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I, Sheeba Rose Mary Susai Manickam, hereby submit this original work as part of the requirements for the degree of Master of Science in Environmental Engineering.

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Dimensionless Design Charts for Exfiltration in Storm Sewers

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Dimensionless Design Charts for Exfiltration in Storm Sewers

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ABSTRACT

The effectiveness of controlled partial exfiltration of storm water from sewers is evaluated as an option for managing urban runoff. Steady and unsteady exfiltration from storm sewers is simulated using a modified version of the USEPA Storm Water Management Model (SWMM) program. Exfiltration is represented in SWMM as a distributed sink term in the St. Venant equations for one-dimensional, gradually varied, unsteady flow. The sink term is modeled as an orifice with discharge coefficient dependent on the velocity head in the pipe. The spatial variation of exfiltration rate along the pipe length is also considered in the model. SWMM simulations indicate that exfiltrating sewers can provide significant reductions in the peak flow and runoff volume. Dimensionless charts are developed to offer a quick design aid to determine the expected performance of an exfiltrating sewer under a wide variety of rainfall loadings and soil conditions. A simple step-wise solution is presented to determine the water surface profile in a perforated pipe. This simplified approach facilitates the determination of exfiltration losses from the pipe under steady state conditions. A life-cycle cost analysis reveals there are economic benefits associated with selecting an exfiltrating storm sewer system over a conventional storm drainage system.

Key words: Exfiltration; perforated pipe; storm water management; dimensionless charts; SWMM
To my Mom..
I wish to express my sincere gratitude to my advisor, Dr. Steven Buchberger for his constant motivation and support which helped in the successful completion of this research. This research would not have been possible but for the guidance and unwavering support provided by him.

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# TABLE OF CONTENTS

ABSTRACT .......................................................................................................................... ii

ACKNOWLEDGMENTS ....................................................................................................... v

TABLE OF CONTENTS .................................................................................................... vi

List of Symbols .................................................................................................................. viii

List of Figures .................................................................................................................... x

List of Tables: ................................................................................................................... xiii

CHAPTER 1 ........................................................................................................................ 1

1.1. INTRODUCTION ...................................................................................................... 1

1.2. OBJECTIVES .......................................................................................................... 3

CHAPTER 2 ........................................................................................................................ 4

2.1. SWMM EXFILTRATION MODEL ............................................................................. 4

2.1.1. Flow in the perforated pipe ............................................................................. 4

2.1.2. Flow through the perforations into the trench .............................................. 6

2.1.3. Flow from trench into native soil ................................................................. 7

2.1.4. Simulating flow through a circular cross section perforated pipe .......... 8

The modified portions of the SWMM source code are shown in Appendix.

CHAPTER 3 ....................................................................................................................... 9

3.1. STEADY AND UNSTEADY STATE ANALYSIS ................................................. 10

3.2. DIMENSIONLESS DESIGN CHARTS ................................................................. 13

3.3. LIFE CYCLE COST ANALYSIS ............................................................................. 15

CHAPTER 4 ....................................................................................................................... 20

4.1. RESULTS - HYDRAULICS .................................................................................. 20

4.1.1. Steady Flow ..................................................................................................... 20
4.1.2. Unsteady Flow ................................................................. 29

4.1.3. Computational method to predict the breakpoint on the dimensionless chart under steady state conditions: .......................................................... 37

4.2. RESULTS - Life-Cycle Cost Analysis ................................................................. 42

CHAPTER 5 ............................................................................................................ 50

5.1. CONCLUSION ............................................................................................... 50

5.2. RECOMMENDATIONS .................................................................................. 50

References ........................................................................................................... 51

APPENDIX ............................................................................................................ 57

MODIFIED SWMM SOURCE CODE ................................................................. 57
## List of Symbols

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross-sectional flow area in the conduit (m²)</td>
</tr>
<tr>
<td>A_b</td>
<td>Bottom area of trench (m²)</td>
</tr>
<tr>
<td>A_p</td>
<td>Area of a single perforation (m²)</td>
</tr>
<tr>
<td>C</td>
<td>Construction cost ($)</td>
</tr>
<tr>
<td>C_d</td>
<td>Coefficient of discharge</td>
</tr>
<tr>
<td>cms</td>
<td>Cubic meters per second</td>
</tr>
<tr>
<td>E_i</td>
<td>Specific energy head at upstream end of section i (m)</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity (m/s²)</td>
</tr>
<tr>
<td>Δh</td>
<td>Depth of water above the center of orifices (m)</td>
</tr>
<tr>
<td>H</td>
<td>Hydraulic head of water in the conduit (m)</td>
</tr>
<tr>
<td>h_f</td>
<td>Head loss due to friction (m)</td>
</tr>
<tr>
<td>h_m</td>
<td>Minor losses (m)</td>
</tr>
<tr>
<td>I</td>
<td>Infiltration rate of the native soil (m³/s)</td>
</tr>
<tr>
<td>K</td>
<td>Saturated hydraulic conductivity (m/s)</td>
</tr>
<tr>
<td>L</td>
<td>Length of conduit or trench (m)</td>
</tr>
<tr>
<td>n</td>
<td>Manning’s roughness coefficient</td>
</tr>
<tr>
<td>N_p</td>
<td>Number of perforations in the conduit (per unit length?)</td>
</tr>
<tr>
<td>N_Li</td>
<td>Number of perforations in one row of the pipe section</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and maintenance costs ($)</td>
</tr>
<tr>
<td>Q</td>
<td>Flow rate in the conduit (m³/s)</td>
</tr>
<tr>
<td>q</td>
<td>Exfiltration rate per unit length of the conduit (cms/m)</td>
</tr>
<tr>
<td>q_i</td>
<td>Exfiltration rate from the conduit section (m³/s)</td>
</tr>
<tr>
<td>Q(t)</td>
<td>Inflow rate at time t, (m³/s)</td>
</tr>
<tr>
<td>S_f</td>
<td>Friction slope</td>
</tr>
<tr>
<td>t</td>
<td>Time step (s)</td>
</tr>
</tbody>
</table>
V \quad \text{Flow velocity (m/s)} \\
V_d \quad \text{Volume of detention basin (m}^3\text{)} \\
V_h \quad \text{Velocity head (m)} \\
V_t \quad \text{Volume of infiltration trench (m}^3\text{)} \\
x \quad \text{Distance along the conduit (m)} \\
\Delta x \quad \text{Length of a pipe section (m)} \\
Y_i, Y_{i+1} \quad \text{Depth of flow in the pipe at section } i \text{ and } i+1 \text{ respectively (m)} \\
\Delta y_i \quad \text{Difference in water surface elevation inside and outside the pipe (m)} \\
Z_i, Z_{i+1} \quad \text{Elevation of the pipe from the datum at section } i \text{ and } i+1 \text{ respectively (m)} \\

\textbf{List of Acronyms} \\
BMP \quad \text{Best Management Practice} \\
ENR \quad \text{Engineering News Record} \\
EPA \quad \text{Environmental Protection Agency} \\
HDPE \quad \text{High Density Poly-Ethylene} \\
LCC \quad \text{Life-Cycle Cost ($)} \\
LCCA \quad \text{Life Cycle Cost Analysis} \\
NOAA \quad \text{National Oceanic and Atmospheric Administration} \\
NRCS \quad \text{National Resources and Conservation Service} \\
OMB \quad \text{Office of Management and Budget} \\
SWMM \quad \text{Storm Water Management Model}
List of Figures

Figure 1: Elevation and cross-sectional view of exfiltration system ........................................ 3

Figure 2: Discharge coefficient as function of the ratio of velocity head to total energy head in a pipe of size 0.305m .................................................................................................................................................. 7

Figure 3: Flow out of and into the perforated pipe based on the depth of water in the trench ........ 8

Figure 4: Orientation of perforations around the circumference of a circular pipe .................... 9

Figure 5: Inflow hydrograph under steady flow conditions of total inflow volume of 1728 m³ .. 10

Figure 6: Inflow hydrograph case 1 under unsteady flow conditions of total inflow volume 1728 m³ .................................................................................................................................................................................. 11

Figure 7: Inflow hydrograph case 2 under unsteady flow conditions of total inflow volume 1728 m³ .................................................................................................................................................................................. 11

Figure 8: Inflow hydrograph of 10-year 24-hour storm event for Cincinnati ............................ 12

Figure 9: Inflow and potential infiltration hydrographs for a 0.2% perforated pipe with K = 11.9 cm/hr .................................................................................................................................................................................. 13

Figure 10: Inflow and outflow hydrographs for a 0.2% perforated pipe with K = 11.9 cm/hr (Y=0.25) .................................................................................................................................................................................. 14

Figure 11: Definition sketch of a conventional storm sewer system with detention basin at outfall .................................................................................................................................................................................. 16

Figure 12: Definition sketch of an exfiltration system with a detention basin at outfall ............ 16

Figure 13: Dimensionless design chart for a square pipe of size 0.305 m with total inflow volume of 1728 m³ under steady flow conditions .................................................................................................................................................................................. 20

Figure 14: Flow hydrographs showing potential infiltration rate of soil and actual exfiltration rate of pipe for different perforated area of pipe corresponding to X = 0.5 on the DC .......... 22

Figure 15: Flow hydrographs showing potential infiltration rate of soil and actual exfiltration rate of pipe for different perforated area corresponding to X=0.7 on the DC ......................... 22

Figure 16: Dimensionless design chart for a square pipe of size 0.2 m with total inflow volume of 1728 cubic meters under steady flow conditions .................................................................................................................................................................................. 24
Figure 17: Dimensionless chart for a pipe size of 0.305 m and total inflow volume of 864 cubic meters under steady flow conditions................................................................. 25

Figure 18: Dimensionless chart for pipe size of 0.2m and total inflow volume of 864 cubic meters under steady flow conditions........................................................................... 26

Figure 19: Dimensionless design chart for a square pipe of size 0.305 m with total inflow volume of 1728 cubic meters under unsteady flow conditions...................................................... 28

Figure 20: Comparison of exfiltration rate for two different K values for a 0.01% perforated area of a square pipe of size 0.305 m with total inflow volume of 1728 cubic meters ................. 30

Figure 21: Dimensionless chart of a pipe size of 0.305m for a total inflow volume of 864 cubic meters under unsteady flow conditions................................................................................... 31

Figure 22: Dimensionless design chart for a square pipe of size 0.2 m with total inflow volume of 864 cubic meters under unsteady flow conditions............................................................... 32

Figure 23: Inflow hydrograph with total duration of 12 hours and the corresponding dimensionless chart for a pipe size of 0.305 m.................................................................................. 33

Figure 24: Dimensionless design chart for a square pipe of size 0.305 m with total inflow volume of 1728 cubic meters under unsteady flow conditions for hydrograph case 2.................. 34

Figure 25: Flow hydrographs for different perforated area of the pipe corresponding to X=1.0 on the DC ................................................................................................................... 35

Figure 26: Dimensionless chart for 10 year 24 hour storm event for pipe size of 0.305m........ 36

Figure 27: Section of the perforated pipe showing the different components of energy equation37

Figure 28: Water surface profile computed using the computational procedure and SWMM Exfiltration model............................................................................................................. 40

Figure 29: Exfiltration rate computed using the computational procedure and SWMM Exfiltration model.................................................................................................................. 40

Figure 30: Water surface profile determined using the computational procedure and SWMM exfiltration model............................................................................................................. 41

Figure 31: Exfiltration rate determined using the computational procedure and SWMM exfiltration model.................................................................................................................. 41

Figure 32: Effect of trench width on the ratio of LCC of Conventional and Exfiltration system for different storm sizes on a drainage area of 1.2 hectares .................................................. 42
Figure 33: Life Cycle Cost Analysis of Conventional storm drainage system and Exfiltration system ................................................................. 46

Figure 34: Ratio of LCC of Conventional to Exfiltration system for different percentage of reduction in the total inflow volume for a drainage area of 0.405 hectare ........................................... 47

Figure 35: Ratio of LCC of Conventional to Exfiltration System for different percentage of reduction in the total inflow volume for a drainage area of 0.81 hectares.............................................. 48

Figure 36: Ratio of LCC of Conventional to Exfiltration system for different percentage of reduction in the total inflow volume for a drainage area of 1.2 hectares............................................ 48

Figure 37: Ratio of LCC of Conventional to Exfiltration system for different percentage of reduction in the total inflow volume for a drainage area of 2.03 hectares................................. 49
List of Tables:

Table 1: Summary of input parameters used in LCCA ......................................................... 43
Table 2: Summary of estimated Life Cycle Costs of the conventional storm drainage system ... 44
Table 3: Summary of estimated Life Cycle Costs of an exfiltration system ............................. 45
CHAPTER 1

1.1. INTRODUCTION

Urbanization has altered the natural hydrologic cycle. In undeveloped areas, most rainfall infiltrates into the ground surface or is evapotranspirated. Whereas in developed areas, the proliferation of impervious surfaces (roads, rooftops, parking lots and driveways) and the reduction in vegetation interferes with natural hydrologic processes like infiltration and evaporation resulting in large volumes of storm water runoff. As a consequence the natural hydrologic cycle has shifted from an infiltration based system to a runoff predominated system in many urban areas (Abi Aad et al., 2010). Impervious surfaces also accumulate a variety of pollutants such as metal elements, residues from tires and road salts which are subsequently carried by the storm water runoff to the receiving waters (Abida et al., 2006, Sansalone et al., 1997). Thus storm water runoff is a major source of pollution of surface waters, making the receiving water unfit for use. Moreover urban runoff is the chief factor causing combined sewer overflows in many cities. A major challenge facing water resources engineers and planners is to manage and control the quantity and quality of storm water runoff.

Traditionally storm water was conveyed through underground pipe systems. However this led to a number of problems such as overloading of pipe systems and downstream flooding (Vestergren, 2010). To control the quantity of water at the end of pipe during a storm event, flow control structures such as detention basins were used. However such basins just redistribute the rate of runoff overtime and do not reduce the total stormwater volume (Abida et al., 2007). Limitations of on-site detention facilities and conventional systems have led to infiltration of urban runoff as a recent goal of stormwater management (NRC, 2008). The final Phase II
Stormwater regulations given by USEPA (2000), requires municipalities to separate storm sewer systems in urbanized areas to implement stormwater management practices that can harvest, infiltrate and evapo-transpirate stormwater. These practices are known as Best Management Practices (BMPs). The BMPs are developed to mitigate the adverse impacts associated with any development activity to the maximum extent possible (USEPA 2004).

The minimum requirements of a BMP are as follows (USEPA 2004):

- Replicate the natural hydrologic conditions as close as possible
- Remove moderate to high levels of storm water pollutants
- Match site conditions, given the physical constraints
- Be cost-effective to construct and to maintain
- Have a neutral impact on the environment

Some examples of BMPs include: dry extended detention ponds, infiltration basins and trenches, grassed swales, wetlands and vegetative controls. Infiltration using basins or trenches is one of the popular methods to control runoff, as it not only reduces the runoff volume but also recharges groundwater (USEPA, 1999). Surface water quality control can also be achieved by using an infiltration trench (Duchene and McBean, 1992). However, insufficient space, high land values, restricted surface area and high costs associated with maintenance limit the use of infiltration trenches in most urban areas.

Storm sewer exfiltration has the potential to reduce the total runoff volume that exits an urban catchment (McCutcheon et al., 2010). An exfiltration system consists of a trench with a subsurface perforated pipe laid in a bed of filter media (Figure 1). A portion of the runoff is discharged into an infiltration trench through the perforations in the pipe. The runoff stored in the
trench eventually infiltrates into the surrounding soil. The perforated pipe promotes infiltration by the quick and even distribution of runoff over the length of the system (Duchene and McBean, 1992).

![Diagram of exfiltration system]

**Figure 1: Elevation and cross-sectional view of exfiltration system**

While the literature has devoted relatively little attention to exfiltration from municipal separate storm sewers, this study will demonstrate that storm sewer exfiltration has promise as an effective technique for reducing the volume of runoff leaving an urban catchment. In order to quantify the reduction achieved in runoff volume, the storm sewer exfiltration is simulated using a modified version of the USEPA Storm Water Management Model (SWMM).

1.2. **OBJECTIVES**

The main objectives of this study are to i) evaluate the performance of the exfiltration system under steady and unsteady flow conditions ii) develop dimensionless charts that would assist in the quick evaluation of design alternatives and iii) identify the economically favorable conditions for an exfiltration system.
CHAPTER 2

2.1. SWMM EXFILTRATION MODEL

SWMM, developed in 1971 by USEPA, is a public domain computer program (http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/) used for complex hydraulic analysis and simulation of spatial and temporal effects of a rainfall event. SWMM has a flexible set of hydraulic capabilities used to route runoff and external inflows through a drainage network of pipes, channels, storage, treatment units and diversion structures (Rossman, 2009). The latest version SWMM 5.0, released to the public in October 2004, includes a Microsoft windows interface and the computational engine written in C language. In this study, the SWMM source code was modified to incorporate exfiltration from storm sewers.

The modified SWMM model consists of three main components namely, the flow in the perforated pipe, the flow through the perforations into the trench and the flow from the trench into the native soil. The modeling process for the three components is sequentially described as follows.

2.1.1. Flow in the perforated pipe

Flow routing within a conduit link is governed by the St.Venant equations. McCutcheon et al., (2010) modified the SWMM source code to include the exfiltration term in the St.Venant’s equations. The St. Venant equations express conservation of mass and conservation of linear momentum in unsteady gradually varied free surface flow as described in Eqs (1) and (2):

\[ \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \]  

(1)
\[
\frac{\partial Q}{\partial t} + \frac{\partial \left( \frac{Q^2}{A} \right)}{\partial x} + gA \frac{\partial H}{\partial x} + gAS + gAh_m = 0
\]  

(2)

Here \( x \) is distance along the conduit, \( t \) is time, \( A \) is cross-sectional area of flow through the conduit, \( Q \) is flow rate, \( H \) is the hydraulic head (elevation head plus pressure head), \( S_f \) is friction slope, \( h_m \) is minor losses, and \( g \) is gravitational acceleration. SWMM executes an iterative method of successive approximations to explicitly solve finite difference forms of Equations (1) and (2) for head, \( H \), and flow rate, \( Q \), during each time step at select points along the conduit.

To represent exfiltration, a distributed sink term \((q)\) is included in the continuity and momentum equations (McCutcheon et al., 2010 and Strelkoff 1969) rewritten below,

\[
\frac{\partial Q}{\partial x} + A \frac{\partial A}{\partial t} - q = 0
\]

(3)

\[
\frac{\partial Q}{\partial t} - 2V \frac{\partial A}{\partial t} - V^2 \frac{\partial A}{\partial x} + 2Vq + gA \frac{\partial H}{\partial x} + gAS_f + gAh_m - \frac{V}{2} q = 0
\]

(4)

Here \( q \) is the lateral exfiltration loss expressed as a discharge per unit length of conduit and \( V \) is the average cross-sectional flow velocity \((V = Q/A)\). The modified version of SWMM also uses the method of successive approximations to solve the St. Venant equations. The incremental mass balance used in SWMM was modified to compensate for exfiltration losses from the conduit at each time step.
2.1.2. Flow through the perforations into the trench

The discharge through the perforations in each pipe section is a function of the differential pressure across the perforation and flow velocity of the pipe section and is given by an equation of the form (Koh and Brooks, 1975)

\[ q_i = C_d A_p N_i \sqrt{2g E_i} \]  

(5)

where \( q_i \) is the exfiltration rate from the section, \( C_d \) is the discharge coefficient, \( N_i \) is the number of perforations in the pipe section, \( A_p \) is the area of a single perforation and \( E_i \) is the specific energy head upstream of the perforations in the pipe section. Specific energy head \( E_i \) is given by,

\[ E_i = y_i + \frac{V_i^2}{2g} \]  

(6)

where \( y_i \) is the depth of flow in the pipe and \( \frac{V_i^2}{2g} \) is the velocity head, upstream of the perforations in the pipe section.

The discharge coefficient \( C_d \) for perforations in a pipe is not constant but varies with flow conditions and depends on the ratio of velocity head to total head in the pipe (Koh and Brooks 1975, Graber 2010). For a sharp edged orifice in a pipe, the discharge coefficient is given by,

\[ C_d = 0.63 - 0.58 \left( \frac{V_i^2}{2g E_i} \right) \]  

(7)

where \( V_i \) is the velocity just downstream of the perforations in the pipe section and \( E_i \) is the specific energy head upstream of the perforations in the pipe section, given in (6). Figure 2 shows how the discharge coefficient varies in response to the flow conditions in a pipe of size 0.305m.
The accuracy of the exfiltration rate determined is sensitive to the value of discharge coefficient. It is assumed that the gravel surrounding the pipe will not have a significant impact on the discharge coefficient (Grace, 1978). For situations requiring high degree of accuracy, designers should experimentally determine the discharge coefficient.

2.1.3. **Flow from trench into native soil**

When water is present in the trench, Darcy’s law is used to simulate infiltration in the vertical direction into the underlying native soil,\

\[ I = K A_b \] (8)
Here $I$ is the infiltration rate into the native soil, $A_b$ is the bottom area of the trench containing the conduit, and $K$ is the saturated hydraulic conductivity of the native soil. Infiltration through the side walls of the trench is not considered.

The SWMM exfiltration model also accounts for flow back into the pipe. Exfiltration from the pipe occurs when the head inside the pipe is greater than the head outside the pipe. Flow back into the pipe happens when the head outside the pipe is greater than inside (Figure 3).

![Diagram of exfiltration and infiltration](image)

**Figure 3**: Flow out of and into the perforated pipe based on the depth of water in the trench

### 2.1.4. Simulating flow through a circular cross section perforated pipe

The SWMM exfiltration model has the capability to simulate flow through pipes with square and circular cross sections. In the case of a circular pipe, the orientation of perforations around the circumference of the pipe is an important factor in determining the exfiltration rate. In
a circular pipe the perforations are arranged at the bottom half of the conduit on 30 degree points equally spaced along the length of the pipe as shown in Figure 4. The orifice equation was modified accordingly to account for the difference in head based on the location of the perforations along the circumference of the pipe. When the depth of water in the pipe was greater than the radius of the pipe (or greater than level 1), and the depth of water in the trench was below the bottom of the pipe, the exfiltration rate was calculated as:

\[ q_i = C_d A_p \sqrt{(2g \left((3.5 y_i - 1.634R) + \frac{V_i^2}{2g}\right)) \times 2 \times N_{Li}} \]  

(9)

where \( N_{Li} \) is the number of perforations in one row of the pipe section, and \( R \) is the radius of the circular pipe.

![Figure 4: Orientation of perforations around the circumference of a circular pipe](image)

The modified portions of the SWMM source code are shown in Appendix.
CHAPTER 3

3.1. STEADY AND UNSTEADY STATE ANALYSIS

Simulations were done under steady and unsteady flow conditions. In this study, only the square cross sectional pipe was used. A variety of scenarios were examined, including two different pipe sizes (0.2 and 0.305 m), four different pipe lengths (100, 250, 500 and 1000 m) and two different inflow rates (0.01 and 0.02 m$^3$/s). The width of the trench was determined based on the pipe size as (Pipe size + 0.91 m). This dimension is greater than the minimum trench width of 0.91m recommended by stormwater management guidelines (PADEP, 2006).

The number of perforations in the pipe was calculated as a percentage of the bottom surface area of the pipe. The perforated area was varied from 0.005% to 1.0%. The discharge coefficient determined using Equation (7) varied from 0.45 to 0.60. To simulate steady flow, a constant inflow rate was chosen and the simulation was run for 24 hours as shown in Figure 5.

![Inflow hydrograph under steady flow conditions of total inflow volume of 1728 m$^3$](image)

*Figure 5: Inflow hydrograph under steady flow conditions of total inflow volume of 1728 m$^3$*
For the unsteady flow case, hydrographs of different shapes (Figure 6 and 7) were chosen such that the total inflow volume (1728 m$^3$) was same as the steady flow case.

Figure 6: Inflow hydrograph case 1 under unsteady flow conditions of total inflow volume 1728 m$^3$

Figure 7: Inflow hydrograph case 2 under unsteady flow conditions of total inflow volume 1728 m$^3$
Simulations were also done for a 10-year 24-hour storm event using the Natural Resources Conservation Service (NRCS) Type II distribution for Cincinnati. The precipitation depth for Cincinnati (10.08 cm) was obtained from the National Oceanic and Atmospheric Administration (NOAA) through the precipitation data frequency server (Figure 8).

![Inflow hydrograph of 10-year 24-hour storm event for Cincinnati](image)

**Figure 8: Inflow hydrograph of 10-year 24-hour storm event for Cincinnati**

The hydrograph was routed as an external inflow to a single inlet node and then through the storm sewer. The inflow and outflow hydrographs were compared to determine the reduction in the total runoff volume at the end of pipe. At the start of each simulation, the depth of water in the trench was assumed to be equal to the bedding depth (depth from bottom of pipe to bottom of trench). The exfiltration rate through the perforations is not constant along the pipe length but varies with the depth of flow. In order to accurately determine the exfiltration rate, an appropriate choice of spatial step in SWMM is important. Simulations were done using different spatial steps and it was found that the outflow volume obtained at the end of pipe stabilized for a spatial step of 10% or less of pipe length.
3.2. DIMENSIONLESS DESIGN CHARTS

Soil and storm characteristics vary from place to place. A number of variables influence the exfiltration rate through the perforations. It would be useful to characterize the limits of an exfiltration system for a range of soil and inflow characteristics. A series of exfiltration performance curves was developed using dimensionless parameters. Each point on the design chart is constructed from two dimensionless ratios.

The $X$-axis represents the potential of the native soil to infiltrate and is determined by site specific conditions. In Figure 9, $X$ is the ratio of the bottom rectangular area (representing the steady potential infiltration) to the triangle (representing the inflow hydrograph). In this example, $X=1.0$ and is computed as follows,

$$X = \frac{\text{Potential infiltration volume ( = KA_bT)}}{\text{Total inflow volume}}$$

(9)

figure 9: Inflow and potential infiltration hydrographs for a 0.2% perforated pipe with $K = 11.9\text{cm/hr}$
The $Y$-axis represents storm sewer performance given by the actual fraction of inflow that reaches the end of pipe. In Figure 10, $Y$ is the ratio of the small triangular area (representing the outflow hydrograph) to the large triangular area (representing the inflow hydrograph). In this example, $Y=0.25$ and is computed as follows,

$$Y = \frac{\text{Total outflow volume at the end of pipe}}{\text{Total inflow volume}}$$  \hspace{1cm} (10)$$

Figure 10: Inflow and outflow hydrographs for a 0.2% perforated pipe with $K = 11.9$ cm/hr ($Y=0.25$)

$X$ axis is varied from 0.0 to 1.0 by changing only the $K$ value in equation (9) and the corresponding $Y$ value is obtained by simulation using the SWMM exfiltration model. For example, for a $K$ value of 11.9 cm/hr and a 0.2% perforated square pipe of size 0.305 m, length 500 m and total inflow volume of 1728 m$^3$, $X = 1$, from Equation (9). The total outflow volume at the end of pipe is obtained from SWMM exfiltration model as 429 m$^3$. From equation (10), $Y$
= 0.25, that is only 25% of the total inflow volume reaches the end of pipe. Similarly, a series of curves are developed for different percentage of perforated wall area of the pipe.

3.3. LIFE CYCLE COST ANALYSIS

Cost plays an important role in choosing a storm water management practice. To compare the economic benefits of a storm sewer exfiltration system over a conventional non-exfiltrating storm drainage system, a Life Cycle Cost Analysis (LCCA) is done. In general, construction costs and maintenance costs have long been considered in computing the cost effectiveness of BMPs. Recent studies show that more meaningful measures of cost effectiveness should include design, construction, maintenance as well as performance of a BMP (USEPA 2004).

In the case of an exfiltration system, a significant reduction in the discharge volume at the end of pipe, results in larger cost savings. For the past few decades the conventional way to control downstream flooding was to use detention basins as end-of-pipe practices. In order to illustrate the economical advantages associated with an exfiltration system over the conventional way, and to include the performance of an exfiltration system in cost estimation, a detention basin is included at the outfall of both the conventional and exfiltration systems (Figures 11 & 12).
The different input variables considered in the LCCA are contributing drainage areas (varied from 0.405 to 4.05 hectares), rainfall depths (2.54 to 15.24 cm), saturated hydraulic
conductivity of the native soil (0.5 to 21 cm/hr), trench width (0.91 to 2.4 m) and perforated area of the pipe (0.01% to 1.0%). All rainfall depths are considered to be 24 hour storm events.

The LCCA is done for different design scenarios by changing one variable at a time. For each scenario a feasible design was made for conventional storm drainage system and exfiltration system. The length of the pipe is chosen to be equal to the length of the plot and the pipe size is determined using Manning’s equation. If the pipe size determined is less than the minimum storm sewer of 0.38 m in diameter (IDNR, 2009) then the minimum pipe size is used. For cases where the cost of a square pipe was not available, the cost of a circular pipe of equivalent area was used. A constant bedding depth of 0.61 m and backfill of 0.305 m is used in all scenarios. In case of exfiltration system, the outflow volume at the end of pipe is obtained from SWMM exfiltration model by assuming steady flow conditions. The design volume of the detention basin required is determined based on the outflow volume at the end of pipe.

The total cost of the conventional system is broken into non-perforated pipe costs, trench excavation costs, bedding costs, backfill costs, manhole costs, inlet costs, curb and gutter costs and detention basin costs. The total cost of the exfiltration system consists of perforated pipe costs, infiltration trench costs and detention basin costs.

The life-cycle cost includes the initial capital costs and the present value of annual operation and maintenance costs that are incurred over time, less the present value of the salvage value at the end of the service life (Sample et al., 2003). The costs for the different components of the conventional system were obtained from the R.S. Means Building Construction Cost Data Handbook (2010). The unit costs provided by R.S. Means include material, labor, equipment and 10% overhead and profit cost.
The construction costs for infiltration trench and detention basin can be estimated using equations (11) and (12) which relates cost as a function of the volume of the facility (USEPA 2004).

\begin{align*}
\text{Equation (11)}: \\
C &= 173 \left( \frac{V_t}{0.02832} \right)^{0.63} \\
\text{Equation (12)}: \\
C &= 12.4 \left( \frac{V_d}{0.02832} \right)^{0.76}
\end{align*}

where $C$ is the construction cost in dollars, $V_t$ is the volume of the infiltration trench and $V_d$ is the volume of the detention basin. The costs obtained from these equations are in terms of 2002 dollars. To obtain the current cost, the total capital cost data is multiplied by the current year cost index and divided by the base year indexes. The current cost resulting from inflation can be calculated using the following equation (USEPA, 2004):

\begin{equation}
\text{Capital cost (adjusted for 2011)} = \frac{\text{Capital cost for 2002} \times \text{ENR cost index for 2011}}{\text{ENR cost index for 2002}}
\end{equation}

The design and contingency costs are expressed as a fraction of the capital costs and are equal to 25% of the capital costs (USEPA 2004). The operation and maintenance costs (O&M) for infiltration trench is taken as 5% of the capital cost and for detention basin as 1% of the capital cost (USEPA 2004). The discount rate over the past 10 years was found by averaging the values provided by the Office of Management and Budget, resulting in an interest rate of approximately 5% (OMB, 2012).

All pipes were assumed to be made of high density poly-ethylene (HDPE) material. A minimum design life of 50 years is assumed for the HDPE pipe (PPI 2012) and a design life of
20 years is used for the detention basin (USEPA 2004). The salvage value and present value of costs was calculated using appropriate formula provided in ASTM F1675 and ASTM C1131.
CHAPTER 4

4.1. RESULTS - HYDRAULICS

4.1.1. Steady Flow

Steady flow results corresponding to a constant inflow rate of 0.02 m$^3$/s are shown on the Dimensionless Chart (DC) for four different pipe lengths in Figure 13.

![Dimensionless Chart for Steady Flow](image)

Figure 13: Dimensionless design chart for a square pipe of size 0.305 m with total inflow volume of 1728 m$^3$

under steady flow conditions

---

1 The legend gives perforated area of the pipe.
The shaded region in the charts corresponds to simulations with $K$ value greater than 21cm/hr. This rate corresponds to hydrologic soil group A (sand) which is taken to be the maximum limit for K value (IDNR 2009). Results show that as the infiltration rate into the soil increases, the total volume reaching the pipe outlet decreases. The 45 degree line that extends from 1.0 on the Y-axis to 1.0 on the X-axis is called the **backbone curve**. The performance of a given exfiltration system for different infiltration rates into the soil can be shown by this single curve. The shape of the backbone curve for steady flow conditions remains the same for the four different pipe lengths.

Figure 14 shows the flow hydrographs for a pipe of length 500 m, size 0.305 m and 0.01% perforated. For $K = 5.9$ cm/hr, $A_b = 607.5$ m$^2$ and total inflow volume of 1728m$^3$, $X = 0.50$ on the DC (Fig 13c). It can be seen from Fig 11c that the actual exfiltration rate from the pipe is same as the potential infiltration rate to the soil for 0.01% and 0.02% perforated pipe. Even though the perforated area is increased to 0.2%, the actual exfiltration rate from the pipe does not change. This is because the infiltration rate of water into the soil is less than the exfiltration rate from the pipe. Hence irrespective of the perforated area, the total outflow volume at the end of pipe is 864m$^3$. Thus per Equation (10) $Y = 0.50$ on the DC (Fig 13) for both 0.01% and 0.2% perforated cases. Whereas for a smaller perforated area namely 0.005%, $Y = 0.67$ on the DC (Fig 13c) i.e. 67% of the total inflow volume reaches the end of pipe. This is because the smaller perforated area inhibits exfiltration so the potential soil infiltration is not achieved. Thus it can be concluded that the backbone curve represents the condition where the perforations are not limiting the amount of water that can enter the trench and therefore the potential exfiltration volume is achieved.
Figure 14: Flow hydrographs showing potential infiltration rate of soil and actual exfiltration rate of pipe for different perforated area of pipe corresponding to $X = 0.5$ on the DC

Figure 15: Flow hydrographs showing potential infiltration rate of soil and actual exfiltration rate of pipe for different perforated area corresponding to $X = 0.7$ on the DC
As we move along the backbone curve on the DC, the series of curves start to break away. This point of departure from the backbone curve is called the **breakpoint**. The breakpoint corresponds to the maximum reduction in inflow volume that can be achieved for a perforated pipe. For example, consider Fig. 13c, for a square pipe of length 500m and size 0.305m with 0.01% perforated area, under a steady flow of 0.02m$^3$/s, the breakpoint occurs at 0.40 along the Y axis, which means the maximum exfiltration losses that can be achieved with a 0.01% perforated pipe (irrespective of the soil condition) is 60% of the inflow volume.

The curve goes flat at the breakpoint indicating that the exfiltration losses are controlled by the perforations in the pipe and is independent of the saturated hydraulic conductivity. This is illustrated in Figure 15. When the perforated area is 0.2% of the bottom wall of pipe, the actual exfiltration rate from the pipe can match the potential infiltration rate into the soil. However when the perforated area drops to 0.01% or 0.005% the exfiltration rate from the pipe is not sufficient to achieve the potential infiltration rate into the soil. Hence on the DC shown in Fig 13c, even if X is increased to 1.0, Y does not change. Thus the breakpoint represents the condition where the exfiltration rate is controlled by the perforations in the pipe.

Figure 16 shows the DC for a pipe size of 0.2 m and total inflow volume of 1728 m$^3$. In this case the backbone curve is a 45 degree line, similar to the previous case of 0.305 m pipe size. But the breakpoint varies with respect to pipe size, length and perforated area.
Figure 16: Dimensionless design chart for a square pipe of size 0.2 m with total inflow volume of 1728 cubic meters under steady flow conditions.
Figure 17: Dimensionless chart for a pipe size of 0.305 m and total inflow volume of 864 cubic meters under steady flow conditions.

Figure 17 shows the DC for a pipe size of 0.305 m and total inflow volume of 864 cubic meters. It can be seen that the backbone curve remains the same as in the case of larger inflow
volume of 1728 cubic meters. However the breakpoint for each perforated pipe is different from the previous case.

![Dimensionless chart for pipe size of 0.2 m and total inflow volume of 864 cubic meters](image)

**Figure 18**: Dimensionless chart for pipe size of 0.2 m and total inflow volume of 864 cubic meters under steady flow conditions

Figure 18 shows the DC for a smaller pipe size of 0.2 m and total inflow volume of 864 cubic meters. The smaller pipe implies a smaller total area of perforated openings which means
less pipe exfiltration, more downstream discharge and, hence, a higher breakpoint than the large size pipe. For example for a pipe length of 100 m with 0.02% perforated area with total inflow volume of 864 m$^3$, breakpoint occurs at 0.6 along the Y axis (60% of the total inflow volume reaches the end of pipe) in case of a larger pipe size of 0.305 m (Fig 17); in case of the smaller pipe (0.2 m) breakpoint occurs at 0.7 along the Y axis (70% of the total inflow volume reaches the end of pipe – Fig 18).
Figure 19: Dimensionless design chart for a square pipe of size 0.305 m with total inflow volume of 1728 cubic meters under unsteady flow conditions.
4.1.2. Unsteady Flow

In case of unsteady flow, the results corresponding to total inflow volume of 1728 m$^3$ for four different pipe lengths is shown in Figure 19. Here, the backbone curve is not a 45 degree line as in the case of steady flow but ends some distance above 0.0 along the Y axis. Figure 20 shows how the actual exfiltration rate varies for different K values for a 0.01% perforated area of the pipe of length 500 m with total inflow volume of 1728 m$^3$. For a smaller K value of 5.9 cm/hr, corresponding to 0.5 along the X-axis on the DC, (a point along the backbone curve) the actual exfiltration rate from the pipe is sufficient to achieve the potential infiltration rate into the soil. Hence the exfiltration rate is constant for most time periods and equal to the potential infiltration rate. For a higher K value of 8.3 cm/hr, corresponding to 0.7 along the X-axis on the DC, the actual exfiltration rate is less than the potential infiltration rate. For X greater than 0.7 on the DC, Y is constant indicating that the perforations control the exfiltration rate from the pipe.
Figure 20: Comparison of exfiltration rate for two different K values for a 0.01% perforated area of a square pipe of size 0.305 m with total inflow volume of 1728 cubic meters

Figure 21&22 shows the DC for two different pipe sizes namely 0.305 and 0.2m with same total inflow volume of 864 cubic meters. In both cases, since the shape of the inflow hydrograph is the same, the shape of the backbone curve remains the same.
Figure 21: Dimensionless chart of a pipe size of 0.305m for a total inflow volume of 864 cubic meters under unsteady flow conditions.
Figure 22: Dimensionless design chart for a square pipe of size 0.2 m with total inflow volume of 864 cubic meters under unsteady flow conditions.
The shape of the backbone curve is not sensitive to the duration of the hydrograph. This is illustrated in Figure 23.

![Figure 23: Inflow hydrograph with total duration of 12 hours and the corresponding dimensionless chart for a pipe size of 0.305 m](image)

Figure 23 shows the inflow hydrograph for a total duration of 12 hours with total inflow volume of 864 cubic meters. Figure 23.b shows the dimensionless chart developed using the hydrograph for a pipe size of 0.305 m. Figures 19 and 21b are dimensionless charts developed for the same pipe size and total inflow volume. The only difference being the duration of the inflow hydrograph. From the Figure 21 and 23b, it is clear that the duration of the hydrograph does not affect the shape of the backbone curve. This is because the values along the X axis on the dimensionless chart depends primarily on the combination of three parameters namely saturated hydraulic conductivity of soil K, bottom area of trench A_b and duration of inflow to the pipe t; and changing any one of these values will not affect the shape of the backbone curve.
The DC for a pipe length of 500 m and inflow hydrograph case 2 is shown in figure 24. The backbone curve ends at 0.19 along the Y axis. Thus it is clear that the backbone curve for unsteady flow is dependent on the shape of the hydrograph. Figure 25 shows the flow hydrographs for a pipe size of 0.305 m and length 500 m. The actual exfiltration rate for different perforated area of the pipe is shown. For the same K value of 11.9 cm/hr (which corresponds to X = 1.0 on the DC), it can be seen how the exfiltration rate varies for different perforated area. In case of 0.005% and 0.01% perforated area, the perforations are limiting the amount of water that can enter the trench. Hence the potential infiltration rate into the soil is not achieved. For a larger perforated area of 0.02%, the perforations are not limiting the amount of water that can enter the trench. Hence the potential infiltration rate into the native soil is achieved.
Figure 25: Flow hydrographs for different perforated area of the pipe corresponding to X=1.0 on the DC

Figure 26 shows the dimensionless chart developed for a 10 year 24 hour storm event of Cincinnati using a pipe of size 0.305m and different pipe lengths. The backbone curve stopped at 0.48 along the Y axis. However, if the soil had a higher hydraulic conductivity such that X>1.0, then it is possible to achieve Y value less than 0.48. For example, for a pipe of length 500 m if the K value was 21 cm/hr (with the same inflow hydrograph), X = 7.5 and Y = 0.118; i.e. nearly 88% reduction in the total inflow volume can be achieved.
Therefore, the breakpoint gives the maximum reduction in inflow volume for a given perforated pipe and the backbone curve gives the maximum reduction for a given soil condition. Thus the charts help to determine the maximum exfiltration losses from a perforated pipe for a given soil condition and inflow hydrograph.
4.1.3. **Computational method to predict the breakpoint on the dimensionless chart under steady state conditions:**

The perforations in the pipe should be designed such that they do not limit the amount of water that can enter the trench. To determine the number of perforations required to achieve the prescribed reduction in inflow volume, the maximum exfiltration losses that can be achieved for a given perforated pipe (breakpoint) should be known. To facilitate this, a computational procedure is developed. In order to calculate the exfiltration losses from the pipe the water surface profile in the perforated pipe should be known.

A step wise procedure similar to the classic Standard Step method is adopted to determine the water surface profile. The computational procedure developed here is influenced by the computational sequence developed for manifold design by several authors including Grace (1978), Fischer *et al.* (1979) and Larock *et al.* (2000). Several assumptions are made in this procedure. It is assumed that the flow is steady and depth of flow reaches the critical depth at outfall. The Manning’s equation is used to determine the frictional slope in each pipe section.

The pipe is divided into short sections (Figure 27) and the computations are done starting from the downstream end at a known flow depth.

![Figure 27: Section of the perforated pipe showing the different components of energy equation](image-url)
A rough estimate of the total exfiltration rate from the pipe is first computed from equation (17) using the specific energy head at inlet of the pipe.

\[ q_{\text{initial}} = C_d A_p N_p \sqrt{2g E_{\text{in}}} \]  

(17)

Where \( q_{\text{initial}} \) is the initial estimate of the total exfiltration rate from the pipe; \( E_{\text{in}} = Y + (V_{\text{in}}^2/2g) \), specific energy head at the inlet of the pipe and \( Y \) is the normal depth computed using the Manning’s equation. \( N_p \) is the number of perforations in the entire pipe length. The outflow rate at the end of pipe can be determined as

\[ Q_{i+1} = Q_{\text{in}} - q_{\text{initial}} \]  

(18)

Where, \( Q_{i+1} \) is the outflow rate at the end of the pipe and \( Q_{\text{in}} \) is the inflow rate to the pipe. The critical depth at outfall is found using this outflow rate. With all the values known at the downstream end of the pipe section, the depth of flow at upstream end of the section is found by solving the energy equation.

\[ y_i + z_i + \frac{v_i^2}{2g} = y_{i+1} + z_{i+1} + \frac{v_{i+1}^2}{2g} + h_f \]  

(19)

Where \( y_i \) and \( y_{i+1} \) is the depth of flow in the pipe at u/s and d/s of \( i^{\text{th}} \) section respectively, \( z_i \) and \( z_{i+1} \) is the elevation of the pipe from the datum, \( \frac{v_i^2}{2g} \) and \( \frac{v_{i+1}^2}{2g} \) is the u/s and d/s velocity head of \( i^{\text{th}} \) section, and \( h_f \) is the head loss due to friction given by

\[ h_f = \frac{(S_{fi} + S_{fi+1}) \Delta x}{2} \]  

(20)

Where \( S_{fi} \) and \( S_{fi+1} \) are friction slopes, found using Manning’s equation. The exfiltration rate from the section is computed using the upstream head and the inflow rate to the section can be found as
\[ Q_i = Q_{i+1} + q_i \] (21)

The results at the upstream end of section \( i \) become the known values for the next section \( i-1 \). This procedure is repeated till the inlet of the pipe is reached. Computations are considered complete when the inflow rate computed at the inlet of the pipe matches the given inflow rate. If it does not match, then the outflow rate at the end of the pipe is adjusted accordingly and the calculations are repeated. The equations were solved using a C++ program and the results were found to be in agreement with the SWMM exfiltration model.

Figure 28 shows the water surface profile determined using the computational method and SWMM exfiltration model. Figure 29 shows the exfiltration rate computed using the computational procedure and SWMM exfiltration model. Thus the total exfiltration rate from the pipe for a given perforated area can be determined using this procedure. For example for 0.01% perforated pipe of size 0.2 m with each perforation of size 0.01 m, length 500 m and inflow rate of 0.02 m$^3$/s, the outflow rate at the end of pipe is determined as 0.0101 m$^3$/s. Assuming the flow to the pipe occurs for 24 hours, the total inflow volume is equal to 1728 m$^3$ and the total outflow volume is equal to 873 m$^3$. Then the actual \( Y \) on the DC can be determined using equation (9) as 0.51. From equation (14) actual \( X \) can be found as 0.49. Therefore the breakpoint of 0.01% perforated pipe is equal to (0.49, 0.51) on the DC which is same as the value obtained from the SWMM exfiltration model (Fig 13). Figure 30 and Figure 31 shows the water surface profile and exfiltration rate determined using the computational method for a pipe size of 0.305 m to be in agreement with the results obtained from SWMM exfiltration model.
Figure 28: Water surface profile computed using the computational procedure and SWMM Exfiltration model

Figure 29: Exfiltration rate computed using the computational procedure and SWMM Exfiltration model
Figure 30: Water surface profile determined using the computational procedure and SWMM exfiltration model

Figure 31: Exfiltration rate determined using the computational procedure and SWMM exfiltration model
4.2. RESULTS - Life-Cycle Cost Analysis

The effect of the different input variables on LCC is analyzed. The ratio of LCC of conventional and exfiltration system is found for each scenario. Figure 32 shows the effect of the trench width on the LCC ratio. The points above 1.0 on the Y axis denote the economically favorable region for exfiltration system. From the analysis it is found that the exfiltration system is more economical than the conventional system for trench width in the range of 1 to 1.5 m.

![Figure 32: Effect of trench width on the ratio of LCC of Conventional and Exfiltration system for different storm sizes on a drainage area of 1.2 hectares](image)

As an example, the LCCA for one scenario is shown here. The summary of input parameters used in this scenario is shown in Table 1. The estimated costs for the conventional and exfiltration system are shown in Table 2 and Table 3.
Table 1: Summary of input parameters used in LCCA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall depth, cm</td>
<td>2.54</td>
</tr>
<tr>
<td>Contributing drainage area, hectares</td>
<td>1.2</td>
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<tr>
<td>Total inflow volume, m³</td>
<td>308</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity, cm/hr</td>
<td>6.12</td>
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<tr>
<td>Width of trench, m</td>
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</tr>
<tr>
<td>Cost index for 2011</td>
<td>9172</td>
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<tr>
<td>Cost index for 2002</td>
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</tr>
<tr>
<td>Cost index for 2010</td>
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</table>
Table 2: Summary of estimated Life Cycle Costs of the conventional storm drainage system

<table>
<thead>
<tr>
<th>No.</th>
<th>PIPE &amp; TRENCH</th>
<th>Project design life, years</th>
<th>50</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>Unit</td>
<td>Unit cost, 2010$</td>
</tr>
<tr>
<td>0.38 m HDPE Non-perforated pipe</td>
<td>LM</td>
<td>67</td>
<td>110</td>
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<tr>
<td>Trench excavation costs</td>
<td>CM</td>
<td>12</td>
<td>185</td>
</tr>
<tr>
<td>Dewatering cost</td>
<td>LM</td>
<td>240</td>
<td>110</td>
</tr>
<tr>
<td>Backfill costs (inc comp)</td>
<td>LM</td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>Bedding costs (inc compaction)</td>
<td>CM</td>
<td>72</td>
<td>87</td>
</tr>
<tr>
<td>Inlet (2.21 m deep)</td>
<td>Each</td>
<td>360</td>
<td>3</td>
</tr>
<tr>
<td>Manholes (1.6 m deep)</td>
<td>Each</td>
<td>2925</td>
<td>2</td>
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<tr>
<td>Curb and gutter</td>
<td>LM</td>
<td>77</td>
<td>220</td>
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<tr>
<td>1 Capital cost for pipe &amp; trench</td>
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<td></td>
</tr>
<tr>
<td>2 Design &amp; contingency costs (25% of C)</td>
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<td>17506</td>
<td></td>
</tr>
<tr>
<td>3 Annual O&amp;M cost (5% of C)</td>
<td></td>
<td>3501</td>
<td></td>
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<tr>
<td>8 Salvage value</td>
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<td>9563</td>
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</tr>
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<td>9 Present value multiplier</td>
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<td>18.26</td>
<td></td>
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<tr>
<td>3 PV of O&amp;M cost</td>
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<td>63930</td>
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DETENTION BASIN

<table>
<thead>
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<th>DETENTION BASIN</th>
<th>Project design life, years</th>
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<tr>
<td>4 Capital cost for basin</td>
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<td>20272</td>
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<td>5 Design &amp; contingency costs (25% of C)</td>
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<td></td>
</tr>
<tr>
<td>Annual O&amp;M cost (1% of C)</td>
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<tr>
<td>Present value multiplier</td>
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<tr>
<td>6 PV of O&amp;M cost</td>
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<td>2526</td>
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</tr>
<tr>
<td>7 Salvage value</td>
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<td>2707</td>
<td></td>
</tr>
<tr>
<td>(1+2+3+4+5+6-(7+8))</td>
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<td>LCC 167054</td>
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</table>

Note: Costs as of December 2011 dollars.
Table 3: Summary of estimated Life Cycle Costs of an exfiltration system

<table>
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<th>No.</th>
<th>Project design life, years</th>
<th>Unit</th>
<th>Unit cost, 2010$</th>
<th>Quantity</th>
<th>Cost, 2011$</th>
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<td>0.38 m HDPE Perforated pipe</td>
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<td>110</td>
<td>8227</td>
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<td>Construction cost of trench</td>
<td>CM</td>
<td>185</td>
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<td>61261</td>
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<td>1</td>
<td>Capital cost for pipe &amp; trench</td>
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<td>2</td>
<td>Design &amp; contingency costs (25% of C)</td>
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<tr>
<td>Annual O&amp;M cost (5% of C)</td>
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<td>8</td>
<td>Salvage value</td>
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<td>3</td>
<td>PV of O&amp;M cost</td>
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DETENTION BASIN

<table>
<thead>
<tr>
<th>No.</th>
<th>Project design life, years</th>
<th>Perforated area of the pipe</th>
<th>Total outflow volume at the end of perforated pipe, m³</th>
<th>Unit</th>
<th>Quantity</th>
<th>Cost, 2010$</th>
<th>Present value multiplier</th>
<th>PV of O&amp;M cost</th>
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<th>LCC</th>
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<td>4</td>
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<td>Design &amp; contingency costs (25% of C)</td>
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<td>Annual O&amp;M cost (1% of C)</td>
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<td>PV of O&amp;M cost</td>
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<tr>
<td>7</td>
<td>Salvage value</td>
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(1+2+3+4+5+6+(7+8)) LCC 151326

Note: Costs as of December 2011 dollars.
From the summary of estimated LCC shown in table 2 and table 3, it can be seen that by using an exfiltration system nearly 9% reduction in the LCC is achieved. Figure 33 shows the different costs computed for conventional and exfiltration system.

The ratio of LCC cost of a conventional to an exfiltration system for different rainfall depths and contributing drainage area of 0.405 hectare, 0.81 hectares, 1.2 hectares and 2.03 hectares is shown in Figures 34, 35, 36 & 37 respectively.
Figure 34: Ratio of LCC of Conventional to Exfiltration system for different percentage of reduction in the total inflow volume for a drainage area of 0.405 hectare

The points above 1.0 denote the economically favorable region for exfiltration system. For a smaller area of 0.405 hectares, for rainfall depth of 7.62 cm or higher, there has to be a minimum of 40% reduction in order for the exfiltration system to be economical; Whereas for storms smaller than 7.62 cm, higher than 40% of reduction in the total inflow volume is needed to obtain a LCC ratio greater than 1.0.
Figure 35: Ratio of LCC of Conventional to Exfiltration System for different percentage of reduction in the total inflow volume for a drainage area of 0.81 hectares

Figure 36: Ratio of LCC of Conventional to Exfiltration system for different percentage of reduction in the total inflow volume for a drainage area of 1.2 hectares
Figure 37: Ratio of LCC of Conventional to Exfiltration system for different percentage of reduction in the total inflow volume for a drainage area of 2.03 hectares

In case of larger area of 1.2 hectares, the LCC ratio is always greater than 1.0, even with a small percentage of reduction (10%). For areas higher than 1.2 and 2.03 hectares, the LCC ratio was found to be always greater than 1.0. In general it can be concluded that the exfiltration system is economically favorable for large contributing drainage areas (1.2 hectares or more).
CHAPTER 5

5.1. CONCLUSION

The increasing urbanization leads to higher peak flows and larger runoff volumes for storm events. This study shows storm sewer exfiltration as a viable option for urban stormwater management. SWMM was used to model exfiltrating storm sewers under steady and unsteady flow conditions. The simulation results show that storm sewer exfiltration has the potential to cause significant reduction in the total volume that reaches the end of pipe. The utility of dimensionless design chart is that it shows theoretical limits and operating ranges for various perforated areas and saturated hydraulic conductivity values. The computational procedure helps in determining the water surface profile for any given perforated pipe and thereby the exfiltration losses can also be determined. The comparison of life cycle costs between the conventional practice and storm sewer exfiltration system shows how reduction in the total volume at the end of pipe results in cost savings. Thus the storm sewer exfiltration system has the ability to mitigate the adverse impacts of urbanization in a cost-effective manner.

5.2. RECOMMENDATIONS

The performance of an exfiltration system could be further investigated by a field study or a laboratory experiment. Results from such studies will be very useful to validate the SWMM exfiltration model. Further studies are required to investigate the effects of gravel on discharge coefficient value for the perforations. Long-term studies are needed on the potential water quality impacts caused by an exfiltration system on ground water resources. Studies are also needed on the effects of clogging of perforations on the performance of an exfiltration system.
References:


APPENDIX

MODIFIED SWMM SOURCE CODE
The modified portions of the SWMM source code are shown here. The two files that were modified are dynwave.c and massbal.c. The lines in green color are comments. The words in blue correspond to keywords of C programming language. The lines in red denote the modified portions.

//dynwave.c

// Project: EPA SWMM5
// Version: 5.0
// Date: 3/11/08 (5.0.013)
// 1/21/09 (5.0.014)
// 4/10/09 (5.0.015)
// 6/22/09 (5.0.016)
// 10/7/09 (5.0.017)
// Author: L. Rossman
// R. Dickinson

// Dynamic wave flow routing functions.

// This module solves the dynamic wave flow routing equations using
// Picard Iterations (i.e., a method of successive approximations)
// to solve the explicit form of the continuity and momentum equations
// for conduits.

// All previous change comments prior to release 5.0.013 were removed
// to improve readability.

// -----------------------------------------------------------------------
#define _CRT_SECURE_NO_DEPRECATE

#include <malloc.h>
#include <math.h>
#include "headers.h"

// -----------------------------------------------------------------------
// Constants
// -----------------------------------------------------------------------
static const double MINSURFAREA = 12.566; // min. nodal surface area (~4 ft diam.)
static const double MAXVELOCITY = 50.; // max. allowable velocity (ft/sec)
static const double MINTIMESTEP = 0.5; // min. time step (sec)
static const double OMEGA = 0.5; // under-relaxation parameter
static const double STOP_TOL = 0.005; // Picard iteration stop criterion
static const int MAXSTEPS = 4; // max. number of Picard iterations

// Data Structures

typedef struct
{
    char converged;       // TRUE if iterations for a node done
    double newSurfArea;  // current surface area (ft2)
    double oldSurfArea;  // previous surface area (ft2)
    double sumdqdh;      // sum of dqdh from adjoining links
    double dYdT;         // change in depth w.r.t. time (ft/sec)
} TXnode;

typedef struct
{
    char bypassed;       // TRUE if can bypass calcs. for a link
    double surfArea1;    // surf. area at upstrm end of link (ft2)
    double surfArea2;    // surf. area at dnstrm end of link (ft2)
} TXlink;

// Shared Variables

static double MinSurfAreaFt2; // actual min. nodal surface area (ft2)
static double VariableStep;   // size of variable time step (sec)
static double Omega;          // actual under-relaxation parameter
static double CriticalDepth;  // critical flow depth (ft)
static double NormalDepth;    // normal flow depth (ft)
static double Fasnh;          // fraction between norm. & crit. depth
static int Converged;         // TRUE if Picard iterations converged
static int Steps;              // number of Picard iterations
static TXnode* Xnode;
static TXlink* Xlink;

// External functions (declared in funcs.h)

// dynwave_init (called by flowrout_init)
// dynwave_getRoutingStep (called by flowrout_getRoutingStep)
// dynwave_execute (called by flowrout_execute)

// Function declarations

static void execRoutingStep(int links[], double dt);
static void initNodeState(int i);
static void findConduitFlow(int i, double dt);
static void findNonConduitFlow(int i, double dt);
static double getModPumpFlow(int i, double q, double dt);
static void updateNodeFlows(int i, double q);
static double getConduitFlow(int link, double qin, double dt);
static int getFlowClass(int link, double q, double h1, double h2,
                      double y1, double y2);
static void findSurfArea(int link, double length, double* h1, double* h2,
                         double* y1, double* y2);
static double findLocalLosses(int link, double a1, double a2, double aMid,
                       double q);
static void findNonConduitSurfArea(int link);
static double getWidth(TXsect* xsect, double y);
static double getArea(TXsect* xsect, double y);
static double getHydRad(TXsect* xsect, double y);
static double checkFlapGate(int j, int n1, int n2, double q);                //(5.0.014 - LR)
static double checkNormalFlow(int j, double q, double y1, double y2,
                               double a1, double a2, double r1);
static void setNodeDepth(int node, double dt);
static void setWetWellVolume(int i, int canPond, double dV, double dt);
static double getFloodedDepth(int i, int canPond, double dV, double yNew,
                              double yMax, double dt);            //(5.0.014 - LR)

static double getVariableStep(double maxStep);
static double getLinkStep(double tMin, int *minLink);
static double getNodeStep(double tMin, int *minNode);
static void checkCapacity(int j);

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// Exfiltration Function declarations

static double ExfiltrationVolume(double Exfil, double length, double dt, double count);
static double TrenchDepth(double ExVol, double length, double dt);
double AvailableVolume(double length);
double APoreVol(double dt, double ExInRate);
double TrenchVolume(double PoreVol, double ExInVol);  //trench is full as initial condition
double TrenchArea(double TWidth, double length);
double BeddingArea(double Bedding, double TWidth);
double BackfillArea(double Backfill, double TWidth);
double SquareArea(double Diam, double TWidth);
double ConduitArea(double Diam);
double PoreVolume(double BedArea, double BfArea, double SqArea, double CondArea, double Totlength);
double ExInfilRate(double TArea);
double ExInfilVolume(double dt, double EIRate);

void updateNodeFlows(int i, double q)
//
// Input:  i = link index
//    q = link flow rate (cfs)
// Output: none
// Purpose: updates cumulative inflow & outflow at link's end nodes.
// //
{ if ( q >= 0.0 )
{ Node[Link[i].node1].outflow = Node[Link[i].node1].outflow + q + (Link[i].ExfilLink);
    Node[Link[i].node2].inflow  = Node[Link[i].node2].inflow + q;
}
else
{ Node[Link[i].node1].inflow   = Node[Link[i].node1].inflow - q;
    Node[Link[i].node2].outflow  = Node[Link[i].node2].outflow - q;
}
}

double getConduitFlow(int j, double qOld, double dt)
//
// Input:  j = link index
//    qOld = flow from previous iteration (cfs)
//    dt  = time step (sec)
// Output: returns new flow value (cfs)
// Purpose: updates flow in conduit link by solving finite difference
//    form of continuity and momentum equations.
//
{
    int k;               // index of conduit
    int n1, n2;         // indexes of end nodes
    double z1, z2;      // upstream/downstream invert elev. (ft)
    double h1, h2;      // upstream/downstream flow heads (ft)
    double y1, y2;      // upstream/downstream flow depths (ft)
    double a1, a2;      // upstream/downstream flow areas (ft2)
    double r1;          // upstream hyd. radius (ft)
    double yMid, rMid, aMid, hMid; // mid-stream or avg. values of y, r, a, & h
    double aWtd, rWtd;   // upstream weighted area & hyd. radius
    double qLast;       // flow from previous iteration (cfs)
    double aOld;        // area from previous time step (ft2)
    double v;           // velocity (ft/sec)
    double rho;         // upstream weighting factor
    double sigma;       // inertial damping factor
    double length;      // effective conduit length (ft)
    double dq1, dq2, dq3, dq4, dq5; // terms in momentum eqn.
    double denom;       // denominator of flow update formula
    double q;           // new flow value (cfs)
    double barrels;     // number of barrels in conduit
    TXsect* xsect = &Link[j].xsect; // ptr. to conduit's cross section data
    char isFull = FALSE; // TRUE if conduit flowing full

    // Local variable declarations for exfiltration
    double ExVol;       // Exfiltration Volume for current time step (ft3)
    double AvEp;        // Available volume for flow back into conduit (ft3) (S)
    double TDepth;      // Trench Depth (ft)
    double deltaH;      // Difference between Trench Depth and Flow Depth (ft)
    double HSize = 0.39; // Hole Size (in) (S)
    double NumHoles = 1; // Number of perforations per conduit
    static double count; // continuous count of elapsed simulation time
    static double hT;    // Trench head (ft)
    double TWidth = 3.67;
    double Size = 0.67;
    static double ExfVol;
    double APVol;
    double TVol;
    double Totlength = 1640; // total length of conduit (ft)
    double Cd;
    double vH;
    double ExInRate;
    double TArea;
}
// --- get most current heads at upstream and downstream ends of conduit
k = Link[j].subIndex;
n1 = Link[j].node1;
n2 = Link[j].node2;
z1 = Node[n1].invertElev + Link[j].offset1;
z2 = Node[n2].invertElev + Link[j].offset2;
h1 = Node[n1].newDepth + Node[n1].invertElev;
h2 = Node[n2].newDepth + Node[n2].invertElev;
h1 = MAX(h1, z1);
h2 = MAX(h2, z2);

// --- get invert elev. of conduit at mid-point //
zMid = (z1 + z2)/2; //

// --- get invert elev. of trench //
zt = zMid - 2.0;

// --- get unadjusted upstream and downstream flow depths in conduit
// (flow depth = head in conduit - elev. of conduit invert)
y1 = h1 - z1;
y2 = h2 - z2;
y1 = MAX(y1, FUDGE);
y2 = MAX(y2, FUDGE);

// --- flow depths can't exceed full depth of conduit
y1 = MIN(y1, xsect->yFull);
y2 = MIN(y2, xsect->yFull);

// --- get flow from last time step & previous iteration
barrels = Conduit[k].barrels;
qOld /= barrels;
qLast = Conduit[k].q1;

// -- get area from solution at previous time step
aOld = Conduit[k].a2;
aOld = MAX(aOld, FUDGE);

// --- use Courant-modified length instead of conduit's actual length
length = Conduit[k].modLength;

// --- find flow classification & corresponding surface area
// contributions to upstream and downstream nodes
Link[j].flowClass = getFlowClass(j, qLast, h1, h2, y1, y2);
findSurfArea(j, length, &h1, &h2, &y1, &y2);
// --- compute area at each end of conduit & hyd. radius at upstream end
a1 = getArea(xsect, y1);
a2 = getArea(xsect, y2);
r1 = getHydRad(xsect, y1);

// --- compute area & hyd. radius at midpoint
yMid = 0.5 * (y1 + y2);
aMid = getArea(xsect, yMid);
rMid = getHydRad(xsect, yMid);

// --- alternate approach not currently used, but might produce better
//   Bernoulli energy balance for steady flows
//aMid = (a1+a2)/2.0;
//rMid = (r1+getHydRad(xsect,y2))/2.0;

// --- check if conduit is flowing full
if ( y1 >= xsect->yFull &&
    y2 >= xsect->yFull) isFull = TRUE;

// --- set new flow to zero if conduit is dry or if flap gate is closed
if ( Link[j].flowClass == DRY ||
    Link[j].flowClass == UP_DRY ||
    Link[j].flowClass == DN_DRY ||
    Link[j].isClosed ||
    aMid <= FUDGE )
{
    Conduit[k].a1 = 0.5 * (a1 + a2);
    Conduit[k].q1 = 0.0;;
    Conduit[k].q2 = 0.0;
    Link[j].dqdh = GRAVITY * dt * aMid / length * barrels;
    Link[j].froude = 0.0;
    Link[j].newDepth = MIN(yMid, Link[j].xsect.yFull);
    Link[j].newVolume = Conduit[k].a1 * link_getLength(j) * barrels;  //(5.0.015 - LR)
    Exfil = 0.0;
    Link[j].ExfilLink = 0.0;
    return 0.0;
}

// --- compute velocity from last flow estimate
v = qLast / aMid;
if ( fabs(v) > MAXVELOCITY ) v = MAXVELOCITY * SGN(qLast);

// --- compute Froude No.
Link[j].froude = link_getFroude(j, v, yMid);
if ( Link[j].flowClass == SUBCRITICAL &&
Link[j].froude > 1.0 ) Link[j].flowClass = SUPCRITICAL;

// --- find inertial damping factor (sigma)
if ( ( Link[j].froude <= 0.5 ) sigma = 1.0;
else if ( Link[j].froude >= 1.0 ) sigma = 0.0;
else sigma = 2.0 * (1.0 - Link[j].froude);

// --- get upstream-weighted area & hyd. radius based on damping factor
// (modified version of R. Dickinson's slope weighting)
rho = 1.0;
if ( !isFull && qLast > 0.0 && h1 >= h2 ) rho = sigma;
aWtd = a1 + (aMid - a1) * rho;
rWtd = r1 + (rMid - r1) * rho;

// --- determine how much inertial damping to apply
if ( InertDamping == NO_DAMPING )   sigma = 1.0;
else if ( InertDamping == FULL_DAMPING ) sigma = 0.0;

// --- use full inertial damping if closed conduit is surcharged
if ( isFull && !xsect_isOpen(xsect->type) ) sigma = 0.0;

// --- find head at midstream location for use in exfiltration computation
hMid = yMid + zMid;

// --- compute terms of momentum eqn.:
// --- 1. friction slope term
if ( xsect->type == FORCE_MAIN && isFull )
    dq1 = dt * forcemain_getFricSlope(j, fabs(v), rMid);
else dq1 = dt * Conduit[k].roughFactor / pow(rWtd, 1.33333) * fabs(v);

// --- 2. energy slope term
dq2 = dt * GRAVITY * aWtd * (h2 - h1) / length;

// --- 3 & 4. inertial terms
dq3 = 0.0;
dq4 = 0.0;
if ( sigma > 0.0 )
{
    dq3 = 2.0 * v * (aMid - aOld) * sigma;
    dq4 = dt * v * v * (a2 - a1) / length * sigma;
}

// --- 5. local losses term
dq5 = 0.0;
if ( Conduit[k].hasLosses )
{
dq5 = findLocalLosses(j, a1, a2, aMid, qLast) / 2.0 / length * dt;

// --- 6. exfiltration term //
// --- Keep track of total elapsed time in simulation.
count += dt; //

// --- Use Orifice Flow Equation to determine Exfiltration and adjust Trench Depth //
// based on Volume exfiltrated from conduit, if Conduit Depth greater than Trench Depth.
// Use Bottom of Trench as Datum for Trench Depth.
if ( (Node[Link[j].node2].oldDepth > FUDGE) && ( hMid > (zT + TDepth) ) )
{
    //velocity head in the conduit section u/s of the perforations in the section (S)
vH = (v * v)/(2 * GRAVITY);

    //discharge coefficient as a function of ratio of velocity head to total energy head (S)
    Cd = 0.63 - (0.58*((vH)/(v1 + vH)));
    fprintf(Output2, "%.10fn",Cd);

    //for a rectangular or square conduit
    Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * ( hMid - (zT+TDepth)))) *(v * v) * NumHoles / length; // (S)

    //for a circular conduit
    if (yMid > ((Diam/2)-(Diam/2)*0.5))
    {
        Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * ( hMid - (zT+TDepth)))) +(v * v) * (NumRows – 2) * NumHoles / length;
    }
    else if (yMid > ((Diam/2)-(Diam/2)*0.866))
    {
        Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * ( hMid - (zT+TDepth)))) +(v * v) * (NumRows – 4) * NumHoles / length;
    }
    else
    {
        Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * ( hMid - (zT+TDepth)))) +(v * v) * NumHoles / length;
    }
if (zMid > (zT + TDepth)) //
{
//for rectangular or square conduit
    Exfil = Cd * SQR(HSize/12) * sqrt((2 * GRAVITY * y1) + (v * v)) * NumHoles / length; //(S)

//for circular conduit
if (yMid > (Diam/2))
{
    Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * (3.5y1 – 1.634(Diam/2))) + (v * v)) * NumHoles / length;
} else if (yMid > ((Diam/2) - ((Diam/2)*0.5)))
{
    Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * (2.5y1 – 0.634(Diam/2))) + (v * v)) * NumHoles / length;
} else if (yMid > ((Diam/2) - ((Diam/2)*0.866)))
{
    Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * (y1/2)) + (v * v)) * NumHoles / length;
} else
{
    Exfil = Cd * (HSize/12) * (HSize/12) * sqrt((2 * GRAVITY * (y1)) + (v * v)) * NumHoles / length;
}

if (zT + TDepth) > (zMid + xsect->yFull) ) Exfil = 0.0; //

ExVol = ExfiltrationVolume(Exfil, length, dt, count); //

if (ExVol > Link[j].oldVolume) //
{
    ExVol = Link[j].oldVolume; //
    Exfil = ExVol / (length * dt); //
}

Link[j].ExfilLink = Exfil * length; //(S)

//to check if exfiltrating volume is greater than available pore volume in trench
TArea = TWidth * length;
ExInRate = ExInfilRate(TArea);
APVol = APoreVol(dt, ExInRate);

if (ExVol > APVol)
{
    ExVol = APVol;
    Exfil = ExVol/(length * dt * 0.5);
    Link[j].ExfilLink = Exfil * length;
}

TDepth = TrenchDepth(ExVol, length, dt); //
if ( TDepth < 0.0 ) TDepth = 0.0; //

hT = (zT + TDepth); //
dq6 = 1.5 * dt * v * Exfil; //

// --- Use Orifice Flow Equation to determine flow back into pipe and adjust Trench Depth
    // based on Volume infiltrated from conduit, if Trench Depth greater than Conduit Depth.
    // Use Bottom of Trench as Datum for Trench Depth.
else if ( (Node[Link[j].node2].oldDept > FUDGE) \&\& ( (zT + TDepth) > hMid ) )
{
    deltaH = ( (zT + TDepth) - hMid ); //

    //available volume of water for flow back into pipe
    AvEp = (deltaH * (TWidth - Size) * length * 0.4)/(Size);

    Exfil = -Cd * SQR( HSzie/12 ) * sqrt(2 * GRAVITY * deltaH ) * NumHoles / length; //(S)
    ExVol = ExfiltrationVolume(Exfil, length, dt, count); //

    if ( ABS(ExVol) > AvEp ) //(S)
    {
        ExVol = -AvEp; //(S)
        Exfil = ExVol / (length * dt * 0.5); //
    }
TDepth = TrenchDepth(ExVol, length, dt); //
if ( TDepth < 0.0 ) TDepth = 0.0; //

hT = (zT + TDepth); //
dq6 = 1.5 * dt * v * Exfil; //

// --- Set Exfiltration and Trench Depth to Zero if no flow in conduit
else
{
    Exfil = 0.0; //
    Link[j].ExfilLink = 0.0;
    ExVol = ExfiltrationVolume(Exfil, length, dt, count); //
    TDepth = TrenchDepth(ExVol, length, dt); //
    if ( hT < zT ) TDepth = 0.0; //
    hT = (zT + TDepth); //
    dq6 = 1.5 * dt * v * Exfil; //
}

if (Steps > 0)
{
    Link[j].newExfilLink = Exfil * length;
    Link[j].ExfilLink = (Link[j].oldExfilLink + Link[j].newExfilLink) * 0.5;
}
else
{
    Link[j].oldExfilLink = Exfil * length;
}

// --- combine terms to find new conduit flow
denom = 1.0 + dq1 + dq5;
q = (qOld - dq2 + dq3 + dq4 - dq6) / denom; //

// --- compute derivative of flow w.r.t. head
Link[j].dqdh = 1.0 / denom * GRAVITY * dt * aWtd / length * barrels;  // (5.0.014 - LR)
// --- check if any flow limitation applies
if ( q > 0.0 )
{
    // --- open channels can't have more than full normal flow
    if ( isFull )
    {
        if ( xsect_isOpen(xsect->type) ) q = MIN(q, Link[j].qFull);
    }

    // --- check for inlet controlled culvert flow
    if ( xsect->culvertCode > 0 && !isFull )
        q = culvert_getInflow(j, q, h1);

    // --- check for normal flow limitation based on surface slope & Fr
    else
        if ( y1 < Link[j].xsect.yFull &&
             ( Link[j].flowClass == SUBCRITICAL ||
               Link[j].flowClass == SUPCRITICAL )
             ) q = checkNormalFlow(j, q, y1, y2, a1, a2, r1);
}

// --- apply under-relaxation weighting between new & old flows;
// --- do not allow change in flow direction without first being zero
if ( Steps > 0 )
{
    q = (1.0 - Omega) * qLast + Omega * q;
    if ( q * qLast < 0.0 ) q = 0.001 * SGN(q);
}

// --- check if user-supplied flow limit applies
if ( Link[j].qLimit > 0.0 )
{
    if ( fabs(q) > Link[j].qLimit ) q = SGN(q) * Link[j].qLimit;
}

// --- check for reverse flow with closed flap gate
if ( link_setFlapGate(j, n1, n2, q) ) q = 0.0;

// --- do not allow flow out of a dry node
//     (as suggested by R. Dickinson)
if( q > FUDGE && Node[n1].newDepth <= FUDGE ) q = FUDGE;
if( q < -FUDGE && Node[n2].newDepth <= FUDGE ) q = -FUDGE;

// --- save new values of area, flow, depth, & volume
Conduit[k].a1 = aMid;
Conduit[k].q1 = q;
Conduit[k].q2 = q;
Link[j].newDepth = MIN(yMid, xsect->yFull);
aMid = (a1 + a2) / 2.0;
aMid = MIN(aMid, xsect->aFull);
Link[j].newVolume = aMid * link_getLength(j) * barrels;     // (5.0.015 - LR)

ExfVol = ExVol + ExfVol;                              // total volume exfiltrated from the conduit (ft3)

fprintf(Output6, "%.10f\n",Exfil);
fprintf(Output7, "%.10f\n",ExfVol);

return q * barrels;

//==================================================
// Function added to compute Exfiltration Volume
//==================================================
double ExfiltrationVolume(double Exfil, double length, double dt, double count)
{
    double EVol;

    // --- Compute Average Exfiltration Volume (in cubic feet) over current time step
    // see setNodeDepth for calculation of dV at a node
    EVol = ( 0.5 * (Exfil * length * dt) );

    return EVol;
}

//==================================================
// Function added to compute Trench Depth for Exfiltration
//==================================================
double TrenchDepth(double ExVol, double length, double dt)
Input: ExVol = Exfiltration volume (ft³)
length = length of conduit (ft)
Output: returns depth of water in excavated trench around storm sewer conduit.
Purpose: determines depth of water in excavated trench around storm sewer conduit.

```
{ double TWidth, // Trench Width (ft)
  BedArea, // Area of Bedding in Trench cross-section (ft²)
  BfArea, // Area of Backfill in Trench cross-section (ft²)
  SqArea, // Trench Width times Conduit Diameter (ft²)
  CondArea, // Area of Conduit in cross-section (ft²)
  TArea, // Bottom Area of Trench (ft²)
  ExInRate; // infiltration rate from exfiltration (cfs)

  double TVol;
  static double Depth; // Trench Depth (ft)
  double Size = 0.67; // Diameter or size of conduit (ft)
  double Bedding; // Depth of Bedding (ft) - typically 0.50
  double Backfill = 0.0; // Depth of Backfill (ft) - typically 1.0

  Bedding = (zMid - zT); //

  // --- Compute Trench Width (in feet) as maximum of conduit diameter
  //     plus 36 inches or 1.5 times conduit diameter plus 12 inches
  TWidth = TrenchWidth(Size); //MAX(Size + (36/12), 1.5 * Size + (12/12) );

  // --- Compute Trench Bottom Area (in square feet) for soil infiltration
  TArea = TrenchArea(TWidth, length); //(TWidth * length);

  // --- Compute Area of Bedding in Trench cross-section (in square feet)
  BedArea = BeddingArea(Bedding, TWidth); //(TWidth * Bedding);

  // --- Compute Area of Backfill in Trench cross-section (in square feet)
  BfArea = BackfillArea(Backfill, TWidth); //(TWidth * Backfill);

  // --- Compute Area of Trench around conduit in Trench cross-section (in square feet)
  SqArea = SquareArea(Size, TWidth); //(TWidth * Diam);

  // --- Compute cross-sectional area of conduit (in square feet)
  CondArea = ConduitArea(Size); //(SQR(Size));

  // --- Compute Pore Volume available for storm water storage (in cubic feet)
  PoreVol = PoreVolume(BedArea, BfArea, SqArea, CondArea, Totlength);
  //(BedArea + BackfillArea + SqArea - CondArea) * length * Porosity;
```
// --- Compute Infiltration Rate (in cfs) for native soil infiltration
ExInRate = ExInfilRate(TArea); // (HydCond * TArea);

// --- Compute Infiltration Volume (in cubic feet) for soil infiltration
ExInVol = ExInfilVolume(dt, ExInRate); // (dt * ExInRate);

// starting with trench full as initial condition
if (ExInVol > (ExVol)) ExInVol = (ExVol);

// --- Compute total trench depth (in feet)
TotDepth = Bedding + Size + Backfill;

// --- Compute Trench Depth (in feet)
Depth += (TotDepth * ( (ExVol - ExInVol) / (PoreVol) ));

if (Depth > TotDepth) Depth = TotDepth;

// --- Return value of trench depth to getConduitFlow
return Depth;
}

// == Function added to compute Trench Width for Exfiltration ==
// ==-------------------------------------------------------------==

double TrenchWidth(double Size)
//
// Input: Diam/Size = diameter of conduit (ft)
// Output: returns width of excavated trench around storm sewer conduit.
// Purpose: determines width of excavated trench around storm sewer conduit.
//
{
    double Width; // Trench Width (ft)

    Width = MAX(Size + (36/12), 1.5 * Size + (12/12));

    // --- Return value of trench width to TrenchDepth
    return Width;
}

// == Function added to compute Bottom Area of Trench for Exfiltration ==
double TrenchArea(double TWidth, double length)
{
    double Area; // Trench Width (ft)
    Area = (TWidth * length);
    // --- Return value of bottom area to TrenchDepth
    return Area;
}

double BeddingArea(double Bedding, double TWidth)
{
    double Barea;
    // --- Compute Area of Bedding in Trench cross-section (in square feet)
    Barea = (TWidth * Bedding);
    return Barea;
}

double BackfillArea( double Backfill, double TWidth)
{
    // Input:  Diam = diameter of conduit (ft)
    // Output:  returns width of excavated trench around storm sewer conduit.
    // Purpose:  determines width of excavated trench around storm sewer conduit.
    //
    double TrenchArea(double TWidth, double length)
    //
    double BeddingArea(double Bedding, double TWidth)
    //
    double BackfillArea( double Backfill, double TWidth)
    //
// Output: returns width of excavated trench around storm sewer conduit.
// Purpose: determines width of excavated trench around storm sewer conduit.
#endif

{ 
    double FillArea;

    // --- Compute Area of Backfill in Trench cross-section (in square feet)
    FillArea = (TWidth * Backfill);

    return FillArea;
}

//====================================================================
=========  // Function added to compute end area of trench around conduit for Exfiltration
//====================================================================

double SquareArea( double Size, double TWidth )
{
    // Input:   Diam/Size = diameter of circular conduit or size of square conduit(ft)
    // Output: returns width of excavated trench around storm sewer conduit.
    // Purpose: determines width of excavated trench around storm sewer conduit.
    
    { 
        double Sarea;

        // --- Compute Area of Trench around conduit in Trench cross-section (in square feet)
        Sarea = (TWidth * Size);
        Sarea = (TWidth * Diam);
        return Sarea;
    }

    // Function added to compute conduit area for Exfiltration
    //===================================
    double ConduitArea(double Size)
    {
        // Input: Diam = diameter of conduit (ft)
        // Output: returns width of excavated trench around storm sewer conduit.
        // Purpose: determines width of excavated trench around storm sewer conduit.
        
        { 
            double Carea;
// --- Compute cross-sectional area of square conduit (in square feet)
Carea = (SQR(Size));

// --- Compute cross-sectional area of circular conduit (in square feet)
// Carea = ((PI/4) * SQR(Diam));

return Carea;
}

// Function added to compute Void Volume for Exfiltration

double PoreVolume(double BedArea, double BfArea, double SqArea, double CondArea, double length)

{
    double PVol;
    double Porosity = 0.40;

    // --- Compute Pore Volume available for storm water storage (in cubic feet)
PVol = (BedArea + BfArea + SqArea - CondArea) * length * Porosity;

    return PVol;
}

// Function added to compute Infiltration to the Native Soil

double ExInfilRate(double TArea)

{
    // Input:  dt = time step (sec)
    // Exfil = Exfiltration rate (cfs/ft)
    // TDepth = Trench depth (ft)
    // Output: returns infiltration rate to soil from exfiltrated volume.
    // Purpose: determines rate of system losses due to infiltration.

}
double HydCond = 0.0006944444; // hydraulic conductivity (ft/s)
double EIR; // Infiltration Rate of soil (cfs)

// --- Use Darcy's Law in the vertical direction to compute
// infiltration losses out of the bottom of the trench
// Q = KA (dH/L); dH = L in vertical direction

EIR = (HydCond * TArea);
return EIR;

//====================================================================
// Function added to compute Infiltration Volume to the Native Soil
//====================================================================

double ExInfilVolume(double dt, double ExInRate)
{
    double EIVol;
    EIVol = ExInRate * dt * 0.5;
    return EIVol;
}

//====================================================================
// Function added to compute Available Volume in the trench (S)
//====================================================================

double AvailableVolume(double length)
{
    double AVol;
    double TWidth = 4.0;
    double Size = 1.0;
    }
double Porosity = 0.4;
// --- Compute Available Volume (in cubic feet)
AVol = ((TWidth * Size) - (Size * Size)) * length * Porosity;

return AVol;

//====================================================================

// Function added to compute Available Volume in the voids (S)
//=====================================================================

double APoreVol(double dt, double ExInRate)
{
    double APVol;

    // --- Compute Available Volume (in cubic feet)
    // APVol = AVol - TVol; // if trench is empty is the initial condition
    APVol = (ExInRate * dt * 0.5); // since trench is full is the initial condition

    return APVol;
}

//====================================================================

// Function added to compute volume of water in trench available for infiltration into soil (S)
//=====================================================================

double TrenchVolume(double AvVol, double ExInVol)
{
    double TVol;

    // if trench is empty as initial condition
    // double Size = 1.5;
    // double Porosity = 0.40;
// if (TDepth > 2) {
  TVol = ((2 * TWidth) + ((TDepth - 2) * (TWidth - Size))) * Totlength * Porosity;
} else {
  TVol = (TDepth * TWidth * Totlength * Porosity);
}
return TVol;
} //for the initial condition that trench is full
TVol = AvVol - ExInVol;
return TVol;

void massbal_addOutflowFlow(double q, int isFlooded) {
  // Input: q = outflow flow rate (cfs)
  // isFlooded = TRUE if outflow represents internal flooding
  // Output: none
  // Purpose: adds flow and exfiltration outflow over current time step to routing totals
  //
  int i; // link index
  double TotExfil = 0; // total exfiltration from entire conduit length/(S)
  for (i = 0; i < Nobjects[LINK]; i++) // (S)
  {
    TotExfil += Link[i].ExfilLink;
  }

  if (q >= 0.0) {
    if (isFlooded) StepFlowTotals.flooding += q;
    else StepFlowTotals.outflow = StepFlowTotals.outflow + q + (TotExfil); // (S)
  }
  else StepFlowTotals.exInflow = StepFlowTotals.exInflow - q;