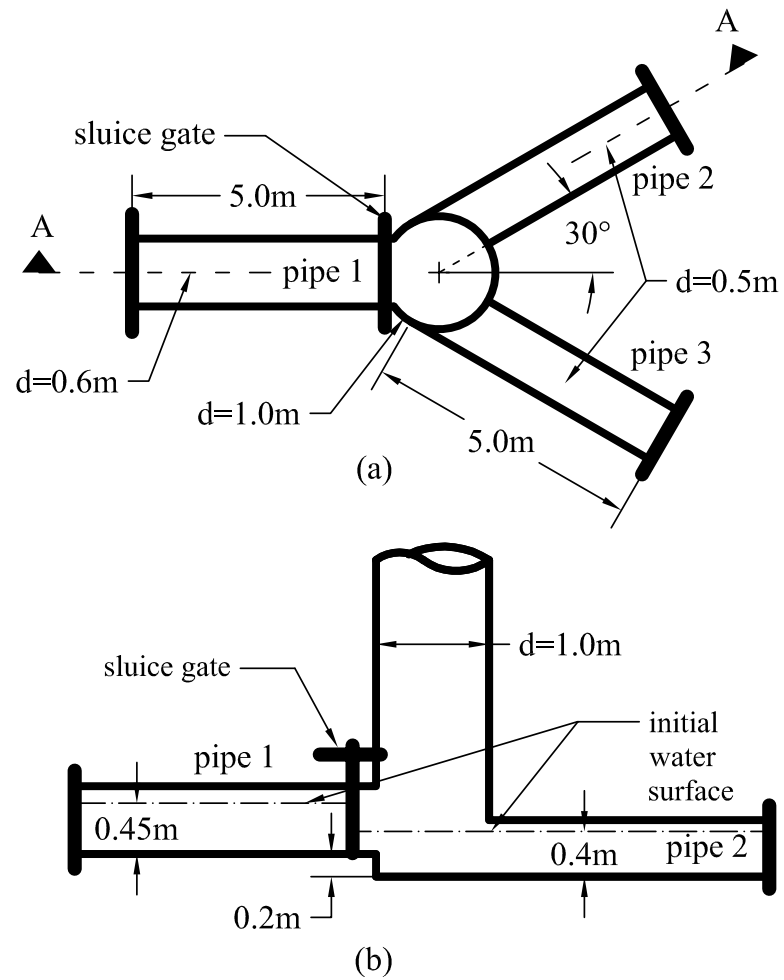


Figure 2.10: (a) Plan and (b) section A-A view for three-way dividing flow hypothetical case.

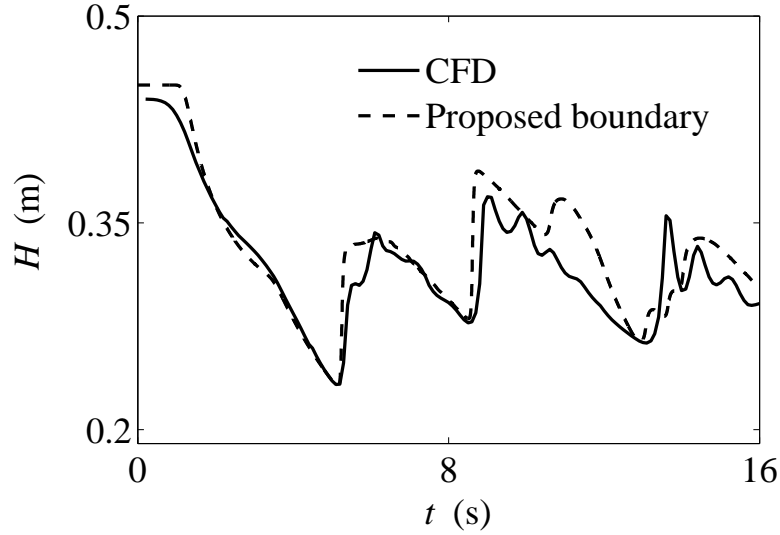


Figure 2.11: Pressure head trace at mid-way of pipe 1.

way of pipes 1 and 2 are presented in Figs. 2.11 and 2.12, respectively. The simulation time for this test case was 16 seconds, however for pipes 2 and 3 (Fig. 2.12) that involve pressurized flows the results are shown only for the first 3.6 seconds. The simulated results using the ITM model were obtained using 200 cells in each pipe and a maximum Courant number of $Cr = 0.8$.

As can be observed in Figs. 2.11 and 2.12, again the agreement between the ITM model and CFD results is good for the frequency and amplitude of free surface and pressurized flow (using acoustic wave model) waves. It is pointed out that the flow in pipes 2 and 3 undergo a flow type change from free surface flow to mixed flow to pressurized flow and in pipe 1 the flow remained fully free surface during the entire simulation. As in the previous test case, for pipes 2 and 3 that involve pressurized transient flows (Fig. 2.12), the pressure heads obtained using FLOW-3D without using the acoustic wave model are much smaller than when using this model. As can be observed in Fig. 2.12, pressure oscillations are simulated using FLOW-3D (with acoustic wave model) between 2 and 2.5 seconds. These oscillations are the result of local pressurization due to fluctuation of free surface flow waves. At about 2.5 seconds, an entire pressurization of pipes 2 and 3 were simulated by the ITM and the FLOW-3D model. The results in Fig. 2.12 also show that the dissipation rate of the pressure waves simulated using the CFD model is slightly faster than the ones simulated using the ITM model.

2.3.5 Experiments of León et al. (2009b) - Oscillation tube

The purpose of this section is to test the ability of the ITM model in simulating pressurized flows in vertical pipes in which water surface level varies rapidly

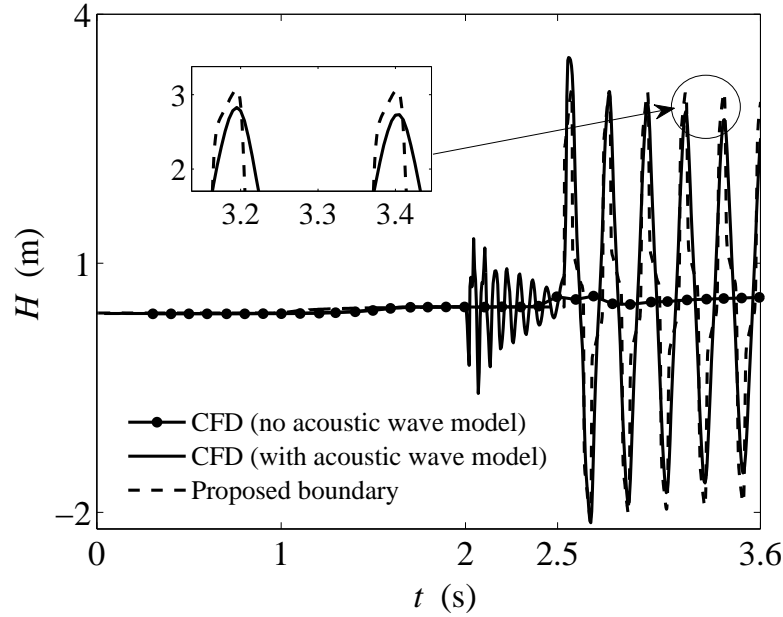


Figure 2.12: Pressure head trace at mid-way of pipe 2.

with time. With this purpose, an experimental facility was built in the Ven Te Chow Hydrosystems Laboratory of the University of Illinois at Urbana-Champaign, which layout is depicted in Fig. 2.13 (a). As shown in Fig. 2.13, the experimental setup consisted of a 4.98 m long horizontal plexiglass pipe connected at its upstream and downstream ends by a 2.2 m long vertical pipe of the same material as the horizontal pipe. The inside diameter of all pipes was 50.8 mm (2"). At the center of the horizontal pipe, a quarter-turn ball valve was installed, which as shown in Fig. 2.13 (b), separated the initial water levels upstream and downstream of the valve. The length of the vertical pipes are intentionally chosen to be of the same scale as of the horizontal pipe so that the vertical flow has a clear effect on the results. The water levels in the upstream vertical pipe (left vertical pipe in Fig. 2.13) were recorded using a Canon GL2 color video camera. For a better visualization of the water levels, the water in the oscillation tube was previously dyed. The acquired images were post-processed using the Image Processing Toolbox of MATLAB. For the MATLAB analysis, the video images were converted first to gray-scale images that in turn were converted to black and white images (binary system: 1 = black and 0 = white). The water level for each image was determined by computing the maximum row that has a pixel with a value of 1.

As a frame of comparison for the ITM model, besides laboratory results, CFD (OpenFOAM) modeling results were used. To ensure that the results of the OpenFOAM CFD code are mesh independent a mesh convergence study was performed. This study was performed for the water level elevation at the upstream drop-shaft using three mesh sizes, which results are shown in Fig. 2.14. The mesh size used in the study from the smallest to the largest were

32352, 71100 and 112229 cells, respectively. As can be observed in Fig. 2.14, mesh convergence is achieved using the intermediate mesh size (71100 cells). The CFD results presented in this section were obtained using a mesh of 112229 cells.

The transient flow in the experiments was obtained by a rapid opening of the valve, which created periodic oscillations of water surface levels in the vertical pipes. The measured and simulated water level traces at the upstream vertical pipe (left vertical pipe in Fig. 2.15) are presented in Fig. 2.15. The simulated results using the ITM model were obtained using 400 cells, a pressure wave celerity of 1000 m/s, a Manning roughness coefficient of $0.010 \text{ m}^{1/6}$ (typical for a plexiglass pipe), and a Courant number of $\text{Cr} = 0.8$. The results show a good agreement between the ITM, CFD, and measured results for the frequency and amplitude of water level oscillations. The results in Fig. 2.15 labelled “mass/energy” are obtained with the ITM model using the mass and energy equation instead of the mass and momentum equation (used in ITM model). As can be observed in Fig. 2.15, the former approach leads to inaccuracies on the frequency of oscillation of the water surface level. For the accurate prediction of frequency and amplitude of rapid variation of water surface levels in drop-shafts the momentum equation and not the energy equation must be used.

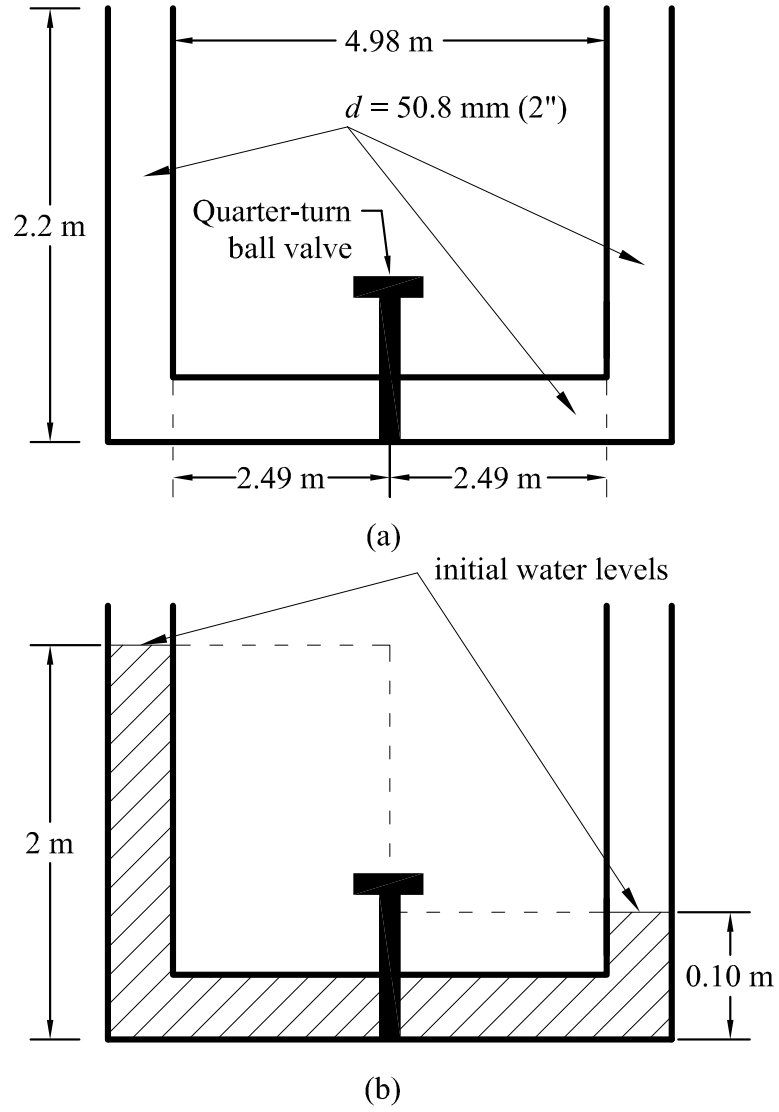


Figure 2.13: Experimental setup of León et al. (2009b) (not to scale) (a) dimensions and (b) initial water levels.

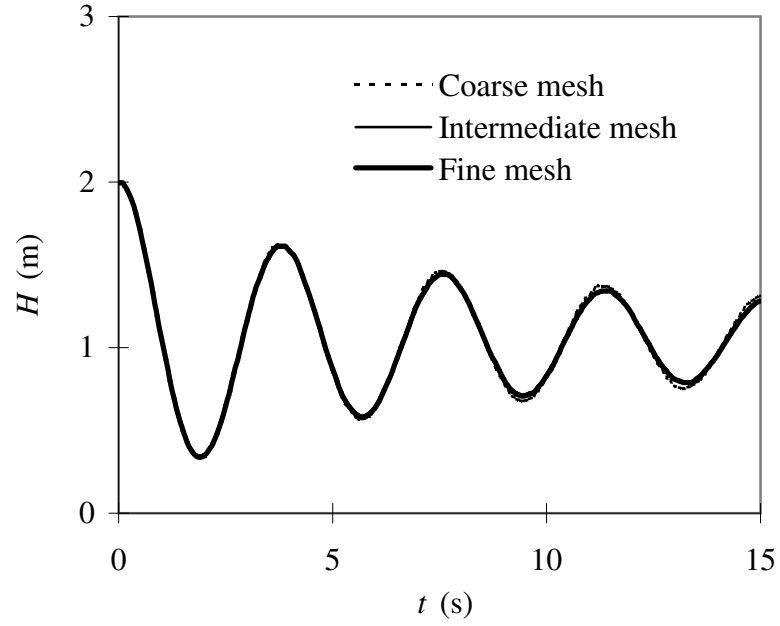


Figure 2.14: CFD mesh convergence for oscillation tube test case (Water level elevation at upstream drop-shaft).

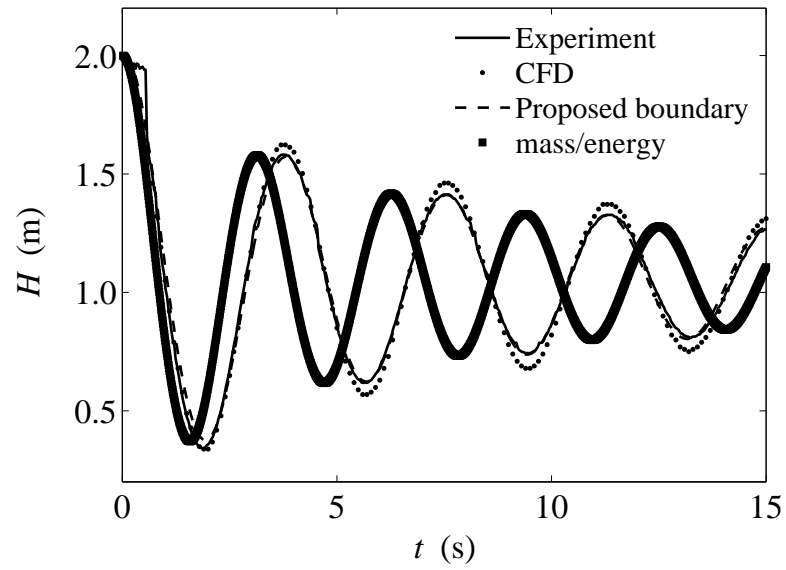


Figure 2.15: Water level elevation at upstream drop-shaft.

Chapter 3

Working with the ITM model

When using the ITM model the user should carry out the following steps:

1. Draw a network representation of the physical components of the closed-conduit system;
2. Add inflow hydrographs;
3. Edit the properties of the objects that make up the system;
4. Specify the set of options for the simulation;
5. Run the simulation; and
6. View the results of the simulation.

As mentioned earlier, the graphical user interface of the ITM model was modified from the graphical user interface of the SWMM model. The SWMM model originally developed by the U.S. EPA has a powerful graphical user-interface but a simple hydraulic model that can not be used for analyzing hydraulic transients. To take advantage of the tools of the SWMM graphical user interface, the graphical user interface of the ITM Model was adapted from the graphical user interface of the SWMM model. In this chapter, only new attributes that are unique to the ITM model are presented. For attributes of the ITM model that are common with the SWMM model the reader is referred to Rossman (2004).

3.1 Network representation

The network representation of the ITM model is very similar to that of the SWMM model. The network elements supported by ITM are four (conduit elements, junctions, reservoirs and constant boundaries) which graphical representation in the ITM model is depicted in Figure 3.1.

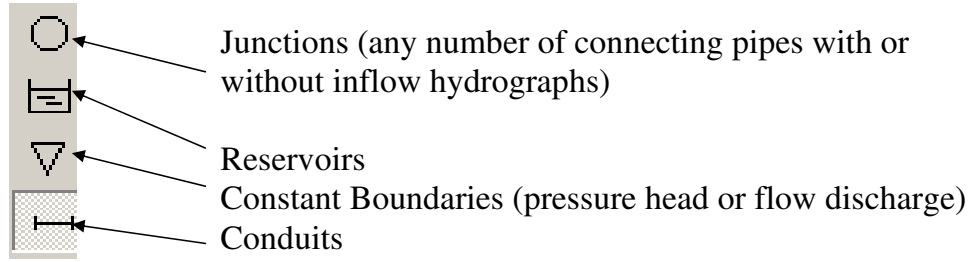


Figure 3.1: Network elements supported by ITM.

All network elements supported by ITM, except the “constant boundary” element, are supported by SWMM. Following, the four network elements will be described making emphasis on the new attributes of the ITM model.

3.1.1 Conduits

The graphical editor for a *conduit* element in the ITM model is presented in Figure 3.2. In comparison to the SWMM model, two aspects in this figure need to be commented. The first aspect is that the current version of the ITM model can handle only circular cross-sections. The second aspect is about how to specify the initial flow depth in the system (*initial depth type*). As shown in Figure 3.2, there are three possibilities, namely, *critical*, *normal* and *constant*. When the option *critical* is selected, the ITM model will compute the critical flow depth and will assign this value to all cells of the conduit under edition. Likewise, when the option *normal* is selected, the ITM model will compute the normal flow depth and will assign this value to all cells of the conduit under edition. When the option *critical* or *normal* is selected, the initial flow (two fields below the *initial depth type* in Figure 3.2) is used for the critical or normal flow computations. When the option *constant* is selected, the ITM model will assign this constant depth to all cells of the conduit under edition.

3.1.2 Junctions

The graphical editor for a *junction* element in the ITM model is presented in Figure 3.3. In comparison to the SWMM model, one aspect in this figure needs to be commented. This aspect is that if an inflow hydrograph (*inflow* in Figure 3.3) is specified at a given node, a horizontal area (*Area* in Figure 3.3) must be specified at this node.

3.1.3 Reservoirs

The graphical editor for a *reservoir* element in the ITM model is presented in Figure 3.4. In comparison to the SWMM model, two aspects in this figure need to be commented. The first aspect is that no inflow hydrographs are allowed at reservoirs, however constant outflows (*Const. outflow* in Figure 3.4) can be

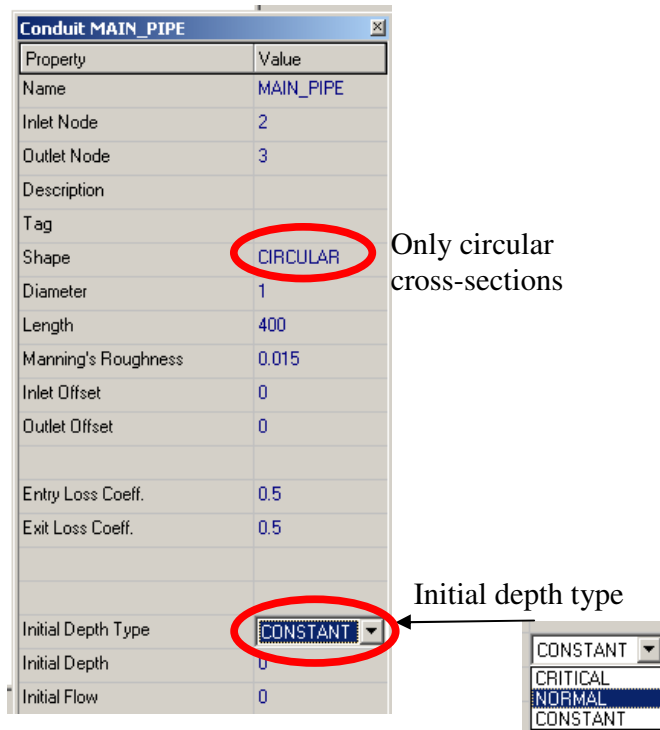


Figure 3.2: Graphical editor for a conduit in ITM.

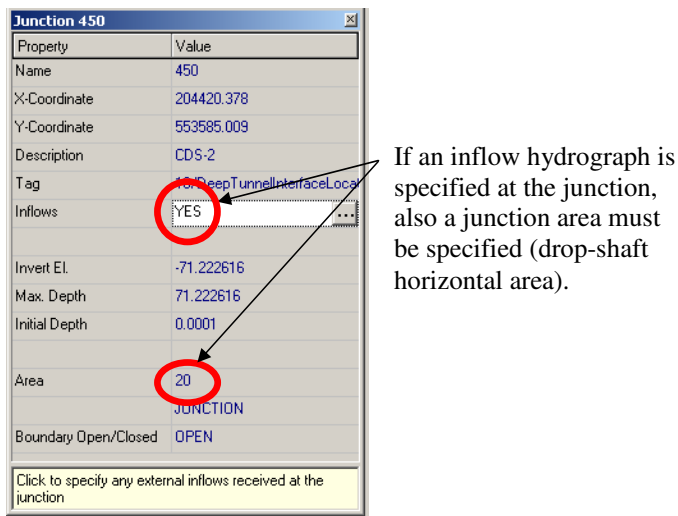


Figure 3.3: Graphical editor for a junction in ITM.

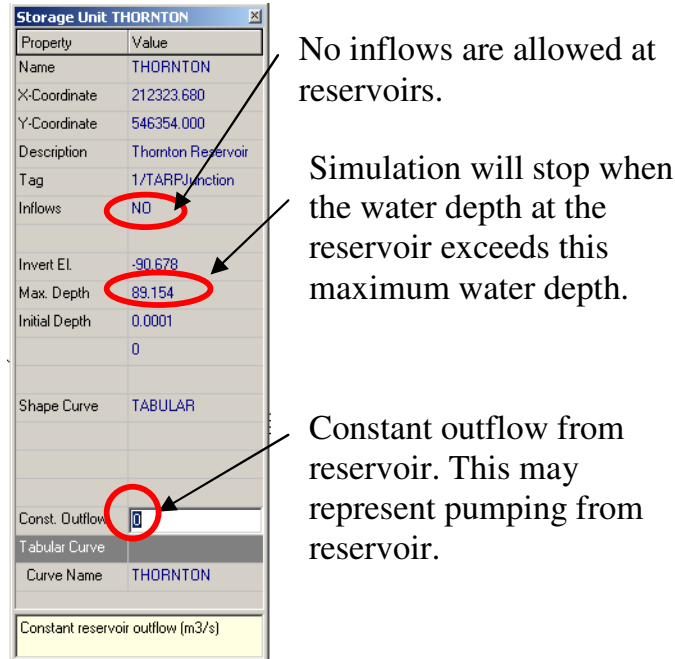


Figure 3.4: Graphical editor for a reservoir in ITM.

specified at this boundary. The second aspect is that the simulation will stop when the water depth exceeds the maximum water depth specified in the field *Max. depth*.

3.1.4 Constant boundaries

The graphical editor for a *constant boundary* element is presented in Figure 3.5. This boundary element can be used *ONLY* when the boundary is connected to *ONE* conduit. As mentioned earlier, the “constant boundary” element is an attribute unique to ITM. In Figure 3.5, three aspects need to be commented. The first aspect is about the field *Boundary Open/Closed*. For this field there are two options, namely *OPEN* and *CLOSED*. The option *CLOSED* must be selected where there is no air ventilation at the boundary (e.g., dead-end tunnel) and *OPEN* when the boundary is ventilated (e.g., lake or river). The second aspect is about the field *Boundary Type*. For this field there are two options, namely, *CONST/FLOW* and *CONST/DEPTH*. The option *CONST/FLOW* must be selected when a constant flow discharge is specified at the boundary. Likewise, the option *CONST/DEPTH* must be selected when a constant depth (or pressure head) is specified at the boundary. For both options (*CONST/FLOW* and *CONST/DEPTH*), the boundary value (flow discharge or pressure head) needs to be specified in the field *Boundary value*.

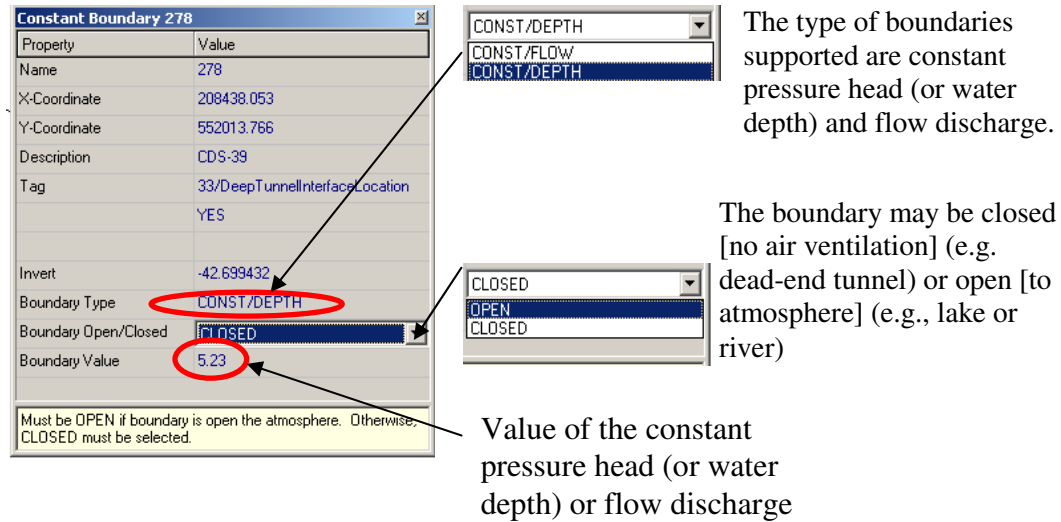


Figure 3.5: Graphical editor for a constant boundary.

3.2 ITM Simulation options

The simulation options for the ITM model are presented in Figure 3.6. As can be observed in this Figure, the ITM simulation options has 14 fields, which are described next.

Field 1: Minimum number of grid options: This field refers to the minimum number of cells to be used for the shortest conduit.

Field 2: Maximum number of cells for each pipe: This field refers to the maximum number of cells that can be used in a conduit.

Field 3: Pressure wave celerity (fully-pressurized flows) [a]: This field refers to the waterhammer wave speed to be used in fully-pressurized flow conditions.

Field 4: Pressure wave celerity (mixed flow conditions): This field refers to the waterhammer wave speed to be used in mixed flows conditions. This value can be set to a smaller value than “a” for achieving faster computations in case of mixed-flow conditions.

Field 5: Reference depth fraction: This field refers to the ratio water depth-diameter at which the transition from free surface to pressurized flow is assumed to occur. In mixed flow conditions, this ratio may be set between 0.80 and 0.99. For fully-pressurized flows, this ratio can be set equal to 1.0.

Field 6: Maximum number of iterations for convergence: This field refers to the maximum number of iterations to be used in the ITM model when solving iterative equations (e.g., non-linear system of equations).

Field 7: Maximum number of cells to plot for each pipe: This field refers to the maximum number of cells to be used for plotting (and storing) the pressure head at each pipe.

Field 8-11: Tolerances: The ITM model uses three different tolerances

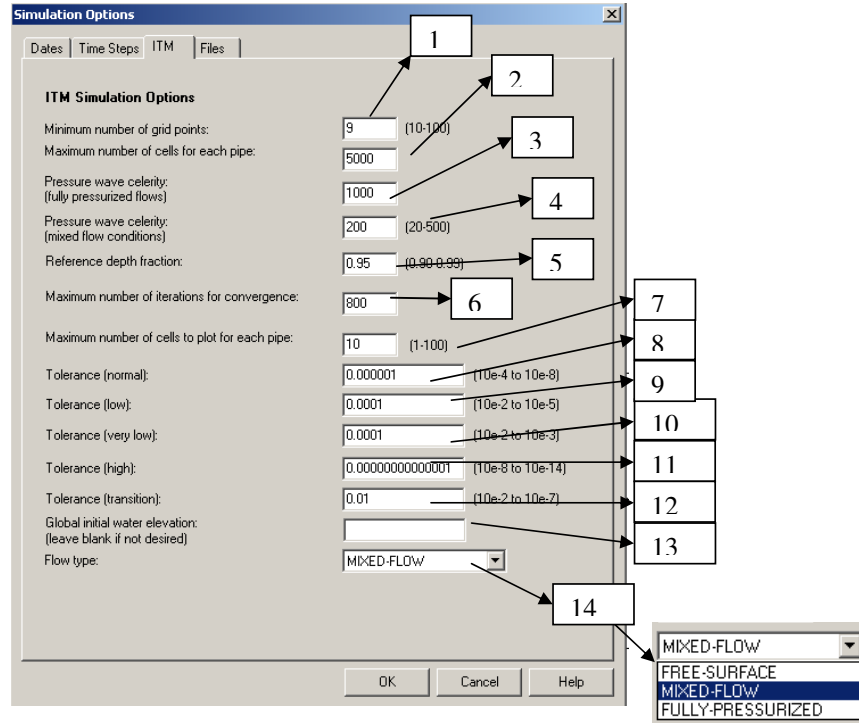


Figure 3.6: Graphical editor for ITM simulation options.

(normal, low and high) for solving iterative equations depending on the precision required. The values suggested for these tolerances are indicated in the graphical editor (right side of these fields).

Field 12: Tolerance (transition): For avoiding numerical instabilities at the transition from free surface to pressurized flow, a threshold value for the pressure head is used in the ITM model (León et al. 2009d). This field refers to the tolerance (fraction of conduit diameter) at which this threshold value is defined (below the reference pressure at which the transition from free surface to pressurized flow occurs).

Field 13: Global initial water elevation (leave blank if not desired): If initially the entire or part of the system is subjected to stationary flow conditions (constant water surface level and zero flow velocity) specify in this field the elevation of this water surface level. If the simulation starts from dry-bed conditions leave this field blank.

Field 14: Flow type: This field refers to the flow type of the simulation. This field is used to avoid checks when running the simulation. For instance, if before hand it is known that fully-pressurized flows will be simulated, no checks for depressurization need to be performed at every time step. In the current version, choosing free surface flow or mixed flow makes no difference. This distinction will be added later. If free surface flow is chosen the program will be terminated when the system is first pressurized (pressurization of an internal cell or boundary).

Chapter 4

ITM Examples

In this chapter, two examples are presented to familiarize the user in setting input data, running and visualizing results when using the ITM model. The first example is a simple hypothetical three-way merging flow and the second one is an actual combined storm-sewer system (Calumet TARP system, Chicago).

4.1 Hypothetical three-way merging flow

This example is very similar in layout (no dimensions) to a test case presented in Chapter 2. The dimensions for the present example were modified from that presented in Chapter 2 to show better the ability of the ITM model in simulating dry-bed flows, free surface flows, the simultaneous occurrence of free surface and pressurized flows (mixed flows) and fully-pressurized flows (waterhammer flows). The network for this example is depicted in Fig. 4.1. Conduits 1 and 2 in this figure were defined to be identical for reducing the number of plots to show. The input file used for the preparation of this example is presented in Appendix A. As can be observed in Fig. 4.1, two inflow hydrographs (identical) were used which are presented in Fig. 4.2. The simulation options used in the ITM model for this example are presented in Fig. 4.3.

The simulation results for the pressure head traces at nodes 1, 3 and 4 (results at node 2 are the same as node 1) are presented in Fig. 4.4. The results for the pressure depth (measured from conduits invert) and flow discharge traces at the center of conduits 1 and 3 are presented in Figs. 4.5 and 4.6, respectively.

Besides plots of pressure head and flow discharge traces, the ITM model (in a similar way to the SWMM model) can display tables, and a summary of the simulation. As illustration, a typical tabular output for flow discharge traces inside conduits is shown in Fig. 4.7; and a typical summary of the simulation is presented in Fig. 4.8.

The ITM model can also generate plots of rating curves (pressure depth

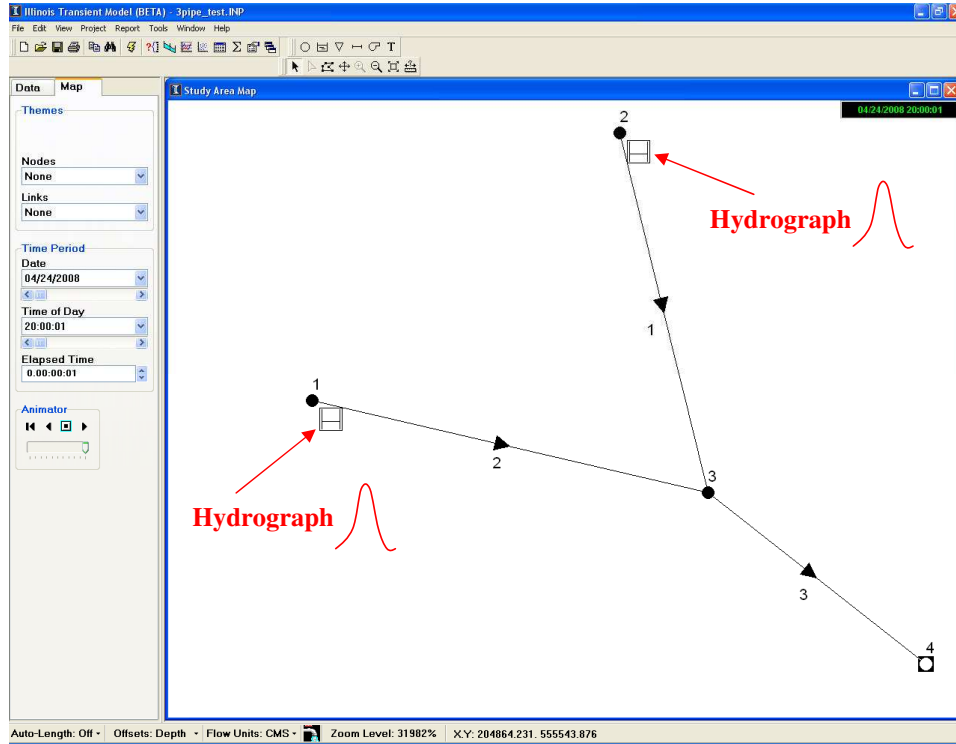


Figure 4.1: Network for hypothetical three-way merging flow example.

versus flow discharge) as can be observed in Fig. 4.9. This figure clearly shows that a rating curve for pressurized flows in transient conditions do not follow the typical rating curve of open channel flows (single or looped correspondence between flow discharge and depth).

The ITM model as the SWMM model can generate an animation for pressure head profiles between two nodes in the system. As illustration, Figs. 4.10 - 4.20 present pressure head profile snapshots between nodes 1 and 4 at different times. These plots can help to visualize the hydraulic behavior of the system. These plots may also help to identify visually the regions of overflow. For instance, Fig. 4.20 shows the conditions under which the hypothetical system first overflows (pressure head exceeds terrain level).

The ITM model also generates a file named *vol-overflows.dat* that contains tabular data for the cumulative trace of overflow volumes (cumulative volume versus time) for all dropshafts, junctions and open boundaries. In addition, the ITM model generates the file *<name of input file>.INP.debug* that is intended for debugging of errors in the input data or simulation options. The list of errors that the ITM model can generate are presented in Appendix C.

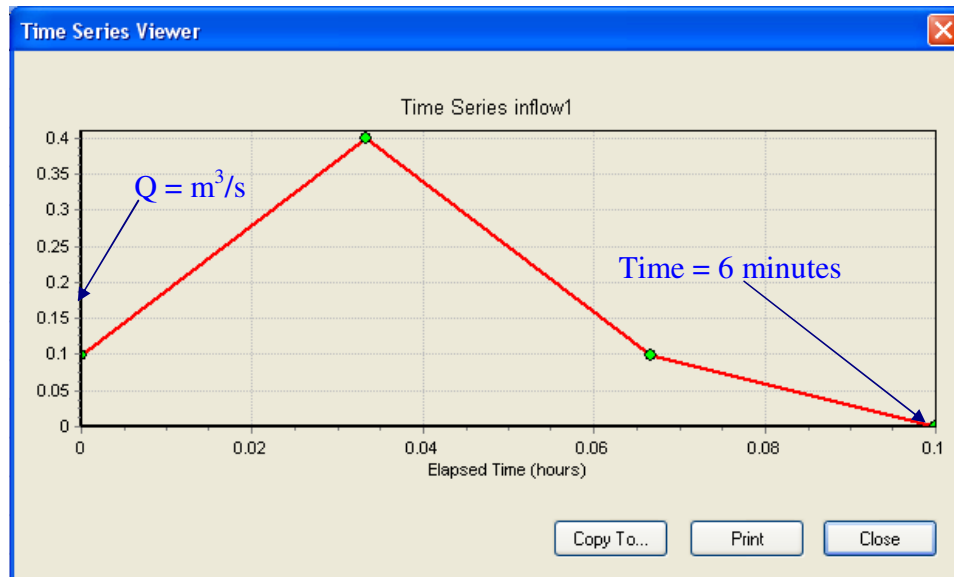


Figure 4.2: Inflow hydrographs for nodes 1 and 2 in hypothetical three-way merging flow example.

Simulation Options

Dates Time Steps ITM Files

ITM Simulation Options

Minimum number of grid points: 40 (10-100)

Maximum number of cells for each pipe: 5000

Pressure wave celerity: (fully pressurized flows) 1000

Pressure wave celerity: (mixed flow conditions) 100 (20-500)

Reference depth fraction: 0.95 (0.90-0.99)

Maximum number of iterations for convergence: 200

Maximum number of cells to plot for each pipe: 40 (1-100)

Tolerance (normal): 0.00001 (10e-4 to 10e-8)

Tolerance (low): 0.0001 (10e-2 to 10e-5)

Tolerance (very low): 0.0001 (10e-2 to 10e-3)

Tolerance (high): 0.000000000000 (10e-8 to 10e-14)

Tolerance (transition): 0.001 (10e-2 to 10e-7)

Global initial water elevation: (leave blank if not desired)

Flow type: MIXED-FLOW

OK Cancel Help

Figure 4.3: Simulation options used in the ITM model for hypothetical three-way merging flow example.

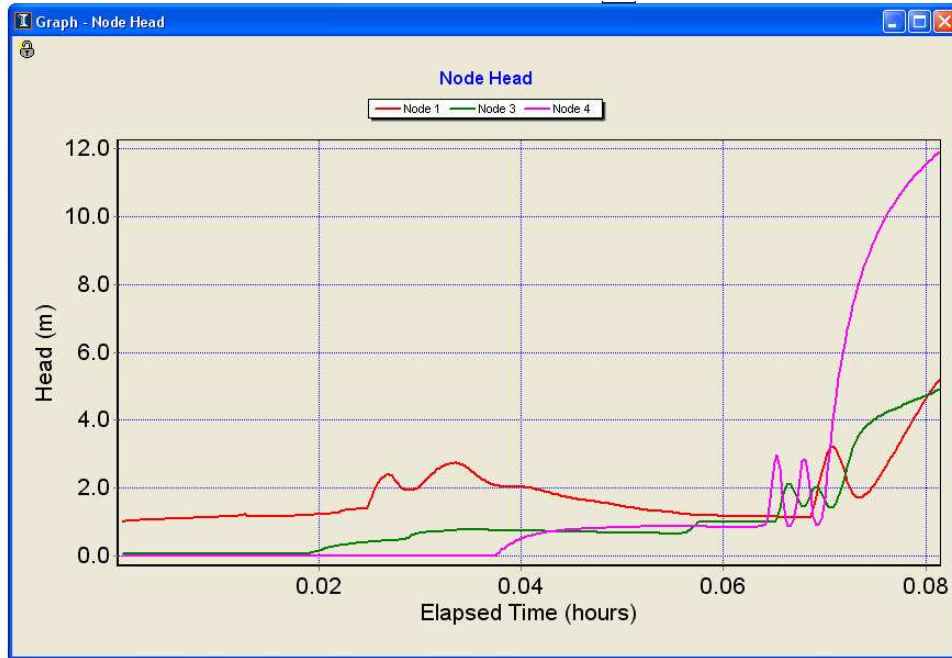


Figure 4.4: Pressure head traces at nodes 1, 3 and 4 for hypothetical three-way merging flow example.



Figure 4.5: Pressure head traces (measured from conduits invert) at the center of conduits 1 and 3 for hypothetical three-way merging flow example.

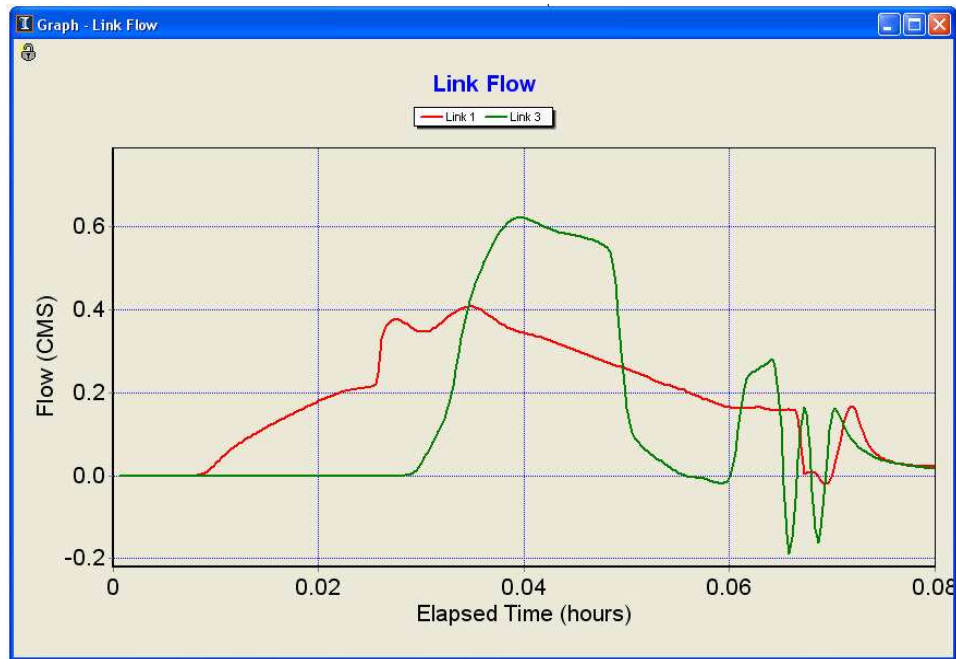


Figure 4.6: Flow discharge traces at the center of conduits 1 and 3 for hypothetical three-way merging flow example.

Days	Hours	Link 3	Link 1	Link 2
0	00:01:35	0.00	0.35	0.35
0	00:01:36	0.00	0.36	0.36
0	00:01:37	0.00	0.37	0.37
0	00:01:38	0.00	0.38	0.38
0	00:01:39	0.00	0.38	0.38
0	00:01:40	0.00	0.38	0.38
0	00:01:41	0.00	0.37	0.37
0	00:01:42	0.00	0.37	0.37
0	00:01:43	0.00	0.36	0.36
0	00:01:44	0.00	0.36	0.36
0	00:01:45	0.01	0.35	0.35
0	00:01:46	0.01	0.35	0.35
0	00:01:47	0.02	0.35	0.35
0	00:01:48	0.03	0.35	0.35
0	00:01:49	0.04	0.35	0.35
0	00:01:50	0.06	0.35	0.35
0	00:01:51	0.07	0.35	0.35
0	00:01:52	0.08	0.35	0.35
0	00:01:53	0.09	0.36	0.36
0	00:01:54	0.11	0.36	0.36
0	00:01:55	0.12	0.37	0.37
0	00:01:56	0.14	0.37	0.37
0	00:01:57	0.16	0.38	0.38

Figure 4.7: Typical tabular output for flow discharge traces inside conduits.

ILLINOIS TRANSIENT MODEL - VERSION 1 BETA

Analysis Options

Flow Units CMS
 Starting Date APR-24-2008 20:00:00
 Ending Date APR-24-2008 20:05:00
 Report Time Step 00:00:01
 Routing Time Step 0.50 sec

Node Depth Summary

Node	Type	Average	Maximum	Time of Max	
		Depth	Depth	Depth	Occur.
		Meters	Meters	days	hr:min
1	JUNCTION	0.01	4.75	0	00:05
2	JUNCTION	0.01	4.75	0	00:05
3	JUNCTION	0.01	5.61	0	00:05
4	JUNCTION	0.01	12.37	0	00:05

Link Flow Summary

Link	Type	Maximum	Time of Max		Max
		Flow	Flow	Occur.	
		CMS	days	hr:min	Depth
1	CONDUIT	0.41	0	00:02	4.93
2	CONDUIT	0.41	0	00:02	4.93
3	CONDUIT	0.62	0	00:02	9.07

Maximum flow discharge
inside conduits

Maximum pressure head
inside conduits

Figure 4.8: Summary of pressure heads and flow discharges for hypothetical three-way merging flow example.

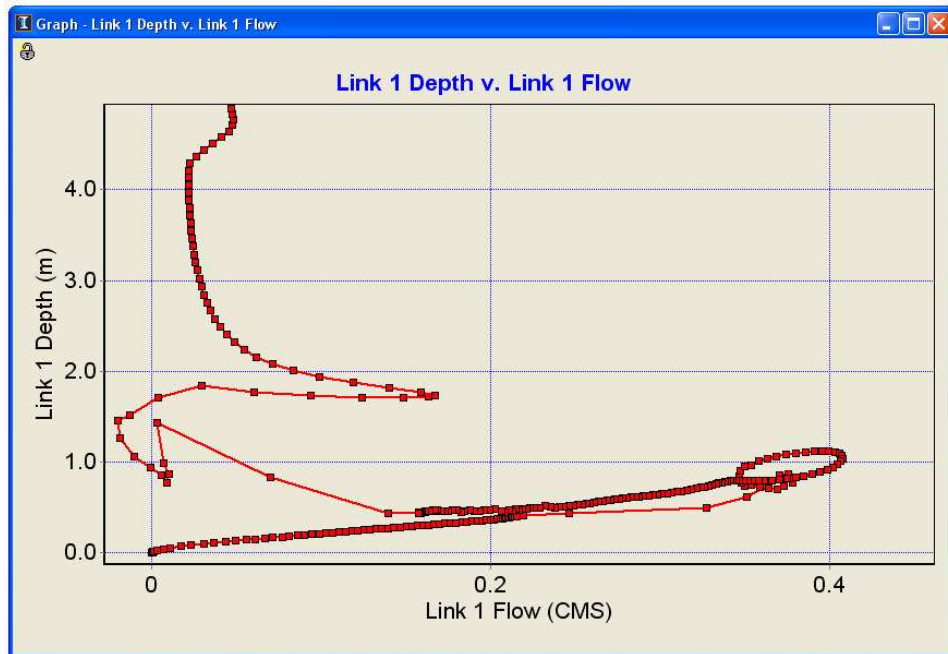


Figure 4.9: Typical relation between pressure head versus flow discharge in transient conditions.

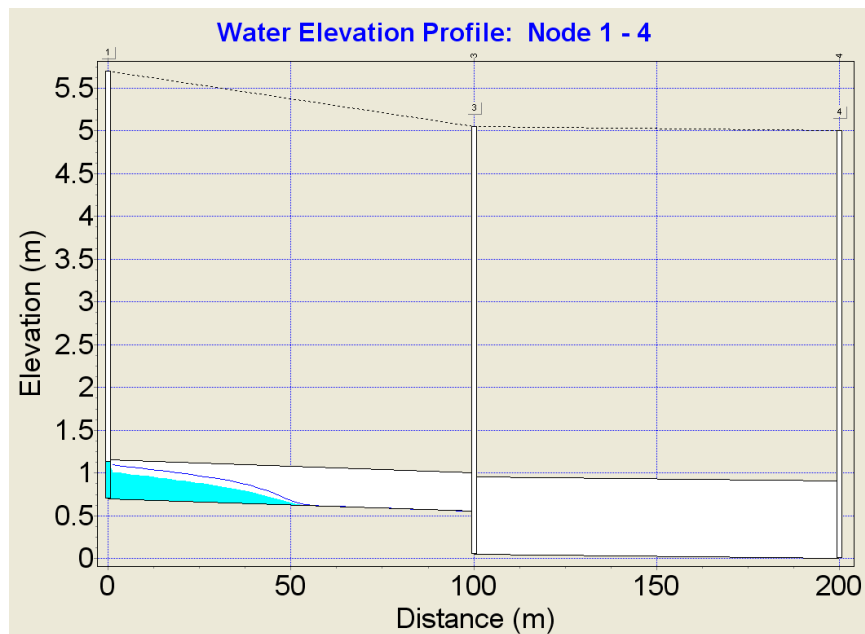


Figure 4.10: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 30$ s.

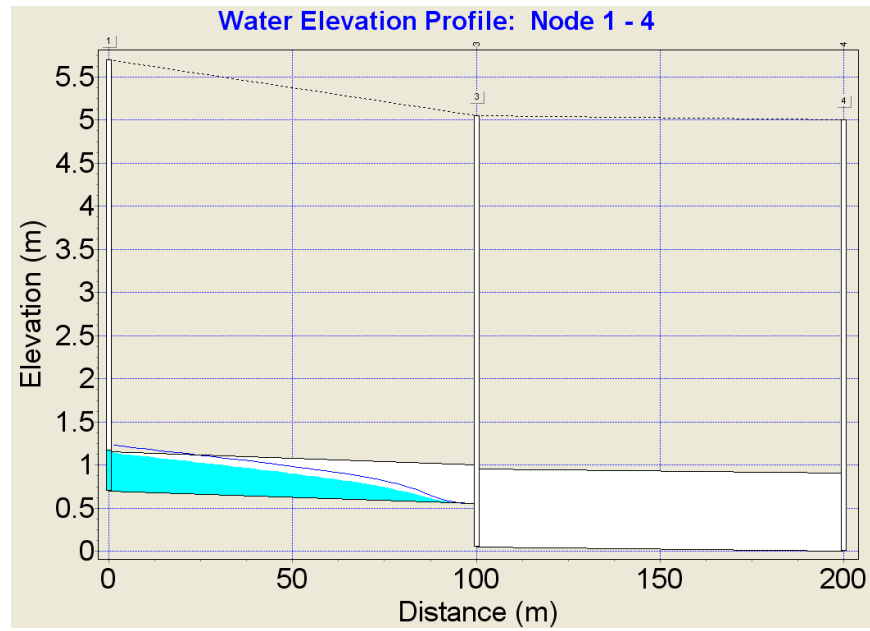


Figure 4.11: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 60$ s.

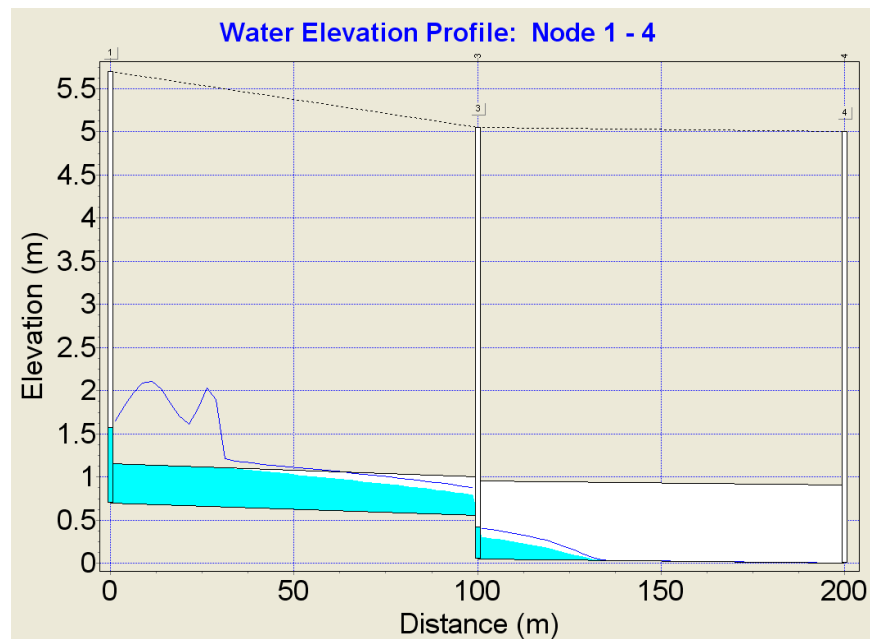


Figure 4.12: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 90$ s.

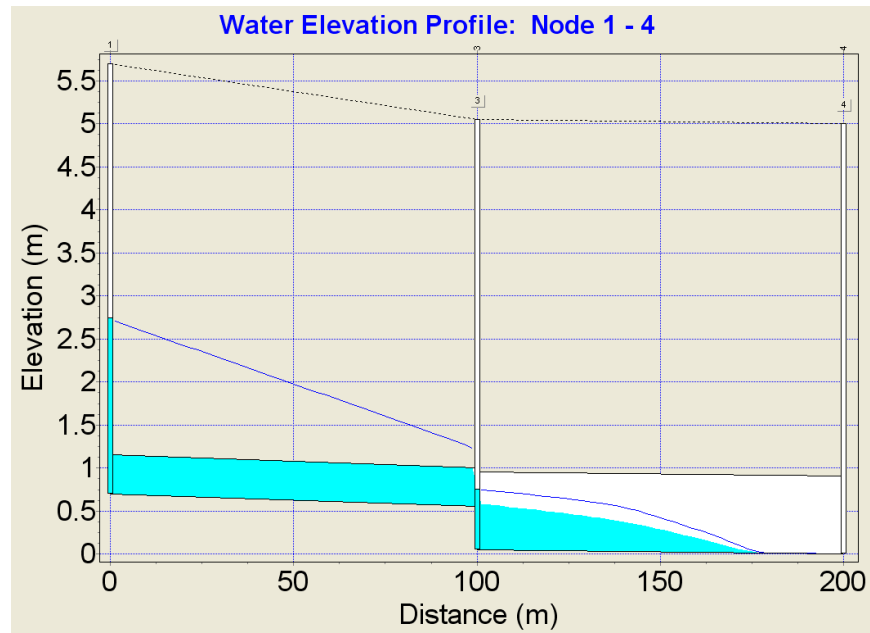


Figure 4.13: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 120$ s.

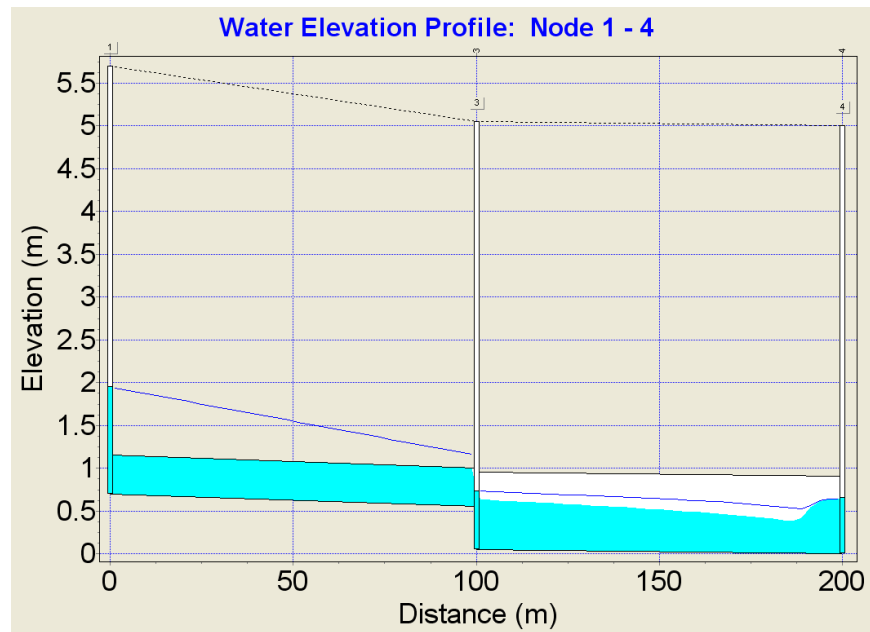


Figure 4.14: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 150$ s.

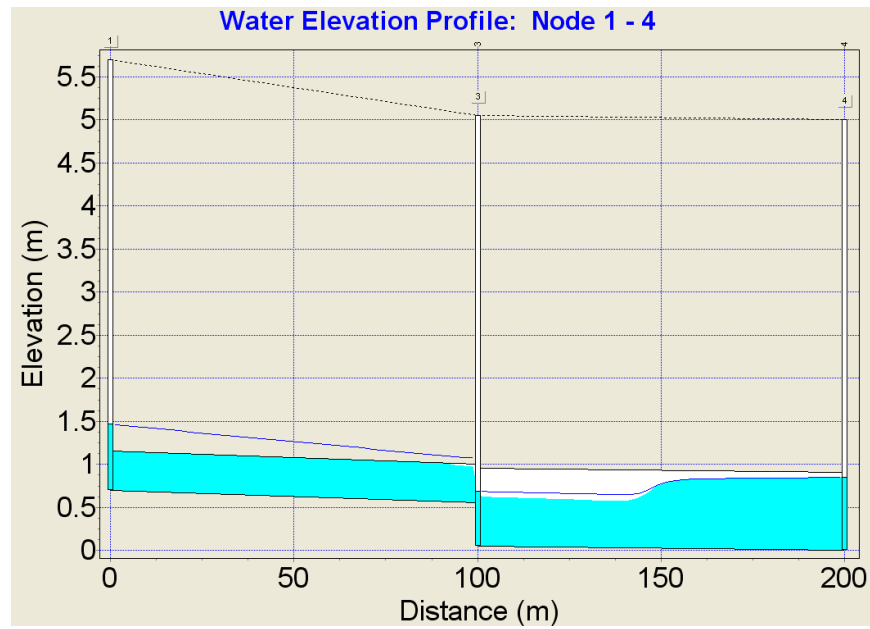


Figure 4.15: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 180$ s.

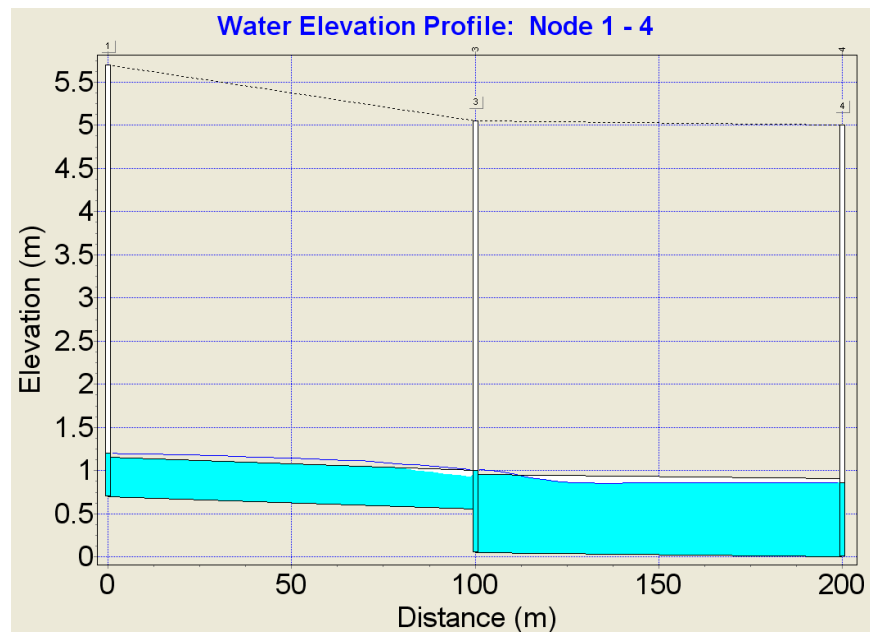


Figure 4.16: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 210$ s.

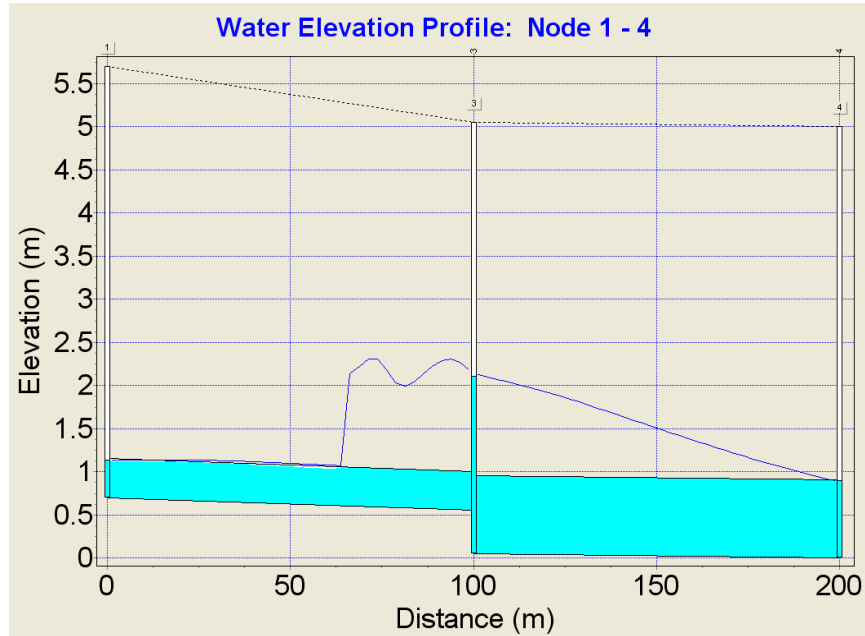


Figure 4.17: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 240$ s.

4.2 Calumet TARP system, Chicago

This example presents an actual combined storm-sewer system (Calumet TARP system) which is operated by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC). The Calumet TARP system consists of about 30 (check????) miles of deep tunnel, bored in rock and lined with concrete. The tunnels range from 9 to 33 ft in diameter and are located 200 to 350 ft below ground. The system includes the Thornton Reservoir (24,200) Acre-Feet, drop shafts, connecting structures, and a pumping station. The Thornton Reservoir is located at the downstream end of the Calumet tunnels to provide additional storage capacity.

The network for this example is depicted in Fig. 4.21. The input file used for the Calumet TARP system example is presented in Appendix B. As can be observed in Fig. 4.21, the Thornton Reservoir is located at the downstream end of the system. The stage-storage curve for this reservoir is presented in Fig. 4.22. For the inflow hydrographs a hypothetical storm was selected. This storm was intentionally amplified in order to show the capability of the ITM model in simulating overflows and pressurization subjected to large inflows. As can be noticed in Fig. 4.21, seven inflow hydrographs were specified for this example. Two of these inflow hydrographs are depicted in Fig. 4.23. The simulation options used in the ITM model for this example are presented in Fig. 4.24.

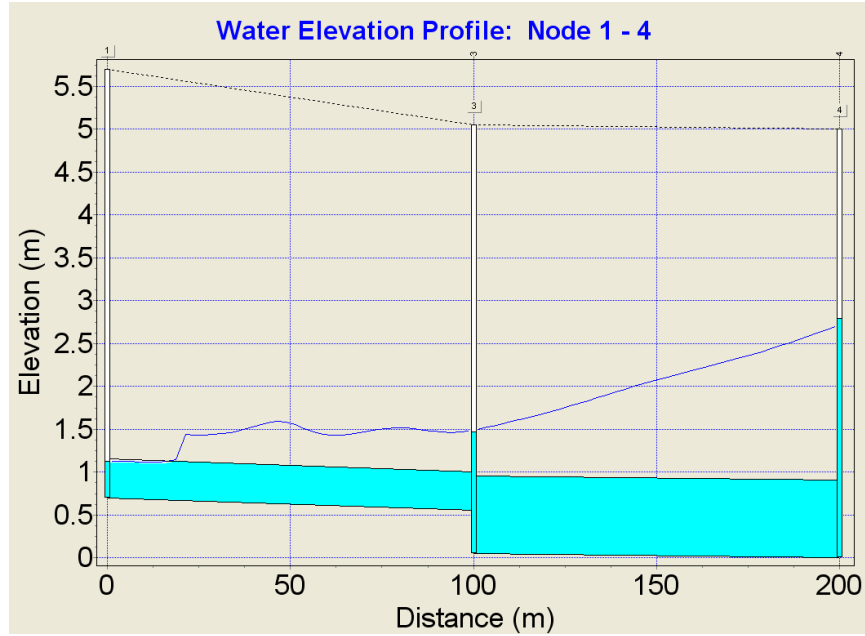


Figure 4.18: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 244$ s.

The simulation results for the pressure head traces at nodes W3, C1, S2, E3 and Thornton Reservoir are presented in Fig. 4.25. The results for the pressure depth (measured from conduits invert) and flow velocity traces at the center of conduits 1, 2, 3, 4 and 7 are presented in Figs. 4.26 and 4.27, respectively.

To help visualize the hydraulic behavior of the Calumet TARP system, pressure head profile snapshots between nodes W1 and the Thornton Reservoir at different times are presented in Figs. 4.28 - 4.33. Fig. 4.33 shows the conditions under which this system first overflows (pressure head exceeds terrain level).

As mentioned in the first example, the ITM model generates a file named *vol-overflows.dat* that contains tabular data for the cumulative trace of overflow volumes (cumulative volume versus time) for all dropshafts, junctions and open boundaries. Using this data, the cumulative trace of overflow volumes for nodes S2, S3, C1, N1 and E1 was prepared, which is presented in Fig. 4.34.

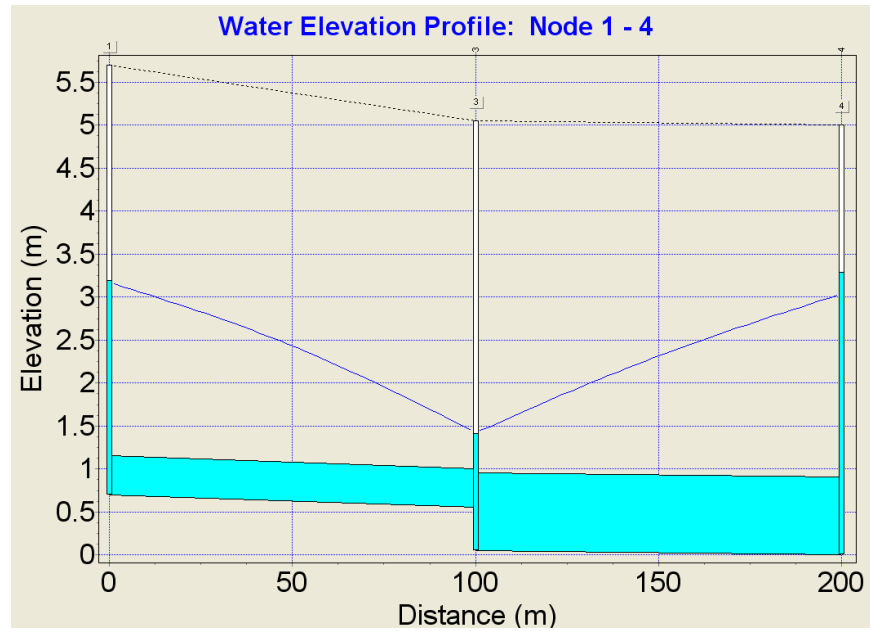


Figure 4.19: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 254$ s.

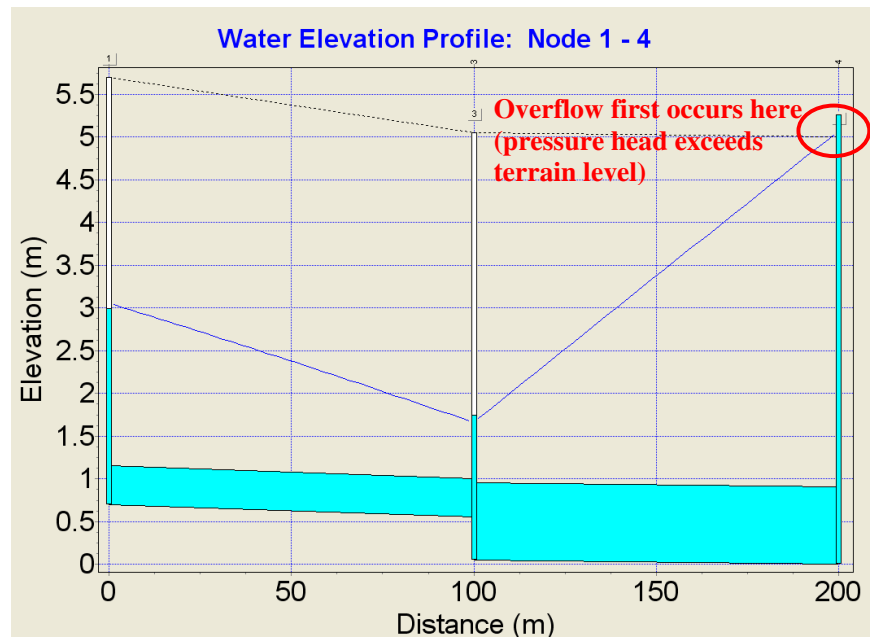


Figure 4.20: Pressure head profile between nodes 1 and 4 for hypothetical three-way merging flow example at $t = 257$ s.

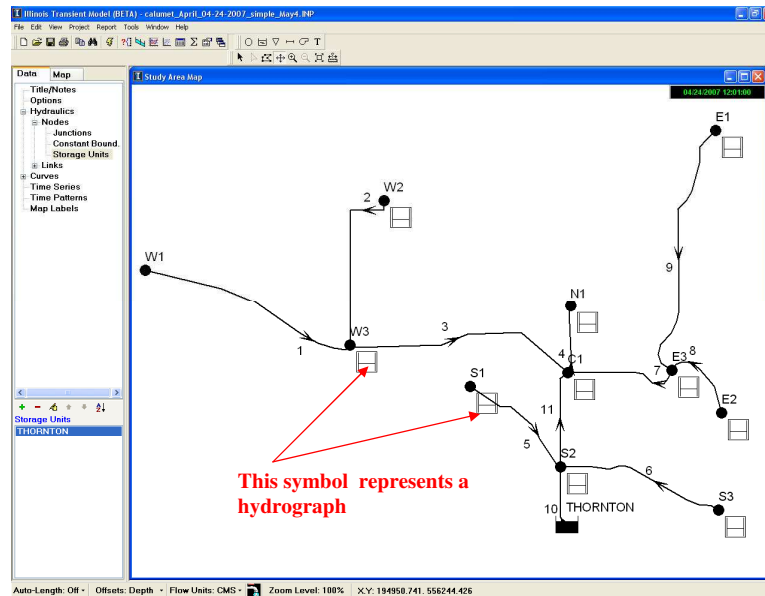


Figure 4.21: Network for Calumet TARP system example.

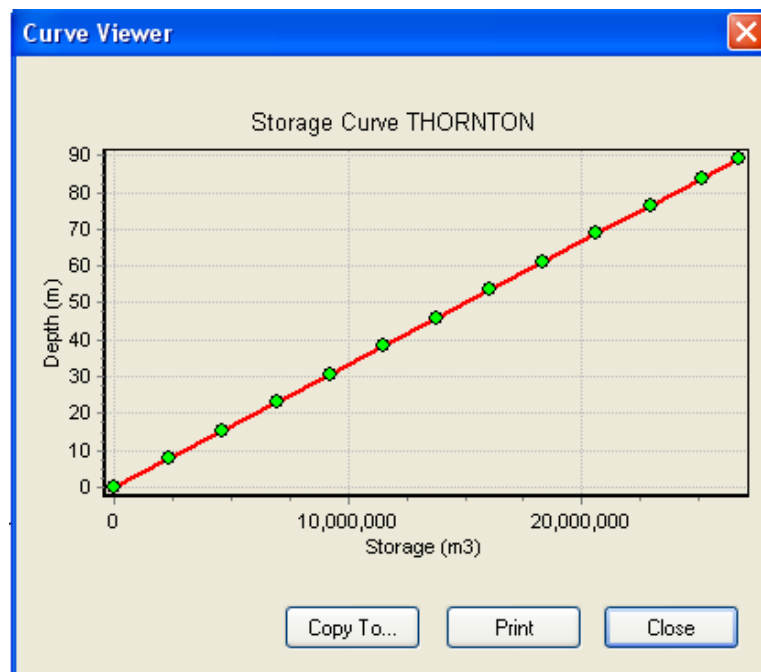
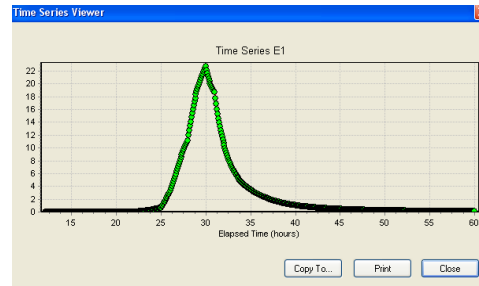
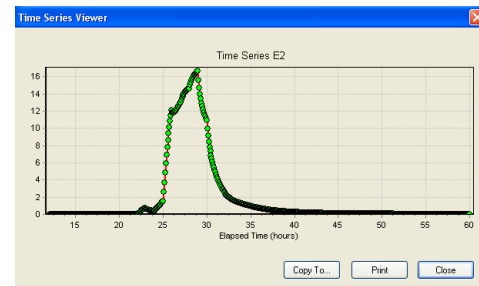


Figure 4.22: Stage-storage curve for Thornton Reservoir (Calumet TARP system).



(a)



(b)

Figure 4.23: Inflow hydrographs for nodes E1 and E2 in Calumet TARP system example.

Simulation Options	
ITM Simulation Options	
Minimum number of grid points:	16 (10-100)
Maximum number of cells for each pipe:	5000
Pressure wave celerity: (fully pressurized flows)	100
Pressure wave celerity: (mixed flow conditions)	100 (20-500)
Reference depth fraction:	0.95 (0.90-0.99)
Maximum number of iterations for convergence:	200
Maximum number of cells to plot for each pipe:	10 (1-100)
Tolerance (normal):	0.000001 (10e-4 to 10e-8)
Tolerance (low):	0.0001 (10e-2 to 10e-5)
Tolerance (very low):	0.0001 (10e-2 to 10e-3)
Tolerance (high):	0.0000000000 (10e-8 to 10e-14)
Tolerance (transition):	0.0001 (10e-2 to 10e-7)
Global initial water elevation: (leave blank if not desired)	
Flow type:	MIXED-FLOW

Figure 4.24: Simulation options used in the ITM model for Calumet TARP system example.

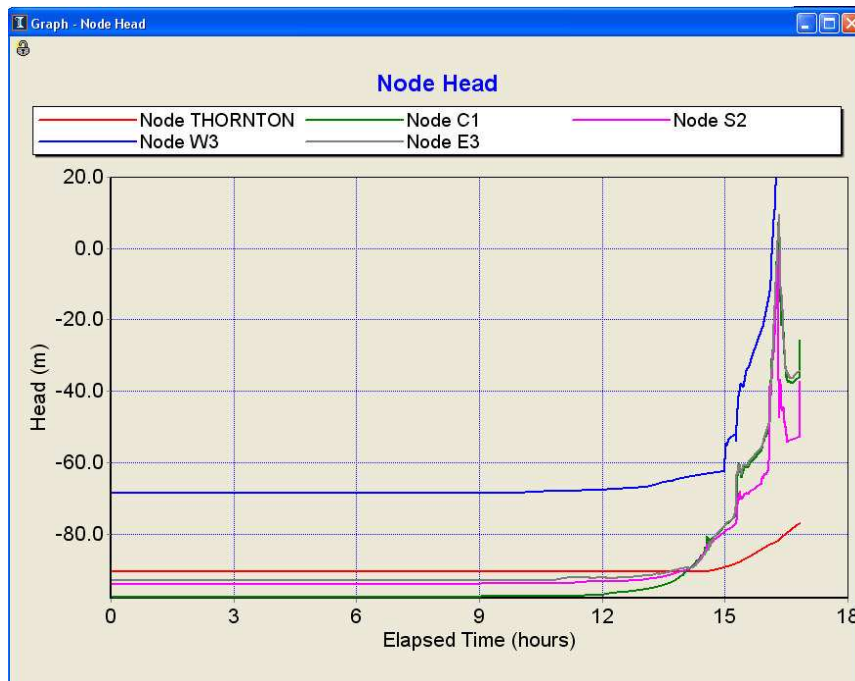


Figure 4.25: Pressure head traces at nodes W3, C1, S2, E3 and Thornton Reservoir for Calumet TARP system.

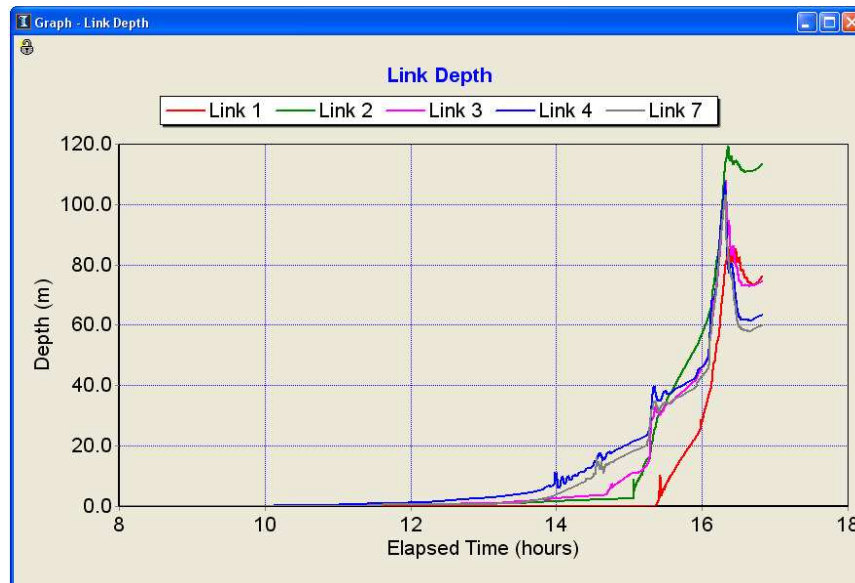


Figure 4.26: Pressure head traces (measured from conduits invert) at the center of conduits 1, 2, 3, 4 and 7 for Calumet TARP system.

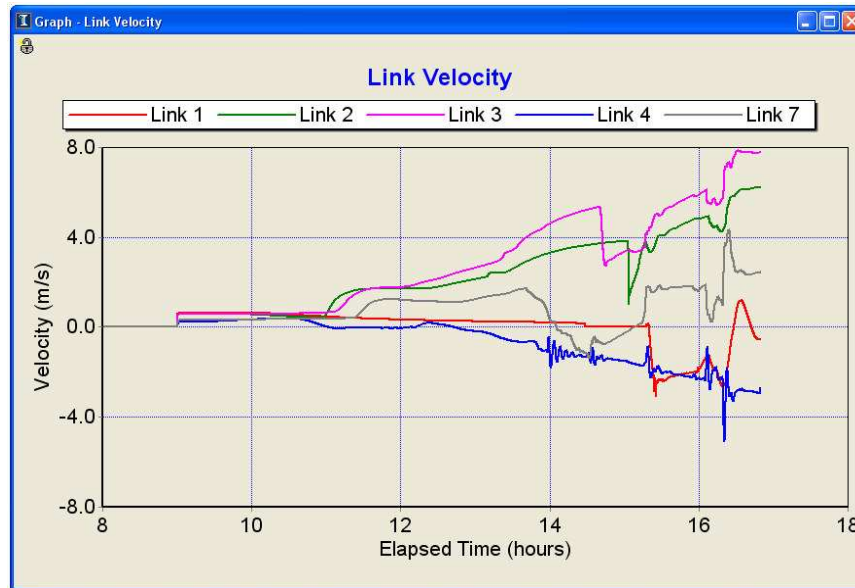


Figure 4.27: Flow velocity traces at the center of conduits 1, 2, 3, 4 and 7 for Calumet TARP system.

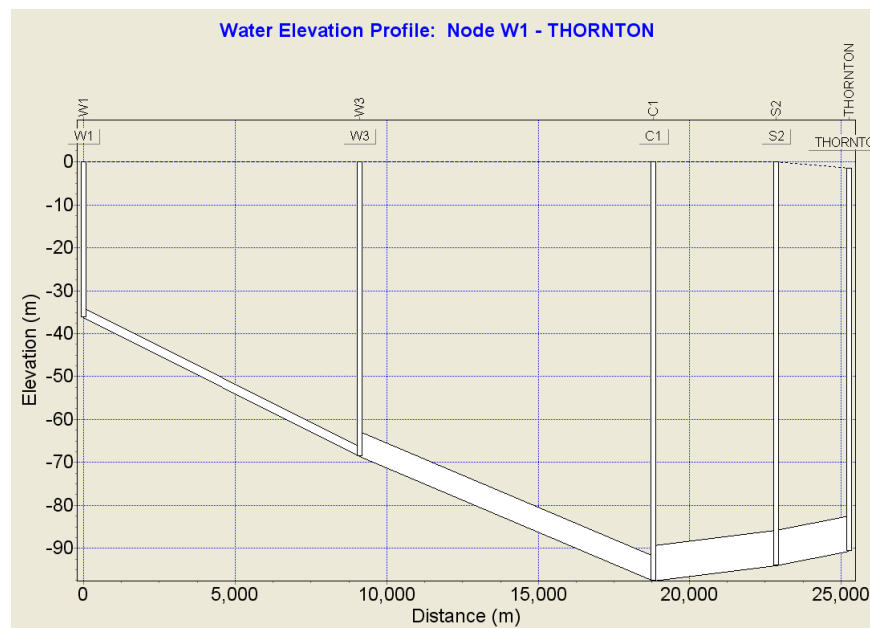


Figure 4.28: Pressure head profile between nodes W1 and Thornton Reservoir for Calumet TARP system at $t = 0$ s.

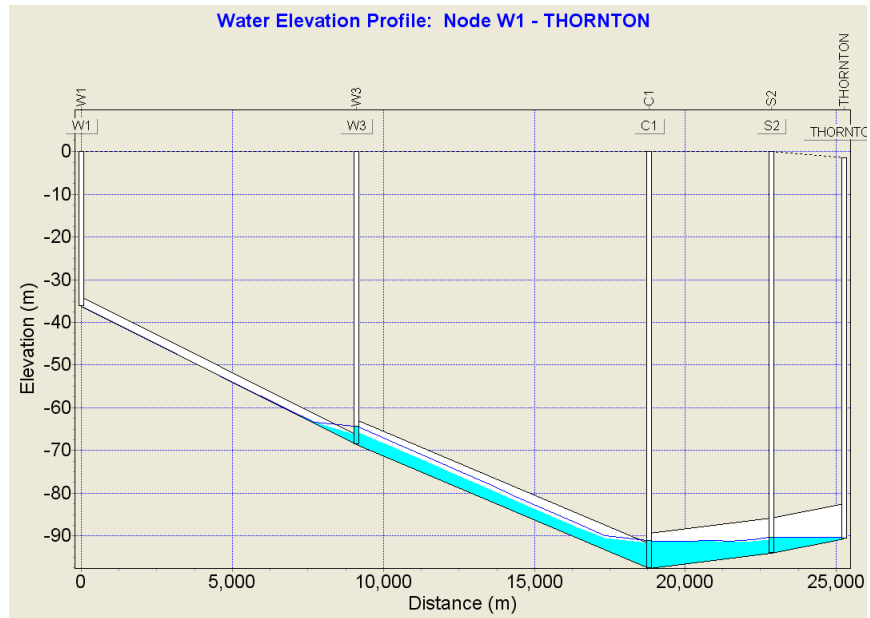


Figure 4.29: Pressure head profile between nodes W1 and Thornton Reservoir for Calumet TARP system at $t = 14$ hours.

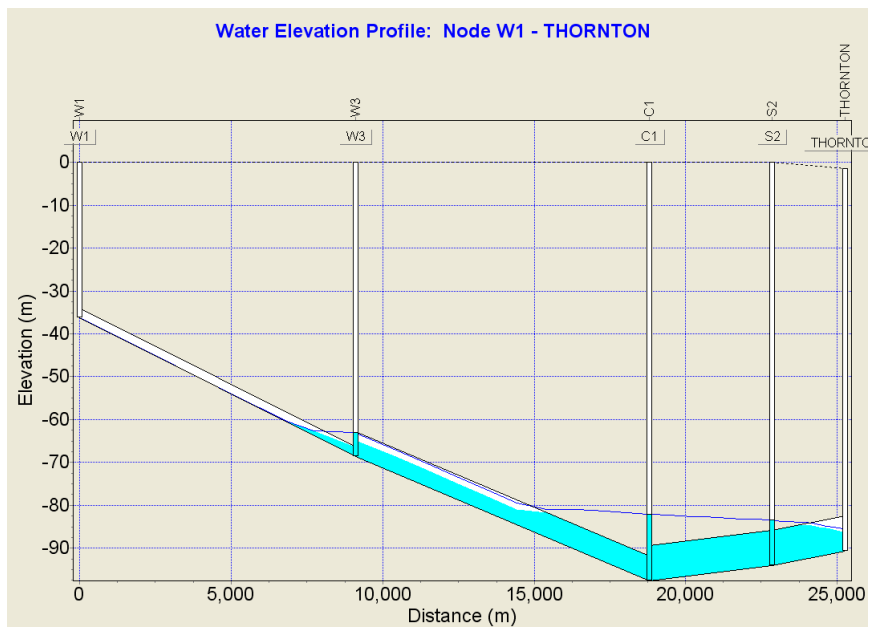


Figure 4.30: Pressure head profile between nodes W1 and Thornton Reservoir for Calumet TARP system at $t = 14$ hours 36 minutes.

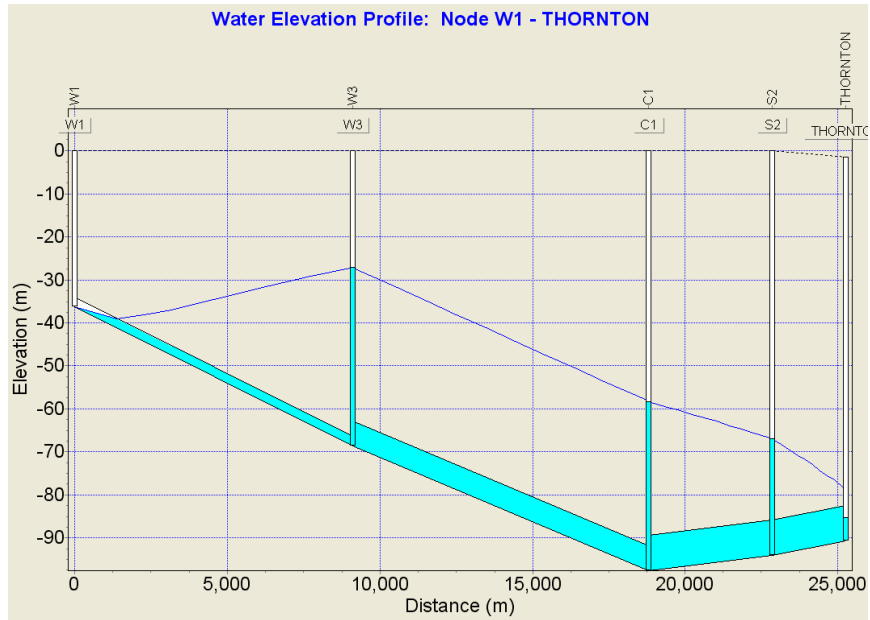


Figure 4.31: Pressure head profile between nodes W1 and Thornton Reservoir for Calumet TARP system at $t = 15$ hours 46 minutes.

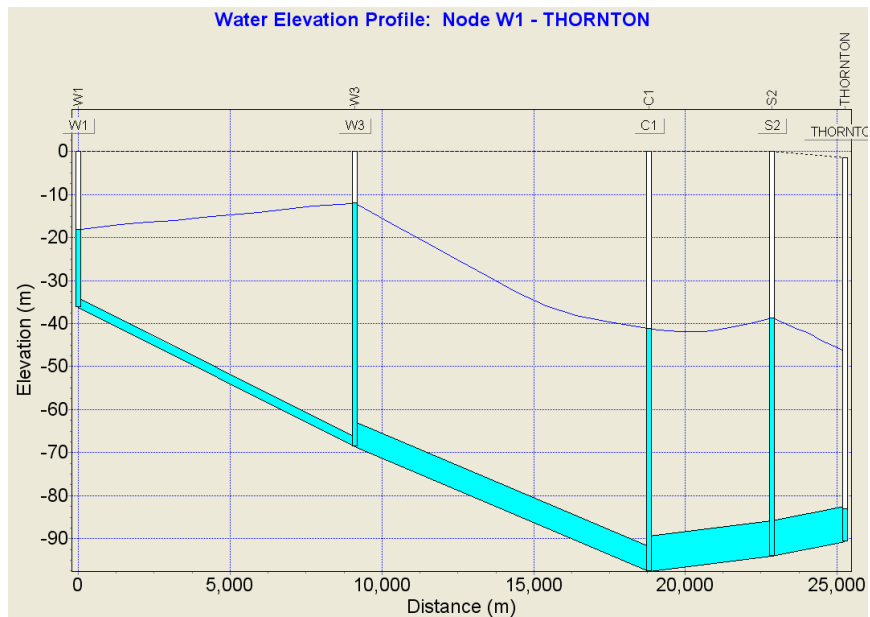


Figure 4.32: Pressure head profile between nodes W1 and Thornton Reservoir for Calumet TARP system at $t = 16$ hours 06 minutes.

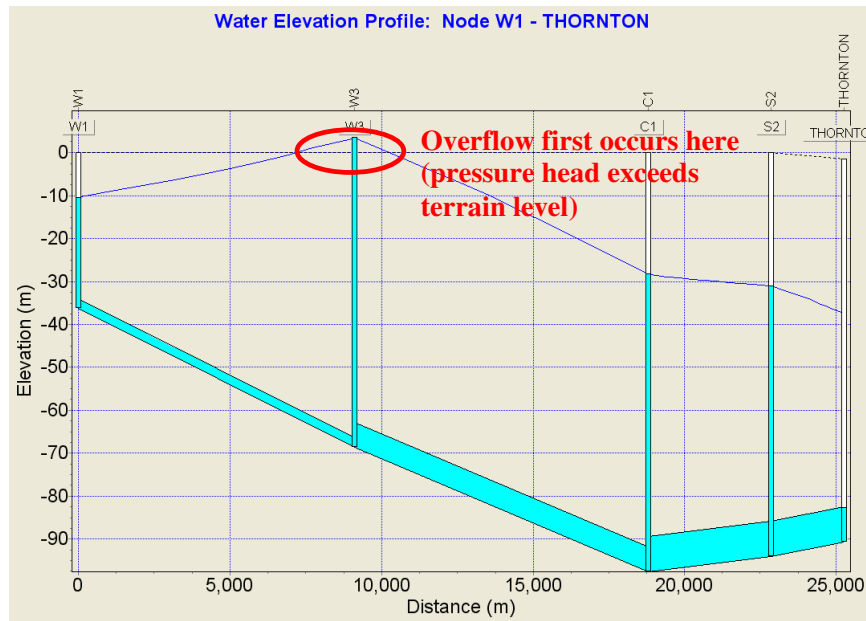


Figure 4.33: Pressure head profile between nodes W1 and Thornton Reservoir for Calumet TARP system at $t = 16$ hours 10 minutes 30 seconds.

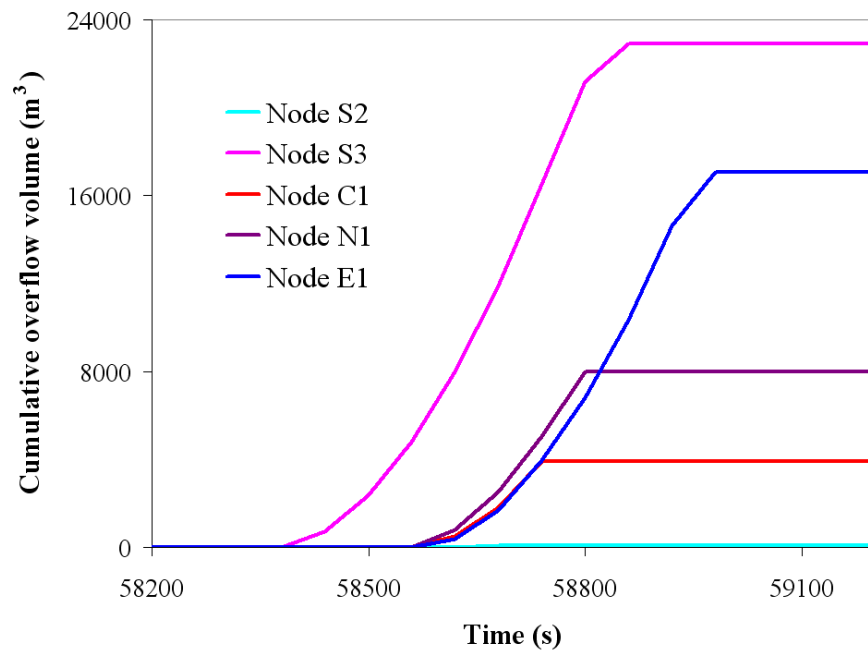


Figure 4.34: Cumulative trace of overflow volumes for nodes S2, S3, C1, N1 and E1 for Calumet TARP system example.

Appendix A

Input file for example 1

[TITLE]

[OPTIONS]

```
FLOW_UNITS      CMS
START_DATE      04/24/2008
START_TIME      20:00:00
END_DATE        04/24/2008
END_TIME        20:05:00
MAX_TIME_STEP    0.5
REPORT_START_DATE 04/24/2008
REPORT_START_TIME 20:00:00
REPORT_STEP      00:00:01
MIN_NUM_GRIDS    40
PRESSURIZED_WAVE_CELERITY 1000
MIXED_FLOW_WAVE_CELERITY 100
REF_DEPTH_FRACTION 0.95
MAX_NUM_ITERATIONS 200
MAX_NUM_CELLS    5000
MAX_NUM_PLOT_CELLS 10
ITM_TOL_NORMAL   0.00001
ITM_TOL_LOW      0.0001
ITM_TOL_VERY_LOW 0.0001
ITM_TOL_HIGH     0.00000000000001
ITM_TOL_TRANSITION 0.001
ITM_FLOW_TYPE    MIXED-FLOW
```

[JUNCTIONS]

;;	Invert	Max.	Init.		Boundary	Boundary
;;Name	Elev.	Depth	Depth	Area	Condition	Open/Closed
1	0.70	5.0	0	0.30	CLOSED	CLOSED
2	0.70	5.0	0	0.30	CLOSED	CLOSED
3	0.05	5.0	0	0.785398	CLOSED	OPEN
4	0	5.0	0	0	CLOSED	CLOSED

[CONDUITS]

;;	Inlet	Outlet		Manning	Inlet	Outlet	Init.	Initial	Initial
;;Name	Node	Node		Length	N	Offset	Offset	Flow	Depth type Depth
1	2	3	100	0.015	0	0.5	0	CONSTANT	0
2	1	3	100	0.015	0	0.5	0	CONSTANT	0
3	3	4	100	0.015	0	0	0	CONSTANT	0

[XSECTIONS]

;;Link	Shape	Diameter
1	CIRCULAR	0.5
2	CIRCULAR	0.5
3	CIRCULAR	1

[LOSSES]

;;Link	Inlet	Outlet
1	0.5	0.5
2	0.5	0.5
3	0.5	0.5

[INFLOWS]

;;		Param	Units	Scale	Baseline	
;;Node	Parameter	Time Series	Type	Factor	Factor	Value
1	FLOW	inflow3	FLOW	1.0	1.0	
2	FLOW	inflow1	FLOW	1.0	1.0	

[TIMESERIES]

;;Name	Date	Time	Value
inflow1		00:00	0.10
inflow1		00:02	0.40
inflow1		00:04	0.10
inflow1		00:06	0
inflow3		00:00	0.10
inflow3		00:02	0.40
inflow3		00:04	0.10
inflow3		00:06	0

[TAGS]

[MAP]

DIMENSIONS 194127.569 545538.065 219766.953 563488.622

Units None

[COORDINATES]

;;Node	X-Coord	Y-Coord
1	204812.974	555575.788
2	204844.111	555602.908
3	204853.015	555566.519
4	204875.056	555549.175

[VERTICES]

;;Link	X-Coord	Y-Coord
;;		

Appendix B

Input file for example 2

[TITLE]

[OPTIONS]

FLOW_UNITS CMS
START_DATE 04/24/2007
START_TIME 12:00:00
END_DATE 04/26/2007
END_TIME 12:00:00
MAX_TIME_STEP 1
REPORT_START_DATE 04/24/2007
REPORT_START_TIME 12:00:00
REPORT_STEP 00:01:00
MIN_NUM_GRIDS 16
PRESSURIZED_WAVE_CELERITY 100
MIXED_FLOW_WAVE_CELERITY 100
REF_DEPTH_FRACTION 0.95
MAX_NUM_ITERATIONS 200
MAX_NUM_CELLS 5000
MAX_NUM_PLOT_CELLS 10
ITM_TOL_NORMAL 0.000001
ITM_TOL_LOW 0.0001
ITM_TOL_VERY_LOW 0.0001
ITM_TOL_HIGH 0.00000000000001
ITM_TOL_TRANSITION 0.0001
ITM_FLOW_TYPE MIXED-FLOW

[JUNCTIONS]

;;	Invert	Max.	Init.		Boundary	Boundary
;;Name	Elev.	Depth	Depth	Area	Condition	Open/Closed
;;	-----	-----	-----	-----	-----	-----
;;S2						
S2	-94.064	94.064	0.10	200	JUNCTION	OPEN
;;S3						
S3	-41.882568	41.882568	0.10	200	DROPSHAFT	OPEN
;;S1						
S1	-42.699432	42.699432	0.10	200	DROPSHAFT	OPEN
C1	-97.630488	97.630488	0.10	200	JUNCTION	OPEN
N1	-99.050856	99.050856	0.10	200	DROPSHAFT	OPEN
W3	-68.573904	68.573904	0.10	200	JUNCTION	OPEN
E3	-93.076776	93.076776	0.10	200	JUNCTION	OPEN
;;E2						
E2	-89.160096	89.160096	0.10	200	DROPSHAFT	OPEN
;;E1						
E1	-80.878680	80.878680	0.10	200	DROPSHAFT	OPEN
W1	-36.2712	36.2712	0.10	200	JUNCTION	CLOSED
W2	-46.9636	46.9636	0.10	200	JUNCTION	CLOSED

[STORAGE]

;;	Invert	Max.	Init.	Shape	Shape	Constant
;;Name	Elev.	Depth	Depth	Curve	Params	Outflow
;;	-----	-----	-----	-----	-----	-----
;;Thornton Reservoir						
THORNTON	-90.678	89.154	0.10	TABULAR	THORNTON	0

[CONDUITS]

;;	Inlet	Outlet		Manning	Inlet	Outlet	Init.	Initial	Initial
----	-------	--------	--	---------	-------	--------	-------	---------	---------

;;Name	Node	Node	Length	N	Offset	Offset	Flow	Depth type	Depth
1	W1	W3	9105	0.015	0	0	0	CONSTANT	0.10
2	W2	W3	7298	0.015	0	0	0	CONSTANT	0.10
3	W3	C1	9704	0.015	0	0	0	CONSTANT	0.10
4	C1	N1	2762.4505	0.015	0	0	0	CONSTANT	0.10
5	S1	S2	5862	0.015	0	36.661039	0	CONSTANT	0.10
6	S3	S2	6182	0.015	0	36.661039	0	CONSTANT	0.10
7	E3	C1	4806	0.015	0	0	0	CONSTANT	0.10
8	E2	E3	3396	0.015	0	0	0	CONSTANT	0.10
9	E1	E3	10509	0.015	0	0	0	CONSTANT	0.10
10	THORNTON	S2	2404	0.015	0	0	0	CONSTANT	0.10
11	S2	C1	4046	0.015	0	0	0	CONSTANT	0.10

[XSECTIONS]

;;Link	Shape	Diameter
1	CIRCULAR	2.4
2	CIRCULAR	3.6
3	CIRCULAR	6.4
4	CIRCULAR	6.447
5	CIRCULAR	4.87
6	CIRCULAR	4.87
7	CIRCULAR	9.19
8	CIRCULAR	4.62
9	CIRCULAR	7.62
10	CIRCULAR	9.14
11	CIRCULAR	9.14

[LOSSES]

;;Link	Inlet	Outlet
1	0.5	0.5
2	0.5	0.5
3	0.5	0.5
4	0.5	0.5
5	0.5	0.5
6	0.5	0.5
7	0.5	0.5
8	0.5	0.5
9	0.5	0.5
10	0.5	0.5
11	0.5	0.5

[INFLOWS]

;;	Param	Units	Scale	Baseline		
;;Node	Parameter	Time Series	Type	Factor	Factor	Value
S2	FLOW	S2	FLOW	1.0	5.0	
S3	FLOW	S3	FLOW	1.0	5.0	
S1	FLOW	S1	FLOW	1.0	5.0	
C1	FLOW	C1	FLOW	1.0	5.0	
N1	FLOW	N1	FLOW	1.0	5.0	
W3	FLOW	W3	FLOW	1.0	5.0	
E3	FLOW	E3	FLOW	1.0	5.0	
E2	FLOW	E2	FLOW	1.0	5.0	

E1	FLOW	E1	FLOW	1.0	5.0
W2	FLOW	W2	FLOW	1.0	5.0

[CURVES]

;;Name	Type	X-Value	Y-Value
;;-----			
THORNTON	Storage	0	0
THORNTON		7.7724	2375593.003
THORNTON		15.3924	4659817.045
THORNTON		23.0124	6944041.087
THORNTON		30.6324	9228265.128
THORNTON		38.2524	11512489.17
THORNTON		45.8724	13796713.21
THORNTON		53.4924	16080937.25
THORNTON		61.1124	18365161.3
THORNTON		68.7324	20649385.34
THORNTON		76.3524	22933609.38
THORNTON		83.6676	25126464.46
THORNTON		89.154	26725421.29

[TIMESERIES]

;;Name	Date	Time	Value
;;-----			
W2	04/24/2007	12:05	0
W2	04/24/2007	12:10	0
W2	04/24/2007	12:15	0
W2	04/24/2007	12:20	0
W2	04/24/2007	12:25	0
W2	04/24/2007	12:30	0
W2	04/24/2007	12:35	0
W2	04/24/2007	12:40	0
W2	04/24/2007	12:45	0
W2	04/24/2007	12:50	0
W2	04/24/2007	12:55	0
W2	04/24/2007	13:00	0
W2	04/24/2007	13:05	0
W2	04/24/2007	13:10	0
W2	04/24/2007	13:15	0
W2	04/24/2007	13:20	0
W2	04/24/2007	13:25	0
W2	04/24/2007	13:30	0
W2	04/24/2007	13:35	0
W2	04/24/2007	13:40	0
W2	04/24/2007	13:45	0
W2	04/24/2007	13:50	0
W2	04/24/2007	13:55	0
W2	04/24/2007	14:00	0
W2	04/24/2007	14:05	0
W2	04/24/2007	14:10	0
W2	04/24/2007	14:15	0
W2	04/24/2007	14:20	0
W2	04/24/2007	14:25	0
W2	04/24/2007	14:30	0
W2	04/24/2007	14:35	0
W2	04/24/2007	14:40	0
W2	04/24/2007	14:45	0

W2	04/24/2007 14:50	0
W2	04/24/2007 14:55	0
W2	04/24/2007 15:00	0
W2	04/24/2007 15:05	0
W2	04/24/2007 15:10	0
W2	04/24/2007 15:15	0
W2	04/24/2007 15:20	0
W2	04/24/2007 15:25	0
W2	04/24/2007 15:30	0
W2	04/24/2007 15:35	0
W2	04/24/2007 15:40	0
W2	04/24/2007 15:45	0
W2	04/24/2007 15:50	0
W2	04/24/2007 15:55	0
W2	04/24/2007 16:00	0
W2	04/24/2007 16:05	0
W2	04/24/2007 16:10	0
W2	04/24/2007 16:15	0
W2	04/24/2007 16:20	0
W2	04/24/2007 16:25	0
W2	04/24/2007 16:30	0
W2	04/24/2007 16:35	0
W2	04/24/2007 16:40	0
W2	04/24/2007 16:45	0
W2	04/24/2007 16:50	0
W2	04/24/2007 16:55	0
W2	04/24/2007 17:00	0
W2	04/24/2007 17:05	0
W2	04/24/2007 17:10	0
W2	04/24/2007 17:15	0
W2	04/24/2007 17:20	0
W2	04/24/2007 17:25	0
W2	04/24/2007 17:30	0
W2	04/24/2007 17:35	0
W2	04/24/2007 17:40	0
W2	04/24/2007 17:45	0
W2	04/24/2007 17:50	0
W2	04/24/2007 17:55	0
W2	04/24/2007 18:00	0
W2	04/24/2007 18:05	0
W2	04/24/2007 18:10	0
W2	04/24/2007 18:15	0
W2	04/24/2007 18:20	0
W2	04/24/2007 18:25	0
W2	04/24/2007 18:30	0
W2	04/24/2007 18:35	0
W2	04/24/2007 18:40	0
W2	04/24/2007 18:45	0
W2	04/24/2007 18:50	0
W2	04/24/2007 18:55	0
W2	04/24/2007 19:00	0
W2	04/24/2007 19:05	0
W2	04/24/2007 19:10	0
W2	04/24/2007 19:15	0
W2	04/24/2007 19:20	0
W2	04/24/2007 19:25	0

W2	04/24/2007 19:30	0
W2	04/24/2007 19:35	0
W2	04/24/2007 19:40	0
W2	04/24/2007 19:45	0
W2	04/24/2007 19:50	0
W2	04/24/2007 19:55	0
W2	04/24/2007 20:00	0
W2	04/24/2007 20:05	0
W2	04/24/2007 20:10	0
W2	04/24/2007 20:15	0
W2	04/24/2007 20:20	0
W2	04/24/2007 20:25	0
W2	04/24/2007 20:30	0
W2	04/24/2007 20:35	0
W2	04/24/2007 20:40	0
W2	04/24/2007 20:45	0
W2	04/24/2007 20:50	0
W2	04/24/2007 20:55	0
W2	04/24/2007 21:00	0
W2	04/24/2007 21:05	0
W2	04/24/2007 21:10	5.66337E-05
W2	04/24/2007 21:15	0.000169901
W2	04/24/2007 21:20	0.000424753
W2	04/24/2007 21:25	0.000821189
W2	04/24/2007 21:30	0.001415842
W2	04/24/2007 21:35	0.002038813
W2	04/24/2007 21:40	0.002718417
W2	04/24/2007 21:45	0.003426338
W2	04/24/2007 21:50	0.004190893
W2	04/24/2007 21:55	0.004955448
W2	04/24/2007 22:00	0.005776637
W2	04/24/2007 22:05	0.009571094
W2	04/24/2007 22:10	0.0235313
W2	04/24/2007 22:15	0.042277052
W2	04/24/2007 22:20	0.063146568
W2	04/24/2007 22:25	0.086961036
W2	04/24/2007 22:30	0.112701049
W2	04/24/2007 22:35	0.140989579
W2	04/24/2007 22:40	0.171260288
W2	04/24/2007 22:45	0.20303179
W2	04/24/2007 22:50	0.236105867
W2	04/24/2007 22:55	0.270482519
W2	04/24/2007 23:00	0.30585026
W2	04/24/2007 23:05	0.308087291
W2	04/24/2007 23:10	0.308880163
W2	04/24/2007 23:15	0.309616401
W2	04/24/2007 23:20	0.310409272
W2	04/24/2007 23:25	0.311032243
W2	04/24/2007 23:30	0.311796798
W2	04/24/2007 23:35	0.312476402
W2	04/24/2007 23:40	0.313184323
W2	04/24/2007 23:45	0.313807294
W2	04/24/2007 23:50	0.314458581
W2	04/24/2007 23:55	0.315081552
W2	04/25/2007 0:00	0.315789473
W2	04/25/2007 0:05	0.354923355

W2	04/25/2007 0:10	0.397653477
W2	04/25/2007 0:15	0.440610133
W2	04/25/2007 0:20	0.483821641
W2	04/25/2007 0:25	0.526976515
W2	04/25/2007 0:30	0.570867627
W2	04/25/2007 0:35	0.61951597
W2	04/25/2007 0:40	0.672326889
W2	04/25/2007 0:45	0.72816771
W2	04/25/2007 0:50	0.786415464
W2	04/25/2007 0:55	0.846617079
W2	04/25/2007 1:00	0.908489389
W2	04/25/2007 1:05	1.120157817
W2	04/25/2007 1:10	1.358557349
W2	04/25/2007 1:15	1.617090158
W2	04/25/2007 1:20	1.888960202
W2	04/25/2007 1:25	2.169353617
W2	04/25/2007 1:30	2.454447629
W2	04/25/2007 1:35	2.741014116
W2	04/25/2007 1:40	3.027297435
W2	04/25/2007 1:45	3.31137204
W2	04/25/2007 1:50	3.592105258
W2	04/25/2007 1:55	3.868364413
W2	04/25/2007 2:00	4.139413269
W2	04/25/2007 2:05	4.399758356
W2	04/25/2007 2:10	4.654015322
W2	04/25/2007 2:15	4.901929314
W2	04/25/2007 2:20	5.143103896
W2	04/25/2007 2:25	5.377340851
W2	04/25/2007 2:30	5.604753446
W2	04/25/2007 2:35	5.824860295
W2	04/25/2007 2:40	6.038057833
W2	04/25/2007 2:45	6.244062891
W2	04/25/2007 2:50	6.443017056
W2	04/25/2007 2:55	6.63514686
W2	04/25/2007 3:00	6.820537254
W2	04/25/2007 3:05	7.263299468
W2	04/25/2007 3:10	7.693205833
W2	04/25/2007 3:15	8.104508029
W2	04/25/2007 3:20	8.497715761
W2	04/25/2007 3:25	8.873565266
W2	04/25/2007 3:30	9.23253793
W2	04/25/2007 3:35	9.575454942
W2	04/25/2007 3:40	9.90288264
W2	04/25/2007 3:45	10.21547231
W2	04/25/2007 3:50	10.51390356
W2	04/25/2007 3:55	10.79894093
W2	04/25/2007 4:00	11.0711791
W2	04/25/2007 4:05	11.49525219
W2	04/25/2007 4:10	11.89703993
W2	04/25/2007 4:15	12.27441854
W2	04/25/2007 4:20	12.62942685
W2	04/25/2007 4:25	12.96410366
W2	04/25/2007 4:30	13.28011967
W2	04/25/2007 4:35	13.57908893
W2	04/25/2007 4:40	13.8624273
W2	04/25/2007 4:45	14.13140902

W2	04/25/2007 4:50	14.38708183
W2	04/25/2007 4:55	14.63060671
W2	04/25/2007 5:00	14.86252169
W2	04/25/2007 5:05	14.67203426
W2	04/25/2007 5:10	14.50757001
W2	04/25/2007 5:15	14.37037489
W2	04/25/2007 5:20	14.25532355
W2	04/25/2007 5:25	14.1587631
W2	04/25/2007 5:30	14.07794682
W2	04/25/2007 5:35	14.01069431
W2	04/25/2007 5:40	13.95516497
W2	04/25/2007 5:45	13.9098297
W2	04/25/2007 5:50	13.87372572
W2	04/25/2007 5:55	13.84569204
W2	04/25/2007 6:00	13.82442609
W2	04/25/2007 6:05	13.01125121
W2	04/25/2007 6:10	12.2783829
W2	04/25/2007 6:15	11.62417879
W2	04/25/2007 6:20	11.03598126
W2	04/25/2007 6:25	10.50444573
W2	04/25/2007 6:30	10.0218134
W2	04/25/2007 6:35	9.582166035
W2	04/25/2007 6:40	9.179953546
W2	04/25/2007 6:45	8.811183253
W2	04/25/2007 6:50	8.471947431
W2	04/25/2007 6:55	8.159357761
W2	04/25/2007 7:00	7.870299391
W2	04/25/2007 7:05	7.559012297
W2	04/25/2007 7:10	7.270095511
W2	04/25/2007 7:15	7.002104875
W2	04/25/2007 7:20	6.753199793
W2	04/25/2007 7:25	6.521567988
W2	04/25/2007 7:30	6.305567082
W2	04/25/2007 7:35	6.1037246
W2	04/25/2007 7:40	5.914936184
W2	04/25/2007 7:45	5.737927575
W2	04/25/2007 7:50	5.57176432
W2	04/25/2007 7:55	5.41542701
W2	04/25/2007 8:00	5.268405942
W2	04/25/2007 8:05	5.130559533
W2	04/25/2007 8:10	5.000330355
W2	04/25/2007 8:15	4.87726534
W2	04/25/2007 8:20	4.760854784
W2	04/25/2007 8:25	4.650532349
W2	04/25/2007 8:30	4.545844968
W2	04/25/2007 8:35	4.44650947
W2	04/25/2007 8:40	4.351931202
W2	04/25/2007 8:45	4.262053531
W2	04/25/2007 8:50	4.176423387
W2	04/25/2007 8:55	4.094672651
W2	04/25/2007 9:00	4.016688055
W2	04/25/2007 9:05	3.956684657
W2	04/25/2007 9:10	3.899626212
W2	04/25/2007 9:15	3.844748163
W2	04/25/2007 9:20	3.792022195
W2	04/25/2007 9:25	3.741278405

W2	04/25/2007 9:30	3.692488479
W2	04/25/2007 9:35	3.645397563
W2	04/25/2007 9:40	3.600062291
W2	04/25/2007 9:45	3.556284447
W2	04/25/2007 9:50	3.514092345
W2	04/25/2007 9:55	3.473202819
W2	04/25/2007 10:00	3.433785768
W2	04/25/2007 10:05	3.387147922
W2	04/25/2007 10:10	3.341897601
W2	04/25/2007 10:15	3.298233024
W2	04/25/2007 10:20	3.256040922
W2	04/25/2007 10:25	3.215321297
W2	04/25/2007 10:30	3.17587593
W2	04/25/2007 10:35	3.13770482
W2	04/25/2007 10:40	3.100723019
W2	04/25/2007 10:45	3.064902208
W2	04/25/2007 10:50	3.030185754
W2	04/25/2007 10:55	2.996517023
W2	04/25/2007 11:00	2.963697798
W2	04/25/2007 11:05	2.929349463
W2	04/25/2007 11:10	2.89587895
W2	04/25/2007 11:15	2.863342894
W2	04/25/2007 11:20	2.83185456
W2	04/25/2007 11:25	2.801130782
W2	04/25/2007 11:30	2.771284825
W2	04/25/2007 11:35	2.742260058
W2	04/25/2007 11:40	2.713999845
W2	04/25/2007 11:45	2.686447553
W2	04/25/2007 11:50	2.659631499
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S2	04/25/2007 22:20	0.011298422
S2	04/25/2007 22:25	0.011185154
S2	04/25/2007 22:30	0.01104357
S2	04/25/2007 22:35	0.010930303
S2	04/25/2007 22:40	0.010817035
S2	04/25/2007 22:45	0.010703768
S2	04/25/2007 22:50	0.010590501
S2	04/25/2007 22:55	0.010448916
S2	04/25/2007 23:00	0.010363966
S2	04/25/2007 23:05	0.010250698
S2	04/25/2007 23:10	0.010137431
S2	04/25/2007 23:15	0.010024164
S2	04/25/2007 23:20	0.009910896
S2	04/25/2007 23:25	0.009797629
S2	04/25/2007 23:30	0.009712678
S2	04/25/2007 23:35	0.009599411
S2	04/25/2007 23:40	0.00951446
S2	04/25/2007 23:45	0.009401193
S2	04/25/2007 23:50	0.009316243
S2	04/25/2007 23:55	0.009202975
S2	04/26/2007 0:00	0.009118025
S2	04/26/2007 0:05	0.009033074
S2	04/26/2007 0:10	0.008948124
S2	04/26/2007 0:15	0.008834856
S2	04/26/2007 0:20	0.008749906
S2	04/26/2007 0:25	0.008664955
S2	04/26/2007 0:30	0.008580005
S2	04/26/2007 0:35	0.008495054
S2	04/26/2007 0:40	0.008410103

S2	04/26/2007 0:45	0.008325153
S2	04/26/2007 0:50	0.008240202
S2	04/26/2007 0:55	0.008155252
S2	04/26/2007 1:00	0.008098618
S2	04/26/2007 1:05	0.008013668
S2	04/26/2007 1:10	0.007928717
S2	04/26/2007 1:15	0.007843767
S2	04/26/2007 1:20	0.007787133
S2	04/26/2007 1:25	0.007702182
S2	04/26/2007 1:30	0.007617232
S2	04/26/2007 1:35	0.007560598
S2	04/26/2007 1:40	0.007475648
S2	04/26/2007 1:45	0.007419014
S2	04/26/2007 1:50	0.007334063
S2	04/26/2007 1:55	0.00727743
S2	04/26/2007 2:00	0.007220796
S2	04/26/2007 2:05	0.007135845
S2	04/26/2007 2:10	0.007079212
S2	04/26/2007 2:15	0.007022578
S2	04/26/2007 2:20	0.006937627
S2	04/26/2007 2:25	0.006880994
S2	04/26/2007 2:30	0.00682436
S2	04/26/2007 2:35	0.006767726
S2	04/26/2007 2:40	0.006682776
S2	04/26/2007 2:45	0.006626142
S2	04/26/2007 2:50	0.006569508
S2	04/26/2007 2:55	0.006512875
S2	04/26/2007 3:00	0.006456241
S2	04/26/2007 3:05	0.006399607
S2	04/26/2007 3:10	0.006342974
S2	04/26/2007 3:15	0.00628634
S2	04/26/2007 3:20	0.006229706
S2	04/26/2007 3:25	0.006173073
S2	04/26/2007 3:30	0.006116439
S2	04/26/2007 3:35	0.006059805
S2	04/26/2007 3:40	0.006031488
S2	04/26/2007 3:45	0.005974855
S2	04/26/2007 3:50	0.005918221
S2	04/26/2007 3:55	0.005861587
S2	04/26/2007 4:00	0.005804954
S2	04/26/2007 4:05	0.005776637
S2	04/26/2007 4:10	0.005720003
S2	04/26/2007 4:15	0.005663369
S2	04/26/2007 4:20	0.005606736
S2	04/26/2007 4:25	0.005578419
S2	04/26/2007 4:30	0.005521785
S2	04/26/2007 4:35	0.005465151
S2	04/26/2007 4:40	0.005436835
S2	04/26/2007 4:45	0.005380201
S2	04/26/2007 4:50	0.005351884
S2	04/26/2007 4:55	0.00529525
S2	04/26/2007 5:00	0.005266933
S2	04/26/2007 5:05	0.0052103
S2	04/26/2007 5:10	0.005181983
S2	04/26/2007 5:15	0.005125349
S2	04/26/2007 5:20	0.005097032

S2	04/26/2007 5:25	0.005040399
S2	04/26/2007 5:30	0.005012082
S2	04/26/2007 5:35	0.004955448
S2	04/26/2007 5:40	0.004927131
S2	04/26/2007 5:45	0.004898814
S2	04/26/2007 5:50	0.004842181
S2	04/26/2007 5:55	0.004813864
S2	04/26/2007 6:00	0.00475723
S2	04/26/2007 6:05	0.004728913
S2	04/26/2007 6:10	0.004700597
S2	04/26/2007 6:15	0.00467228
S2	04/26/2007 6:20	0.004615646
S2	04/26/2007 6:25	0.004587329
S2	04/26/2007 6:30	0.004559012
S2	04/26/2007 6:35	0.004502379
S2	04/26/2007 6:40	0.004474062
S2	04/26/2007 6:45	0.004445745
S2	04/26/2007 6:50	0.004417428
S2	04/26/2007 6:55	0.004389111
S2	04/26/2007 7:00	0.004332478
S2	04/26/2007 7:05	0.004304161
S2	04/26/2007 7:10	0.004275844
S2	04/26/2007 7:15	0.004247527
S2	04/26/2007 7:20	0.00421921
S2	04/26/2007 7:25	0.004190893
S2	04/26/2007 7:30	0.004162576
S2	04/26/2007 7:35	0.00413426
S2	04/26/2007 7:40	0.004077626
S2	04/26/2007 7:45	0.004049309
S2	04/26/2007 7:50	0.004020992
S2	04/26/2007 7:55	0.003992675
S2	04/26/2007 8:00	0.003964359
S2	04/26/2007 8:05	0.003936042
S2	04/26/2007 8:10	0.003907725
S2	04/26/2007 8:15	0.003879408
S2	04/26/2007 8:20	0.003851091
S2	04/26/2007 8:25	0.003822774
S2	04/26/2007 8:30	0.003794457
S2	04/26/2007 8:35	0.003766141
S2	04/26/2007 8:40	0.003737824
S2	04/26/2007 8:45	0.003709507
S2	04/26/2007 8:50	0.00368119
S2	04/26/2007 8:55	0.003652873
S2	04/26/2007 9:00	0.003652873
S2	04/26/2007 9:05	0.003624556
S2	04/26/2007 9:10	0.00359624
S2	04/26/2007 9:15	0.003567923
S2	04/26/2007 9:20	0.003539606
S2	04/26/2007 9:25	0.003511289
S2	04/26/2007 9:30	0.003482972
S2	04/26/2007 9:35	0.003454655
S2	04/26/2007 9:40	0.003454655
S2	04/26/2007 9:45	0.003426338
S2	04/26/2007 9:50	0.003398022
S2	04/26/2007 9:55	0.003369705
S2	04/26/2007 10:00	0.003341388

S2	04/26/2007 10:05	0.003313071
S2	04/26/2007 10:10	0.003313071
S2	04/26/2007 10:15	0.003284754
S2	04/26/2007 10:20	0.003256437
S2	04/26/2007 10:25	0.003228121
S2	04/26/2007 10:30	0.003199804
S2	04/26/2007 10:35	0.003199804
S2	04/26/2007 10:40	0.003171487
S2	04/26/2007 10:45	0.00314317
S2	04/26/2007 10:50	0.003114853
S2	04/26/2007 10:55	0.003114853
S2	04/26/2007 11:00	0.003086536
S2	04/26/2007 11:05	0.003058219
S2	04/26/2007 11:10	0.003058219
S2	04/26/2007 11:15	0.003029903
S2	04/26/2007 11:20	0.003001586
S2	04/26/2007 11:25	0.002973269
S2	04/26/2007 11:30	0.002973269
S2	04/26/2007 11:35	0.002944952
S2	04/26/2007 11:40	0.002916635
S2	04/26/2007 11:45	0.002916635
S2	04/26/2007 11:50	0.002888318
S2	04/26/2007 11:55	0.002860002
S2	04/26/2007 12:00	0.002860002

[TAGS]

Node	S2	38/DropShaftLocation
Node	S3	59/DeepTunnelInterfaceLocation
Node	S1	33/DeepTunnelInterfaceLocation
Node	C1	231/TARP_Net_Junctions
Node	N1	442/TARP_Net_Junctions
Node	W3	335/TARP_Net_Junctions
Node	E3	244/TARP_Net_Junctions
Node	E2	55/DeepTunnelInterfaceLocation
Node	E1	67/DeepTunnelInterfaceLocation
Node	THORNTON	1/TARPJunction

[MAP]

DIMENSIONS 194127.569 545538.065 219766.953 563488.622
Units None

[COORDINATES]

;;Node	X-Coord	Y-Coord
;;-----		
S2	212095.285	548755.500
S3	218492.924	547020.291
S1	208438.053	552013.766
C1	212374.285	552576.394
N1	212492.073	555279.318
W3	203578.075	553686.147
E3	216596.112	552668.080
E2	218601.527	550933.876
E1	218361.769	562419.094
W1	195293.983	556772.142
W2	204950.968	559577.706
THORNTON	212323.680	546354.000

[VERTICES]

;;Link	X-Coord	Y-Coord
;;-----		
1	198354.251	556019.164
1	199652.965	555501.060
1	201580.311	554126.357
1	202284.933	553739.506
1	202927.382	553552.989
1	203390.221	553490.817
2	204949.081	559199.320
2	203602.489	559190.160
3	203848.176	553574.157
3	207270.460	553680.865
3	208322.298	554122.942
3	210494.572	554176.296
4	212503.742	552683.762
4	212518.838	552925.289
4	212438.329	555083.939
5	209669.265	551183.700
5	210089.421	551178.313
5	210940.508	550456.505
5	211274.479	549853.203
5	211908.305	548898.486
5	211974.298	548810.495
6	218183.152	547199.162
6	218058.040	547210.161
6	217932.928	547221.160
6	217682.704	547243.158
6	217209.753	547430.138
6	214894.494	548739.002
6	214630.521	548810.495
6	214416.044	548788.497
6	214047.582	548667.510
6	213750.613	548711.505
6	213387.651	548771.999
7	216461.821	552354.287
7	216260.600	552110.383
7	215797.181	552140.871
7	215431.325	552512.825
7	215169.128	552555.509
8	218303.300	552000.626
8	218187.445	552159.164
8	217724.027	552695.754
8	217522.805	552872.584
8	217364.268	552951.853
8	217181.339	553000.634
8	216955.728	552964.049
8	216754.506	552903.072
9	217993.842	562057.199
9	217741.864	561763.225
9	217741.864	561175.276
9	217405.893	559943.384
9	217167.914	559579.416
9	216845.943	559257.444
9	216873.940	555491.774

9	216873.940	555071.811
9	216789.947	554637.849
9	216565.967	554161.890
9	216146.004	553699.931
9	216048.012	553279.968
9	216160.003	552957.996
10	212103.326	546730.541
11	212074.876	552316.052