Integrated Urban Wastewater System Modelling with Conceptual Surrogate Models

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MSc Thesis (WSE-HI.09-10)
April 2009
Integrated Urban Wastewater System Modelling with Conceptual Surrogate Models

Master of Science Thesis
by
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"The work in this report received funding from the EU 6th Framework SWITCH project (no.018530)"

This research is done for the partial fulfilment of requirements for the Master of Science degree at the UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Delft
April 2009
The findings, interpretations and conclusions expressed in this study do neither necessarily reflect the views of the UNESCO-IHE Institute for Water Education, nor of the individual members of the MSc committee, nor of their respective employers.
Abstract

Due to the need of integrated urban wastewater modelling, efforts have been placed on linking existing physically-based models of different urban wastewater components (sewer system, wastewater treatment plant and receiving water) over the past decade. Although, some models have been integrated successfully, it is really time consuming and less cost effective work. Further more, these models are impractical when dealing with strategic planning purpose which aims at getting an overall picture of entire system with relatively rough results and requires quick responses of scenarios from model. Thus, to undertake a holistic analysis of urban wastewater cycle by using relatively simple models of reasonable accuracy is needed. And CITY DRAIN which is a conceptual and integrated model is chosen to meet the purpose and to simulate case study area.

In this research, CITY DRAIN model of Ljubljana City was built and calibrated against an existing Ljubljana MOUSE model. From the assessment of the results, CITY DRAIN model provides a reliable simulation of Ljubljana integrated urban wastewater system. Because of the feature of quick running and capable of providing general perspective, it is proved to be an effective tool to assist decision maker in making efficient strategies.

Besides, since CITY DRAIN model is fully integrated ensuring parallel simulation of three components, Real Time Control blocks (feed back/forward control with P controller) were developed for CITY DRAIN software in this research in order to achieve a good management of interactions in between. Although some limitations exit due to control time lag, generally speaking, in Ljubljana case, RTC blocks successfully controlled discharge of overflows and wastewater treatment plant effluent depending on the environmental requirement of target river location by sending control signals to WWTP and CSO (weirs).

Keywords: CITY DRAIN©, MOUSE, Integrated urban wastewater modelling, Conceptual model, Strategic planning, Real Time Control, CSO Receiving water quality
Acknowledgements

First of all, I would like to thank Assoc. Prof. Zoran Vojinovic for providing me the valuable opportunity to undertake this research and for his continuous guidance during last 6 months as well as studying period.

Next, I want to give my sincere gratitude to Mr. S. Seyoum, MSc. Without his generous help and encouragement from time to time, it is impossible for me to fulfil this research with a high standard.

Thank Prof. Arthur E. Mynett and Prof. Guan for being my examination committee members to give me suggestions and recommendations of my thesis. These will become the treasure in my academic life.

Besides, grateful acknowledge should go to Peter van der Steen and SWITCH project for their financial support. I really appreciate it, which helps me go on to do my research in UNESCO-IHE.

Further more, I want to take this opportunity to express my appreciation to all the staffs in IHE for bring me a cosy life in the Netherlands, to all the teachers who gave me lectures for guiding me in my academic life and to my dearest classmates and colleagues for sharing my experiences and spending the memorable time together.

Finally, special thanks certainly go to my parents and other families. Their unconditional love and support help me overcome lots of difficulties in my life. They are my strength for the road ahead.

Ying Chen
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April, 2009
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<th>Description</th>
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<tr>
<td>CA</td>
<td>Sub-catchment</td>
</tr>
<tr>
<td>CD</td>
<td>CITY DRAIN</td>
</tr>
<tr>
<td>CSO</td>
<td>Combined Sewer Overflow</td>
</tr>
<tr>
<td>DWF</td>
<td>Dry Whether Flow</td>
</tr>
<tr>
<td>PE</td>
<td>Population Equivalent</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>RTC</td>
<td>Real Time Control</td>
</tr>
<tr>
<td>WWTP</td>
<td>Wastewater Treatment Plant</td>
</tr>
</tbody>
</table>
1 Introduction

This chapter presents an introduction of research area – integrated urban wastewater modelling, a brief statement of limitations within the area and objectives as well as significances going to achieve. Finally, it presents the flow chart of methodology showing research methods step by step and the framework of the thesis.

1.1 Brief overview of research area

Urban water cycle is a complex system. It begins with water extracted from streams and aquifers, usually stored in reservoirs and then processed to potable quality via filtration and chlorination processes before delivery through an extensive pipe system to residential, commercial and industrial developments. The effluent from users (so-called wastewater) is then transported through sewer system to wastewater treatment plants which discharge effluent into receiving waters such as rivers, lakes and oceans. Rainfall falling on the catchment contributes to the urban catchment’s stormwater that is collected by an extensive drainage system for disposal into receiving waters through weirs. As for combined network, drainage system for stormwater and sewer system for wastewater is the same network. However, for a separated system they are independent from each other (Coombes and Kuezera, 2002).

1.1.1 The need for integrated model

This research focuses on urban wastewater cycle, which mainly consists of three components (sewer system, WWTP and receiving waters). Figure 1.1 depicts wastewater cycle in urban environment.

![Fig. 1.1: Wastewater cycle in urban environment](Adopted from Achleitner, 2006)

Due to the complexity of wastewater cycle and for the sake of achieving better management, computer models have been used to analyse and predicate system
performance contributing to provide executable solutions. At present, the use of computer models pervades all aspects of water management. In urban water sector, no serious investment decisions are being made without the use of computer models to evaluate various scenarios (Vojinovic and Seyoum, 2008).

Conventionally, three components in urban wastewater cycle are considered and simulated by physically-based models independently. However, with the increasing requirements of urban water environmental management, there has been urgent need to analyse urban wastewater system in an integrated way. This is because interactive connections in between, such as discharges from combined sewer overflow (CSO) during storms and effluents from the treatment plants, have a major impact on the quality of the receiving water (Meirlaen et al, 2001).

The need of assessing integrated wastewater cycle gives rise to the development of integrated model, which aims at realising parallel simulation of each component and their interactions, so that series of feedbacks among them are generated through time and can have a quick impact and respond to each other. All these ensure modelling processes are similar to real processes, providing us reliable results under intensive interactions such as the back-water from receiving waters to sewer system. And real time control technology also can be applied in the system, especially to monitor the transition compartment. All of these can not be put into practice unless the application of integrated models which manage water in a holistic and dynamic way.

1.1.2 Statement of the problem

Although integrated urban wastewater model is urgently needed, the development of it is a challenging task. The main bottleneck is the complexity of the total system that prevents a simple linkage of existing physically-based models of the individual subsystem to an entity (Rauch et al, 2004).

The compatibility between different physically-based sub-models becomes the main issue for their integration. Firstly, this is due to different models being responsible for different components of real urban water cycle, giving rise to lots of parameters and variables. Secondly, it is due to spatial and temporal diversity of each sub-model. Models that need to be linked may not correspond to each other. To be more specific, time steps and duration periods used during computational process within each model differ from each other. To link different models using a common time step and spatial scale tends to require larger amount of data and considerable interpolation in space which is a time consuming work and may not be cost effective. Finally, different data formats embedded in sub-models may cause difficulties when trying to solve the problem of compatibility.

Indeed, over the past decade, efforts have been placed into this area, and some integrated physically-based models have been built successfully. However, they usually take a substantially long time for simulation of detail processes within the whole system, which is impractical to many applications, particularly relevant to those dealing with strategic planning purpose where simulations of long term scenarios are crucial, while detailed routing and reaction processes for sub-catchments, pipe network, WWTP and river branches are not important.
Thereby, to undertake a holistic analysis of urban wastewater cycle by setting up relatively simple models of reasonable accuracy is needed. The idea is to replace individual physically-based models by fast surrogates (simplified models) and link them up on the same platform. So it can run as a whole entity (Vojinovic and Seyoum, 2008). This is referred here as an integrated conceptual modelling approach.

1.1.3 Significances of the research

This research presents an ongoing research work undertaken within the work package 1.2 of the EU funded SWITCH (Sustainable Water Management Improves Tomorrow’s Cities Health) project. The purpose is to contribute the development of a set of tools that can be used to validate scenarios and strategies for integrated urban water management and to assist in finding the right balance between the systems needs, environment and stakeholders’ interests, and enable much more effective decision-making process.

This research addresses an integrated conceptual model (CITY DRAIN model) of urban wastewater system for case study area (Ljubljana City) and evaluates the performance of the model. It demonstrates that such approach can be used for strategic planning of urban wastewater management by simulating diverse scenarios in terms of different storm events, climate change, growth of population and increasing of impervious area. Besides, another research output is the development of RTC blocks, which extends the capability of CITY DRAIN software, and can be used to control river pollution by diverting excessive overflows and WWTP effluent into a designated storage.

1.2 Statement of purpose

1.2.1 Objectives

The overall objective is to build an integrated conceptual model (CITY DRAIN model) to simulate urban wastewater cycle including pipe collection system, receiving waters and WWTP in case study area (Ljubljana City) and to evaluate the capability and effectiveness of modelling system.

More specific objectives are:

- To study and get better insight into urban wastewater system components and their interactions.
- To set up CITY DRAIN model for Ljubljana City and calibrate it against physically-based model (MOUSE).
- To analyse its performance in relation to MOUSE model.
- To discuss the use of CITY DRAIN model for strategic planning purpose.
- To make improvements and to extend current capability of CITY DRAIN software by developing RTC blocks.
1.2.2 Research methods

Figure 1.2 shows methodology flowchart of present research. CITY DRAIN model is set up, calibrated and verified against an existing MOUSE model for Ljubljana City. And then it will act as a surrogate to simulate Ljubljana wastewater system for strategic planning purpose. Besides, RTC application was developed and implemented in CITY DRAIN model to have a better management of entire system.
1.3 Scope and framework of the thesis

1.3.1 Scope of the study
This research places efforts to build CITY DRAIN model, a kind of integrated conceptual model, for the simulation of Ljubljana wastewater system. Analyse the results against exiting MOUSE model and discuss its application for strategic planning purpose. And in order to have a better management of entire system, RTC blocks were developed and applied in CITY DRAIN model to control river pollution by diverting excessive overflows and WWTP effluent in to a designated storage.

1.3.2 Framework of the thesis
This thesis is composed of 7 main chapters. The following paragraphs provide an overview of each chapter.

Chapter 1 presents an introduction of research area – integrated urban wastewater modelling, a brief statement of limitations within the area and objectives as well as significances going to achieve. Finally, it presents the flow chart of methodology showing research methods step by step and the framework of the thesis.

After stating limitations of exiting research results in chapter1 generally, chapter 2 provides literature reviews of the limitations. By comparing features of different integrated urban wastewater models, conclusion is drawn to choose CITY DRAIN, a kind of conceptual integrated model, as an effective tool to simulate urban wastewater system for strategic purpose.

Since CITY DRAIN is selected as the modelling tool, a detail introduction of this model is given in chapter 3. It explains the general features and theoretical basis of the model, and introduces interfaces of main blocks, corresponding parameters as well as computational processes underlying. Further more, there is also an introduction of MOUSE model, which is a physically-based urban wastewater model, because CITY DRAIN will be built and calibrated against it in chapter 4.

Chapter 4 applies CITY DRAIN for case study area, Ljubljana City. It prepares input data for the model and focuses on showing how to build CD model step by step. After setting up the model successfully, parameters need to be adjusted are calibrated in order to get a good match with MOUDE results.

Chapter 5 discusses results generated by CD model and analyse them by comparison with MOUSE results. It proves the results are qualified in most case. However, errors appear under flooding condition, and explanations are provided to help get a deep view of the model. Besides, the prepared model is used to predicate system performance regarding to different situations in the future for the sake of assisting strategic planning.

Due to a good simulation approved in chapter 5, additional RTC blocks are developed in chapter 6 and applied to Ljubljana CD model in order to realise better management of interactions among different urban wastewater components. The basic idea is controlling discharge of overflows and WWTP effluent depending on the environmental requirement in target river location by sending control signals to WWTP and corresponding CSO (weirs).
Chapter 7 is the last part of the thesis. It lists the conclusions of present research, provides limitations and shows recommendations for future research.
2 Background of the Research

After stating limitations of exiting research results in chapter 1 generally, this chapter provides literature review of the limitations. By comparing features of different integrated urban wastewater models, conclusion is drawn to choose CITY DRAIN, a kind of conceptual integrated model, as an effective tool to simulate urban wastewater system for strategic purpose.

2.1 Development of integrated model

Over the last decade, more extensive research has been undertaken to address integrated urban wastewater modelling practice.

Beck (1976) presented the concept of integrated modelling as early as 1976 and the first integrated model was applied many years ago (Gujer et al., 1982). However, the early approaches consider only total emissions from sewer system and treatment plant (Durchschlag et al., 1991). Rauch, Harremoës (1996), Schütze et al.,(1996) and Vanrolleghem et al., (1996) applied deterministic models to the total system, which laid emphasis on the integration of treatment plant, combined sewer overflow to receiving waters as well as total sewer system.

Recently, due to the development of appropriate software platforms, it is possible to develop academic software for the entire urban wastewater system (Rauch et al, 2004).

According to Mark and Williams (2000), Danish Hydraulic Institute (DHI) and Water Research centre in GB (WRc) developed an “Integrated Catchment Simulator (ICS)” sponsored by EU “Technology Validation Project”. ICS provides a graphical interface to build and run integrated models. The present version encompasses MOUSE to simulate sewer system, Mike 11 to simulate rivers, STOAT to simulate wastewater treatment plants as well as costal areas. With the development of ICS, the existing models firstly are linked in a sequential way and later in a simultaneous way. Although there is a significant improvement, the complexity of sub-modules constrains further applications.

WEST is another software platform, which is originally developed for wastewater treatment modelling. The strength of it is to compute the dynamics between each interlinked elements in the whole network, while the function to describe water motion and transport process within each element (representing catchments, CSO-structures, reactors, clarifiers, river reaches, etc) is limited (Meirlaen et al., 2001).

SIMBA® is a simulation platform running on top of MATLAB®/SIMULINK® which is delivered by institute fur Automation und Kommunikation e.V. Magdeburg, Germany (http://www.ifak.de) (Freni et al, 2003). Due to MATLAB®/SIMULINK® environment, other users can develop their components to meet the specific condition making the software more flexible and more applicable. Therefore, it can stimulate the motivation of other users and shorten the distance between the developer and user (Rauch et al, 2004). It is similar to WEST with respect to the network concept, which
means SIMBA is just the simulation of single dynamic events with interactions between treatment plant and sewer system focus on the interactive relationship and feedbacks between each component. Hence, SIMBA sewer is not a replacement for conventional sewer system but a special tool to investigate managed sewer systems and integrated systems. Besides, since the theoretical basis of Saint Venant equation, it is able to simulate any closed or open kind of cross section profile, changing roughness along the wetted perimeter, and pressurized flow.

SYNOPSIS (“software package for Synchronous optimization and simulation of the urban wastewater system”) is composed of three main simulation sub-programs for modelling water flow and quality processes in the urban drainage system, WWTP and river system. And the urban drainage sub-model is based on the KOSIM program, the WWTP sub-model is based on a slight simplification of the IWA Activated Sludge Model No.1, and the river sub-model is based on the DUFLOW shell program. The three sub-models can be integrated into one simulation program, within which the urban drainage system and WWTP are running simultaneously, while the river sub-model is running as a sequential process. The simulation of the integrated system in this manner satisfies the requirements for investigating the relationship between overflows and receiving water quality (Zacharof et al, 2004). However compare with fully integrated model such as CITY DARIN, this kind of partially integrated model still need to be modified for a better simulation in a holistic manner.

CITY DRAIN is open source software for the integrated modelling of urban drainage systems and was developed by Achleitner and Rauch at the Institute of Environmental Engineering at the University of Innsbruck, Austria (Achleitner, 2006). Similar to SIMBA, it is also developed in the MATLAB®/SIMULINK® environment, enabling a block wise modelling of the different parts of the urban drainage system. Consequently, it has the same advantage with SIMBA in terms of open source software. However different from SIMBA, it can not only simulate the feedback of the interactive compartments but also processes within each elements and run as an entire system. The Muskingum method is used for flow routing in the catchment, sewer and river blocks. Besides, mass transport of pollutants is implemented for conservative matter/tracer substances. Because of Muskingum method which is used to calculate open channel flow, CITY DRAIN is not capable enough to model pressurized flow, surface flooding and backwater flow.
2.2 Comparison of existing integrated models

Table 2.1 lists the comparison between existing integrated models.

<table>
<thead>
<tr>
<th>Name</th>
<th>Features</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICS</td>
<td>Graphical interface to build &amp; run physically-based model (DHI &amp; WRC)</td>
<td>Applicable in design &amp; operation stage</td>
<td>Complexity of sub-modules limits further application and time consuming simulation</td>
</tr>
<tr>
<td>WEST</td>
<td>Belgian simulator platform</td>
<td>Dynamics between interlinked elements</td>
<td>Limited in simulating processes within elements</td>
</tr>
<tr>
<td>SIMBA</td>
<td>Simulation platform on top of MATLAB/SIMULINK</td>
<td>Capable to compute different kinds of flow conditions</td>
<td>Limited in simulating processes within elements</td>
</tr>
<tr>
<td>SYNOPSIS</td>
<td>Components simulated by different models</td>
<td>Sewer and WWTP modules run simultaneously</td>
<td>Partial parallel simulation</td>
</tr>
<tr>
<td>City Drain</td>
<td>Simulation platform on top of MATLAB/SIMULINK</td>
<td>Fully integrated, parallel simulation/open source</td>
<td>Incapable to compute pressurized flow</td>
</tr>
</tbody>
</table>

From the above comparison, it can be concluded that CITY DRAIN model is the most suitable tool for strategic planning purpose. Since it supports fully integrated and parallel simulation, it can provide a big picture of the whole system which benefit decision maker to get a comprehensive overview easily. And due to simplified computational method underlying, it can finish long term simulation at a fast speed, predicating system performances under different conditions in a short time. CD model is implemented on catchment level, without look into detailed physical processes.

Thus, CITY DRAIN model is chosen for Ljubljana case and it is a convenient tool for the sake of strategic planning.
3 Modelling Tools Used in the Research

Since CITY DRAIN is selected as the modelling tool, a detail introduction of this model is given in this chapter. It explains the general features and theoretical basis of the model, and introduces interfaces of main blocks, corresponding parameters as well as computational processes underlying. Further more, there is also an introduction of MOUSE model, which is a physically-based urban wastewater model, because CITY DRAIN will be built and calibrated against it.

3.1 CITY DRAIN

3.1.1 General features of CITY DRAIN

CITY DRAIN (Copyright© 2007, Stenfan Achleitner and Wolfgang Rauch, Unit of Environmental Engineering – Institute of Infrastructure, University of Innsbruck) is an integrated and conceptual software to simulate urban wastewater system. The purpose of integration is to meet the increasing requirements of improving urban water quality based on the overall management of river basin (Blöch, 1999). Besides, for allowing long term simulation and for the convenience of integration, the blocks implemented in CITY DRAIN are based on simple conceptual model. Thus, the main function of CITY DRAIN shifts from design purpose to strategic planning compared with traditional urban wastewater models.

As software for integrated modelling, CITY DRAIN encompasses all the main components in urban water system. Figure 3.1 shows the main components and the information flow between them.

![Fig. 3.1: Schematic on the main components and information flow in CITY DRAIN](Adopted from Rauch et al., 2002a)
Computational aspects for hydraulics

Flow of water in both sewers and rivers is described by the continuity and storage equations in CITY DRAIN. The latter one is called Muskingum Method which is a simplified discrete method (kinematic wave) to replace momentum equation. It has first been applied to flood control work on the Muskingum River, therefore it has been called Muskingum Method (Roberson et al., 1995).

Together with continuity equation, they are used to calculate flow routing through channels. However, backwater effects and flooding condition of sewer system can not be well simulated.

Computational aspects for transport and conversion of matter

For limiting the effort of modelling only relevant pollutants and processes need to be considered. Neglecting issues of secondary importance is required to avoid unnecessary complexity of models. Transport models describe in principle only the flow of soluble and conservative matter through the system. Effects such as physical or biological conversion processes (sedimentation, degradation, etc) are considered by extension of the transport equations. (Achleitner and Rauch, 2007)

Overall the computation in CITY DRAIN is based on a fixed discrete time steps approach where each subsystem uses the same time increments, usually being predetermined by the timely resolution of the rain data used. Models implement for hydraulics and mass transport are formulated for discrete time steps. (Achleitner and Rauch, 2007)

Realising CITY DRAIN in MATLAB/SIMULINK

The principle of block-wise modelling of integrated system in CITY DRAIN has been developed in a MATLAB/SIMULINK environment. It is because the platform is not only tailored for dynamic and time dependent simulations but also hand an available graphical user interface.

Units in CITY DRAIN

- Q [m³/s] – Flow
- V [m³] – Volume
- L [m] – Length
- t, Δt [s] – Time
- C [g/m³] – Concentration
- M [g] – Mass
- R [mm] – Rainfall, initial loss or permanent loss
- A [hectare] – Area
3.1.2 Main blocks in CITY DRAIN

CITY DRAIN library

All blocks in CITY DRAIN are listed in the library. And they are classified into 5 sections, (see figure 3.2) which are source block, catchment/sewer block, wastewater treatment block, river block and tools block. Core block for every simulation is “CD parameters” organizing global settings for each simulation.

Core block

Core element of every CITY DRAIN simulation is the block “CD – Simulation Parameters” (see figure 3.3).
This block ensures that simulation parameters in the MATLAB/SIMULINK are defined correctly. And within this block, the user can set the pollutants going to simulate, time step for computation (Sampling Time), and time duration (Start Time and Stop Time).

**Source blocks**

- **Rainread**
  Rainread (see fig 3.4) reads data from ASCII files having a predefined format (the supporting formats are ‘ixx’, ‘km2’ and ‘mse’). It generates the volume of rain per time step in mm/Δt and running time is virtually transferred to the SIMULINK environment.

  ![Rainread Block](image)
  ![Rainread Parameters](image)
  
  **Fig. 3.4: Block of Rainread**

- **Flowread**
  Flowread (see figure 3.5) reads flow data from ASCII files containing time t, flow Q and concentration C as input. Data is to be provided column wise. First row in the file allows holding an alpha-numeric descriptor for column data. Data provided may either represent grab samples (measurement at specific point of time) or composite samples (values representing the mean concentration/flow over time).

  It generates flow and pollutant concentration which is automatically inherited from the ASCII file storing the raw data.

  ![Flowread Block](image)
  ![Flowread Parameters](image)
  
  **Fig. 3.5: Block of Flowread**
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Catchment/Sewer blocks

Here just introduce the blocks used in the model for case study area.

- **Catchment CSS**

Catchment CSS block (see Figure 3.6) is designed to simulate a combined sewer system on catchment level. The block deals with the major drainage-related processes in an urban area and returns for each time step both the discharge and pollutant concentration of the outflow from the catchment. And the input parameters are:

\[
\begin{align*}
  r_L & \quad \text{Rain volume per time step [mm/Δt];} \\
  Q_{DWF,L} & \quad \text{Dynamic dry weather flow [q(m}^3\text{/s)} C(g/m}^3\text{)];} \\
  Q_{P,L} & \quad \text{Dynamic flow parasite water [q(m}^3\text{/s)} C(g/m}^3\text{)];} \\
  Q_e & \quad \text{Waste/storm water from an upstream catchment [q(m}^3\text{/s)} C(g/m}^3\text{)].}
\end{align*}
\]

![Fig. 3.6: Block of Catchment CSS](image)

Multiple sub-reaches theory is applied in Muskingum method under this block, which divides the catchment into many sub-reaches (for detail explanation refers to page18).

Figure 3.7 shows the routing processes under Catchment CSS block

![Fig. 3.7: Routing processes under Catchment CSS block](image)

(1) Catchment loss model

The function of this step is to subtract initial and permanent loss to a given precipitation. And to get effective runoff height.

\[
\begin{align*}
  h_e &= (r_L - h_i - h_p) \varphi \\
  \varphi &= \frac{A_p}{A}
\end{align*}
\]
where:

- \( h_i \) – Initial loss;
- \( h_p \) – Permanent loss;
- \( \varphi \) – Runoff coefficient, in the range of \([0, 1]\);
- \( A_e \) – Effective area (impervious area);
- \( A \) – Whole area;
- \( h_e \) – Effective runoff per time step (output);
- \( r_i \) – Rain volume per time step (input).

(2) Catchment Flow Model – SW

The function of this step is to generate outflow \( q_e \) from a given effective runoff height \( h_e \). And then the pollutant concentrations – given as constant parameters – are added to the flow.

\[
q_e = A * h_e / (1000 * \Delta t)
\]

where:

- \( A \) – Catchment area;
- \( \Delta t \) – time step, inherited from the global setting;
- \( h_e \) – Effective runoff per time step (input);
- \( q_e \) – Stormwater runoff (output).

\[
Q_e = [q_e, C_1, \ldots, C_n]
\]

After the concentrations are added, the output is in the form of vector \( Q_e \).

(3) Muskingum Method

This method is not only used in Catchment CSS block, but also is the theory of river block.

In Muskingum Method, for a wave passing a reach of a channel (see figure 3.8), the storage is described as a function of inflow \( (Q_i) \) and outflow \( (Q_e) \):

\[
V = K * Q_e + K * X * (Q_i - Q_e)
\]

Where:

- \( K \) – Time required for a unit discharge wave travelling through the reach \((K \approx \Delta t)\);
- \( X \) – Dimensionless weighting factor related to the amount of wedge storage.

Fig. 3.8: Flow in channels (a) Steady – uniform flow and (b) Flood – wave flow
The first term of the right side represents the prismatic storage where the second represents the wedge storage. Since \( K \approx \Delta t \), the term for prismatic storage can be written as:

\[
K \cdot Q_E = \Delta t \cdot Q_E = \Delta t \cdot V \cdot A_0 = L \cdot A_0
\]

With the continuity equation:

\[
\Delta V / \Delta t = Q_I - Q_E
\]

The flow \( Q_I \) and \( Q_E \) as well as storage \( V \) vary over time. They are approximated by their values at time \( (i+1) \):

\[
Q_I = (Q_{I,i} + Q_{I,i+1}) / 2,
Q_E = (Q_{E,i} + Q_{E,i+1}) / 2
\]

\[
\Delta V = V_{i+1} - V_i
\]

Thus, the continuity equation can be written as:

\[
Q_{I,i} + Q_{I,i+1} + 2V_I / \Delta t - Q_{E,i} = Q_{E,i+1} + 2V_{i+1} / \Delta t
\]

The storage equation is formulated for time step \( i \) and \( i+1 \) as well:

\[
V_i = K \cdot [X \cdot Q_{I,i} + (1-X) \cdot Q_{E,i}]
V_{i+1} = K \cdot [X \cdot Q_{I,i+1} + (1-X) \cdot Q_{E,i+1}]
\]

Substitute storage volumes \( V_i \) and \( V_{i+1} \) in the continuity equation leads to:

\[
Q_{E,i+1} = C_0 \cdot Q_{I,i+1} + C_1 \cdot Q_{I,i} + C_2 \cdot Q_{E,i}
\]

The three coefficients are specific for Muskingum Method.

\[
C_0 = \frac{0.5 \cdot \Delta t - K \cdot X}{K \cdot (1-X) + 0.5 \cdot \Delta t}, \quad C_1 = \frac{0.5 \cdot \Delta t + K \cdot X}{K \cdot (1-X) + 0.5 \cdot \Delta t}, \quad C_2 = \frac{K \cdot (1-X) - 0.5 \cdot \Delta t}{K \cdot (1-X) + 0.5 \cdot \Delta t}
\]

For numerical stability the following boundary conditions are to be fulfilled:

\( K \geq \Delta t \) (for assessing the wave travelling through the reach)
\( C_0, C_1, C_2 \geq 0 \) (all terms are required to contribute to a generated outflow)

This leads to the final relation to be fulfilled for combinations of \( K, X \) with constant time steps \( \Delta t \):

\[
\frac{1}{2(1-X)} \leq \frac{K \cdot \Delta t}{2X} \leq \frac{1}{2X}
\]

Further, the dimensionless weighing factor \( X \) has to fulfill that:

\[
\frac{1}{2(1-X)} \leq \frac{1}{2X}
\]

Consequently, valid numerical values for \( X \) are in the range between 0 and 0.5. Further, the two extremes for \( X \) define special cases. The lower limit (\( X=0 \)) represents the linear hydraulic storage where the upper limit (\( X=0.5 \)) equals the translation without peak damping.
Applying the Muskingum Method for flood routing with multiple sub-reaches, the same equations are generally used. Adaptations are needed with regard to nomenclature that needs to include the numbering of sub-reaches \( j \) (1...n) (see Figure 3.9).

![Fig. 3.9: Schematic on nomenclature for multiple sub-reaches](image)

The Muskingum parameter \( K \) applies to the total reach. For simplicity a reach is always split for \( n \) equal sub-reaches, each having an associated Muskingum parameter \( K' \):

\[
K' = \frac{K}{n}
\]

The flow from the sub-reach \( j \) can be written as

\[
Q_{i+1}^{j+1} = C_0 * Q_{i+1}^j + C_1 * Q_i^j + C_2 * Q_{i-1}^j
\]

Using

\[
C_0 = \frac{0.5 * \Delta t - K' * X}{K' * (1 - X) + 0.5 * \Delta t}
\]

\[
C_1 = \frac{0.5 * \Delta t + K' * X}{K' * (1 - X) + 0.5 * \Delta t}
\]

\[
C_2 = \frac{K' * (1 - X) - 0.5 * \Delta t}{K' * (1 - X) + 0.5 * \Delta t}
\]

Current Volume stored for a sub-reach \( j \) is calculated as:

\[
V_{i+1}^j = K' * [X * Q_{i+1}^j + (1 - X) * Q_{i+1}^j]
\]

And the total volume in the reach is

\[
V_{i+1} = \sum_{j=1}^{n} V_{i+1}^j
\]

Figure 3.10 shows the schematic computation processes under CITY DRAIN catchment block. Surface runoff and sewer flow routing process are lumped with each other.

![Fig. 3.10: Schematic on nomenclature for multiple sub-reaches](image)
CSO

CSO (see figure 3.11) is used for simulation of an overflow structure for either combined or separate sewer. Inflow ($Q_i$) is routed downstream via the effluent outlet ($Q_e$) which is limited by a maximum effluent flow rate $Q_{E,MAX}$. Flow exceeding the structures storage capacity ($V_{MAX}$) is routed via the CSO overflow ($Q_W$).

![Image of CSO](image)

The basic differential equation of hydraulic mass balance for CSO structure is:

$$\frac{\partial V}{\partial t} = Q_i(t) - Q_E(t) - Q_W(t)$$

The flows $Q_i$, $Q_E$ and $Q_W$ (see figure 3.12) are considered as mean flows occurring during the discrete timely period. Thereby, the volume is related to discrete points of time. The mass balance equation is

$$\frac{V_i - V_{i-1}}{\Delta t} = Q_{i,i} - Q_{E,i} - Q_{W,j}$$

Where $i$ denotes the time step considered. Restrictions are usually given by the maximum volume of the CSO structure ($V_{MAX}$) and the maximum outflow from the structure $Q_{E,MAX}$.

Depending on the magnitude of inflow $Q_{Li}$ and the previous volume stored ($V_{i-1}$), three different cases applied. The cases can be differentiated considering the hydraulics mass balance with no overflow $Q_W = 0$ and fully developed outflow $Q_E = Q_{E,MAX}$. The virtual volume $V_{i}'$ from this mass balance denotes

$$V_{i}' = (Q_{Li} - Q_{E,MAX})\Delta t + V_{i-1}$$
Case 1
If \( V_i' \leq 0 \)
Then \( V_i = 0; \quad Q_{E,i} = \frac{Q_{i-1}}{\Delta t} \leq Q_{E,\text{MAX}}; \quad Q_{W,i} = 0; \)

Case 2
If \( V_i' \geq V_{\text{MAX}} \)
Then \( V_i = V_{\text{MAX}}; \quad Q_{E,i} = Q_{E,\text{MAX}}; \quad Q_{W,i} = Q_{i} - Q_{E,\text{MAX}} - \frac{(V_{\text{MAX}} - V_{i-1})}{\Delta t}; \)

Case 2
If \( 0 < V_i' < V_{\text{MAX}} \)
Then \( V_i = (Q_{i} - Q_{E,\text{MAX}}) \frac{\Delta t}{\Delta i}; \quad Q_{E,i} = Q_{E,\text{MAX}}; \quad Q_{W,i} = 0; \)

### Pumping station
The block (see figure 3.13) is to describe a pumping station with a number of pumps, each with its fixed pumping rate and its set point (water level) for turning pump either on or off.

It generates \( Q_p \) as pumped flow to the following sewer network and \( Q_w \) as overflow which excess the pumped flow, as well as the current volume and concentration of water stored in the pumping station.

![Function Block Parameters: Pumping Station](image)

**Fig. 3.13: Block of Pumping station**
WWTP block

The block (see figure 3.14) models a WWTP that is considered to fulfil predefined requirements of
-- removal efficiency $R_{\text{E,MIN}}$ and
-- maximum effluent concentration $C_{E,\text{MAX}}$

Thus, emission standards are considered to be fulfilled, regardless the hydraulic or pollutant load associated. In the model no process are considered.

River block – Muskingum_sM_QC

Muskingum_sM_QC block (figure 3.15) describes the flood routing by the Muskingum Method (the same with that under Catchment CSS block). The block provides hydraulic routing as well as routing of pollutants using a user defined number of multiple sub-reaches.
3.2 MOUSE

An existing MOUSE model of case study area is used to provide input data to CITY DRAIN model. And for the comparison between two models.

MOUSE is a physically-based model for simulation of urban drainage system. It combines complex hydrology, hydraulics, water quality in a completely graphical interface (see figure 3.16).

Essentially, MOUSE divides an urban wastewater system into two parts: urban catchments and drainage network (see figure 3.17). The two parts are distinguished by the description of the processes and by the structural description. Also, different types of boundary data are specified for each part. The explicit distinction is underlined by the fact that the numerical computational engines are fully separated and based on different algorithmic solutions. The run-off processes are computed by one of the MOUSE Runoff Models, and the MOUSE Hydrodynamic Pipe Flow Model computes the network flows. The hydrodynamic computations are then used as a basis for the computation of other relevant processes.

Fig. 3.16: Graphic interface of MOUSE

Fig. 3.17: Schematic computation processes in MOUSE

[Adopted from Achleitner, 2006]
3.2.1 MOUSE catchment – surface runoff module

The modelled urban area can be divided into a large number of MOUSE catchments with several catchments attached to each network node. The central MOUSE element of the system data related to surface runoff process is the MOUSE catchment. The catchments are identified by catchment names. Each MOUSE catchment is attached to one of the nodes of pipe network node (manhole) and this link is essentially identified by the node ID. The information related to one catchment includes all relevant physical and hydrological properties for the geographical area with the specified catchment boundaries.

MOUSE surface runoff module includes five types of surface runoff computation (Time/area Method, Non-linear Reservoir Method, Linear Reservoir Method (Dutch runoff model, French runoff model) and Unit Hydrograph Model). This means that the surface runoff computation can be adjusted according to the amount of available information. However, in one simulation run it is not possible to combine different runoff computation concepts for various model areas. The computed hydrographs are used as input to the MOUSE Pipe Flow Model.

3.2.2 MOUSE drainage network – hydrodynamic pipe flow model

The drainage network in Mouse is geographically and topographically fully determined (x, y and z co-ordinates), so that a MOUSE network in fact resembles a schematized view of a real network. Each MOUSE network consists of nodes, which are connected by links. Two nodes determine each link. There are several types of node—manhole, basin, storage node and outlet—representing some structural element of a real drainage network. For the pipe, users can also define shape and material of them.

Computational foundation underlying drainage network is MOUSE hydrodynamic Pipe Flow Model, which solves the complete St. Venant (dynamic flow) equations throughout the drainage network, which allows for modelling of backwater effects, flow reversal, surcharging in manholes, free-surface and pressure flow. And the program has been designed to handle any type of pipe network system with alternating free surface and pressurized flows as well as open channel network.

3.2.3 Boundary conditions

For surface runoff module, rainfall data is the main boundary condition. While for pipe flow, boundary conditions can be water levels, inflow discharges and dry weather load discharge.
Modelling Tools Used in the Research
4 The Case Study

This chapter applies CITY DRAIN for case study area, Ljubljana City. It prepares input data for the model and focuses on showing how to build CD model step by step. After setting up the model successfully, parameters need to be adjusted are calibrated in order to get a good match with MOUDE results.

4.1 Description of the case study area

CITY DRAIN was applied to model integrated urban wastewater system of Ljubljana City. Ljubljana is capital of Slovenia (see figure 4.1), located at an altitude of 298 metres in the valley of the river Ljubljanica (see figure 4.2), with an urbanized catchment area of approx. 4,000ha, among which 600ha has impervious surface.

The length of the sewer system is about 700km and it is combined sewer network. Sewer systems and sub catchments are distributed along River Ljubljanica in the city (see figure 4.2). 72 overflow structures are distributed over the whole system. Most of them are along the river. And it has a WWTP located downstream. The system has a daily load of about 343,906 PE.
4.2 Preparation of input data

CITY DRAIN model was built against existing MOUSE Model of Ljubljana City (see figure 4.3). The red lines represent Ljubljanica river in Ljubljana, the blue lines stand for the direction of CSO and pipe network represents combined sewer system along the two rivers. Thereby, most of the data needed for building CITY DRAIN can be read directly from MOUSE.

![Fig. 4.3: MOUSE model of Ljubljana](image)

Table 4.1 lists required data from MOUSE. Among them, some are fixed data that cannot be changed during calibration, while some were used as starting point and were corrected in calibration.
Table 4.1 Data required from MOUSE

<table>
<thead>
<tr>
<th>Sub-catchments (CA)</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE Population equivalents</td>
<td>[-]</td>
</tr>
<tr>
<td>$t_{f}$ Time of concentration in CA</td>
<td>[s]</td>
</tr>
<tr>
<td>A Sub-catchment area</td>
<td>[ha]</td>
</tr>
<tr>
<td>$\varphi$ Run-off coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$h_i$ Initial loss</td>
<td>[mm]</td>
</tr>
<tr>
<td>$h_p$ Permanent loss</td>
<td>[mm/ \Delta t]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CSO</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{MAX}}$ Basin volume of CSO</td>
<td>[m$^3$]</td>
</tr>
<tr>
<td>$Q_{E,\text{MAX}}$ Maximum effluent flow</td>
<td>[m$^3$/s]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pumping stations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>V Basin volume of Pumping station</td>
<td>[m$^3$]</td>
</tr>
<tr>
<td>$Q_p$ Mean pumping rate</td>
<td>[m$^3$/s]</td>
</tr>
<tr>
<td>$h_{\text{on}}$ Water level of ON set point</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_{\text{off}}$ Water level of Off set point</td>
<td>[m]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rain data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$ Accumulate rainfall height in $\Delta t$</td>
<td>[mm]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DWF Dry weather flow hydrograph</td>
<td>[m$^3$/s] and [g/m$^3$]</td>
</tr>
<tr>
<td>River Boundary condition of River</td>
<td>[m$^3$/s] and [g/m$^3$]</td>
</tr>
</tbody>
</table>

(* in CITY DRAIN $t_{f}$ is taken place by Muskingum parameters $K$ and $N$ effecting peak time of outflow)

4.2.1 Global parameters

Table 4.2 Global parameters

<table>
<thead>
<tr>
<th>CD parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Model substance list (pollutant simulated)</td>
<td>ammonia</td>
</tr>
<tr>
<td>Sample time (time step)</td>
<td>300 sec</td>
</tr>
<tr>
<td>Start time (1995,4,24)</td>
<td>0 sec</td>
</tr>
<tr>
<td>Stop time (1995,4,26 two days)</td>
<td>172800 sec</td>
</tr>
</tbody>
</table>

4.2.2 Sub-catchment parameters

Refer to table 4.1; there are 6 parameters for a sub-catchment. When tried to interpret MOUSE into CITY DRAIN, some CAs in MOUSE were lumped as one CA. Therefore, parameters PE and A of CITY DRAIN are just the sum of corresponding CAs in MOUSE. PE and A don’t need to calibrate. As for $\varphi$, basically it is calculated for each CAs according to MOUSE data. However in some occasion, it can be slightly modified to achieve a better fitness.

$t_{f}$ was adjusted through calibration. Because of different routing processes within conceptual models and physically-based models, these parameters can not just inherited from MOUSE.

Value of $h_i$ was copied from MOUSE. Besides, $h_p$ was taken into account only during dry weather periods, so it was neglected in CITY DRAIN when run series of rainfall events.
4.2.3 CSO parameters
The value of $V_{\text{MAX}}$ and $Q_{E,\text{MAX}}$ of weirs in MOUSE is very important reference for setting CSOs in CD. However, they were calibrated in CITY DRAIN in order to get a good fitting of the results.

4.2.4 Pumping station parameters
The values of pumping station were all inherited from MOUSE. However, in CITY DRAIN, two pumps were used to simulate the condition of changing pumping rate from one state to another. The effect was the same. Table 4.3 lists parameters of it.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin Volume</td>
<td>1260 m$^3$</td>
</tr>
<tr>
<td>Number of pumps</td>
<td>2</td>
</tr>
<tr>
<td>Pumping rate</td>
<td>[0.078 0.01]</td>
</tr>
<tr>
<td>Volume on</td>
<td>[644 32900]</td>
</tr>
<tr>
<td>Volume off</td>
<td>[400 644]</td>
</tr>
</tbody>
</table>

4.2.5 Rainfall data and flow data

**Rainfall data**
Rainfall data was exported from MOUSE and separated as different rainfall events. MSE format was chosen for rainfall input files.

**DWF**
In MOUSE, DWF data is produced depending on the inhabitant of the sub-catchment, PE based average discharge of wastewater per day and diurnal hourly factor. Whereas, the unit of value stored in the CITY DRAIN DWF input file is m$^3$/s. Thus, the following equation was used to transfer data.

\[
\text{Average value m}^3/\text{PE/day} = \frac{0.182}{24 \times 3600} = 2.1 \times 10^{-6} \text{ m}^3/\text{PE/s}
\]

Among which

\[
\text{Total seconds of a day} = 0.182 / (24 \times 3600) = 2.1 \times 10^{-6} \text{ m}^3/\text{PE/s}
\]

PE of each sub-catchment (see table 4.4)

<table>
<thead>
<tr>
<th>Catchment ID</th>
<th>PE</th>
<th>Catchment ID</th>
<th>PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment CSS01</td>
<td>3938</td>
<td>Catchment CSS12</td>
<td>5568</td>
</tr>
<tr>
<td>Catchment CSS02</td>
<td>17113</td>
<td>Catchment CSS13</td>
<td>7416</td>
</tr>
<tr>
<td>Catchment CSS03</td>
<td>18202</td>
<td>Catchment CSS14</td>
<td>3654</td>
</tr>
<tr>
<td>Catchment CSS04</td>
<td>2767</td>
<td>Catchment CSS15</td>
<td>5691</td>
</tr>
<tr>
<td>Catchment CSS05</td>
<td>8856</td>
<td>Catchment CSS16</td>
<td>643</td>
</tr>
<tr>
<td>Catchment CSS06</td>
<td>3436</td>
<td>Catchment CSS17</td>
<td>9346</td>
</tr>
<tr>
<td>Catchment CSS07</td>
<td>983</td>
<td>Catchment CSS18</td>
<td>1056</td>
</tr>
<tr>
<td>Catchment CSS08</td>
<td>39433</td>
<td>Catchment CSS19</td>
<td>15928</td>
</tr>
<tr>
<td>Catchment CSS09</td>
<td>3952</td>
<td>Catchment CSS20</td>
<td>10535</td>
</tr>
<tr>
<td>Catchment CSS10</td>
<td>164919</td>
<td>Catchment CSS21</td>
<td>3080</td>
</tr>
<tr>
<td>Catchment CSS11</td>
<td>6855</td>
<td>Catchment CSS22</td>
<td>10535</td>
</tr>
</tbody>
</table>

**SUM** 343906
Diurnal hourly factor (see table 4.5)

<table>
<thead>
<tr>
<th>hour</th>
<th>00-01</th>
<th>01-02</th>
<th>02-03</th>
<th>03-04</th>
<th>04-05</th>
<th>05-06</th>
<th>06-07</th>
<th>07-08</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>0.78</td>
<td>0.72</td>
<td>0.66</td>
<td>0.63</td>
<td>0.64</td>
<td>0.72</td>
<td>0.91</td>
<td>1.08</td>
</tr>
<tr>
<td>hour</td>
<td>08-09</td>
<td>09-10</td>
<td>10-11</td>
<td>11-12</td>
<td>12-13</td>
<td>13-14</td>
<td>14-15</td>
<td>15-16</td>
</tr>
<tr>
<td>value</td>
<td>1.15</td>
<td>1.17</td>
<td>1.18</td>
<td>1.17</td>
<td>1.19</td>
<td>1.16</td>
<td>1.15</td>
<td>1.14</td>
</tr>
<tr>
<td>hour</td>
<td>16-17</td>
<td>17-18</td>
<td>18-19</td>
<td>19-20</td>
<td>20-21</td>
<td>21-22</td>
<td>22-23</td>
<td>23-24</td>
</tr>
<tr>
<td>value</td>
<td>1.13</td>
<td>1.11</td>
<td>1.13</td>
<td>1.15</td>
<td>1.14</td>
<td>1.06</td>
<td>0.97</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Besides, concentration of pollutant in DWF is the same with MOUSE (only ammonia was considered, and it is a constant value equals to 33.8 g/m³).

**Boundary condition of river**

Boundary conditions of river include discharge and concentration. There were two boundary conditions required. They were all read from MOUSE (see table 4.6).

<table>
<thead>
<tr>
<th>river</th>
<th>Discharge (constant value)</th>
<th>Concentration (ammonia constant value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ljubljanica</td>
<td>20</td>
<td>0.45</td>
</tr>
<tr>
<td>Ljubljanica (small)</td>
<td>5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**4.2.6 WWTP parameters**

Since MOUSE can not model WWTP, parameters of it are not available. When setting up WWTP in CITY DRAIN, we assumed removal efficiency $R_{E,MIN} = 0.75$ and maximum effluent concentration $C_{E,MAX} = 1.5$ g/m³

**4.3 Set up Ljubljana CD model**

The following points are considered in setting up the sub-catchments in CITY DRAIN.

- Since water quality simulation of river is an important factor in my research, river nodes receiving sewer overflow are very important locations in the network.

- On the basis of basic principal in second step, very flexible methods were applied according to the various distribution of sewer network in Ljubljana.

- Other users may find the best way to divide sub-catchment according to their different research requirements and the feature of their sewer systems.

The following text shows steps how to build CITY DRAIN Model as a surrogate for MOUSE in this research.

Firstly, selected main river nodes which receive overflow from sewer system in MOUSE.

Figure 4.4 shows 12 marked river nodes and blue lines stand for the direction of CSO.
Fig. 4.4: River nodes which receive overflow from sewer system
Secondly, sub-divided CAs in CITY DRAIN according to selected river nodes.

That is to say, CAs in MOUSE which have overflows flow to the same receiving river node as well as CAs which don’t have overflows but near the above CAs were lumped as a CA in CITY DRAIN. Overflow 4 and surrounding sewer network (see figure 4.5) in MOUSE is taken as an example to explain.

Thirdly, set up sewer network (including WWTP) of CITY DRAIN model. Still take overflow 4 as an example. For the rest overflows, similar way was applied.

Sewer network in figure 4.5 was lumped as one CA in CITY DRAIN (see green block in figure 4.6). And then rainfall data (white block in figure 4.6) and DWF data (orange block in figure 4.6) of this CA were set as input file. Besides, CA block was followed by CSO block to divert extra water to river.

Finally, set up river network of CITY DRAIN model. The principle is to model each overflow from sewer system separately. Overflow mixes with upstream flow firstly, and then goes into the next river branch. Figure 4.7 shows the example of overflow 4.
4.4 Overview of Ljubljana CD model

Fig. 4.8: Overview of Ljubljana CITY DRAIN network
4.5 Calibration of Ljubljana CD model

Ljubljana CD model was calibrated against data generated by MOUSE model. That is because no observed data for calibration and MOUSE simulates the detail physical process based on the conservation of mass and momentum. The result is assumed to be accurate enough for calibrating CITY DRAIN.

In wastewater system, once water comes into sewer system, it flows from upstream to downstream. Excess water above crest level of CSO is diverted into river and the remaining wastewater goes to WWTP discharged into river as effluent finally. Thus, discharge of overflows along the sewer network and the discharge of effluent from WWTP are two main important factors to measure and used to calibrate sewer network. Besides, as for CD river network calibration, comparisons are between discharges of certain locations of river both from MOUSE and from CD.

Rainfall event from April 24, 1995 to April 26, 1995 was chosen to run in CD model and MOUSE model respectively. In order to minimize the difference between their results, some parameters in CITY DRAIN were modified. During the process, two types of calibration approaches were applied: manual and automatic. Manual calibration is standard trial-and-error approach. Automatic approach is developed based on pattern-search algorithm in MATLAB. By using patternsearch function, parameters to be calibrated can be adjusted resulting in a minimum difference. The patternsearch function is: \( x = \text{patternsearch}(@\text{fun},x0) \). In which function (\( @\text{fun} \)) computes the value of objective function \( f(x) \), \( x0 \) is an initial point for the algorithm. Local minimum of objective function can be found by searching proper value for \( x \). From the calibrated results, it was concluded it was better to combine these two methods. This is because if automatic algorithm is applied independently, due to the feature of local optimization approach, there is possibility it can not find global minimum unless initial point and search domain is set properly. Thus, manual approach must be applied as a complement.

### 4.5.1 Parameters to be calibrated

Lots of parameters were set when building CITY DRAIN. Some just copied from MOUSE as input data, while some were uncertain and adjusted through calibration process. Table 4.2 lists parameters calibrated in CITY DRAIN.

<table>
<thead>
<tr>
<th>Catchments Block</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( K )</td>
<td>time for a unit discharge wave travelling through a sub-reach of a CA</td>
<td>[s]</td>
</tr>
<tr>
<td>( N )</td>
<td>number of sub-reaches of one CA</td>
<td>[-]</td>
</tr>
<tr>
<td>( \varphi )</td>
<td>weighting factor for the amount of wedge storage</td>
<td>[-]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CSO Block</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{MAX}} )</td>
<td>Basin volume of CSO</td>
<td>[m³]</td>
</tr>
<tr>
<td>( Q_{\text{E,MAX}} )</td>
<td>Maximum effluent flow</td>
<td>[m³/s]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>River Block</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( K )</td>
<td>time for a unit discharge wave travelling through a sub-reach of a CA</td>
<td>[s]</td>
</tr>
<tr>
<td>( N )</td>
<td>number of sub-reaches of one CA</td>
<td>[-]</td>
</tr>
<tr>
<td>( \varphi )</td>
<td>weighting factor for the amount of wedge storage</td>
<td>[-]</td>
</tr>
</tbody>
</table>
In catchment block, Muskingum method is used to rout the flow. Compared with
MOUSE, Muskingum parameters $K$ and $N$ replace time of concentration parameter $t_f$
effecting peak time of outflow discharge, where $K$ is time for a unit discharge wave
ravelling through a sub-reach of a CA, and $N$ is the number of sub-reaches. Besides, in
Muskingum method, $X$ represents weighting factor for the amount of wedge storage.

- For numerical stability and for assessing the wave travelling through a reach, $K \geq \Delta t$. For Ljubljana case, $\Delta t = 300$.
- $N$ was adjusted mainly depending on the fitness of peak time for outflow.
- $X$ was also adjusted from 0 to 0.5 according to the fitness of peak value.
- In River block, $K$, $N$ and $X$ were adjusted in the same way.
- $V_{\text{MAX}}, Q_{E,\text{MAX}}$ were estimated from MOUSE, but calibrated regarding to the
fitness of the result. Usually because $V_{\text{MAX}}$ is too small to affect $Q_W$ and $Q_E$, it
is not an important factor.
- For most CAs, $\varphi$ was calculated according to data (percentage of impervious
area) in MOUSE, but in some case it was slightly changed to get a better
matching.

### 4.5.2 Calibration results

- **Catchment parameters**

For each sub-catchment, permanent loss equals to 0, initial loss equals to 0.6 (inherent
from MOUSE), No of pollutants equals to 1(ammonia), and Vector of Rain-
Concentration equals to 0. Other calibrated parameters are lists in table 4.8.

<table>
<thead>
<tr>
<th>Catchment ID</th>
<th>Area (copied from MOUSE)</th>
<th>$\varphi$</th>
<th>$N$</th>
<th>$K$</th>
<th>$X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment CSS01</td>
<td>49.4</td>
<td>0.32</td>
<td>2</td>
<td>300</td>
<td>0.2</td>
</tr>
<tr>
<td>Catchment CSS02</td>
<td>309.5</td>
<td>0.11</td>
<td>5</td>
<td>300</td>
<td>0.2</td>
</tr>
<tr>
<td>Catchment CSS03</td>
<td>232</td>
<td>0.12</td>
<td>2</td>
<td>300</td>
<td>0.4</td>
</tr>
<tr>
<td>Catchment CSS04</td>
<td>41.7</td>
<td>0.67</td>
<td>1</td>
<td>300</td>
<td>0.5</td>
</tr>
<tr>
<td>Catchment CSS05</td>
<td>81.6</td>
<td>0.20</td>
<td>1</td>
<td>300</td>
<td>0.3</td>
</tr>
<tr>
<td>Catchment CSS06</td>
<td>24.7</td>
<td>0.55</td>
<td>1</td>
<td>300</td>
<td>0.0</td>
</tr>
<tr>
<td>Catchment CSS07</td>
<td>7.8</td>
<td>0.334</td>
<td>1</td>
<td>300</td>
<td>0.2</td>
</tr>
<tr>
<td>Catchment CSS08</td>
<td>99</td>
<td>0.45</td>
<td>1</td>
<td>300</td>
<td>0.4</td>
</tr>
<tr>
<td>Catchment CSS09</td>
<td>15.3</td>
<td>0.067</td>
<td>1</td>
<td>300</td>
<td>0.2</td>
</tr>
<tr>
<td>Catchment CSS10</td>
<td>1522.4</td>
<td>0.10</td>
<td>5</td>
<td>420</td>
<td>0.2</td>
</tr>
<tr>
<td>Catchment CSS11</td>
<td>54.7</td>
<td>0.20</td>
<td>2</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment CSS12</td>
<td>55.4</td>
<td>0.32</td>
<td>1</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment CSS13</td>
<td>89</td>
<td>0.47</td>
<td>7</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment CSS14</td>
<td>46.5</td>
<td>0.50</td>
<td>4</td>
<td>300</td>
<td>0.2</td>
</tr>
<tr>
<td>Catchment CSS15</td>
<td>127.2</td>
<td>0.10</td>
<td>9</td>
<td>420</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment CSS16</td>
<td>6.7</td>
<td>0.27</td>
<td>1</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment CSS17</td>
<td>64.9</td>
<td>0.50</td>
<td>10</td>
<td>300</td>
<td>0.2</td>
</tr>
<tr>
<td>Catchment CSS18</td>
<td>11.1</td>
<td>0.27</td>
<td>1</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Catchment CSS19</td>
<td>272.1</td>
<td>0.18</td>
<td>1</td>
<td>300</td>
<td>0.3</td>
</tr>
<tr>
<td>Catchment CSS20</td>
<td>99.7</td>
<td>0.70</td>
<td>8</td>
<td>300</td>
<td>0.3</td>
</tr>
<tr>
<td>Catchment CSS21</td>
<td>123.2</td>
<td>0.2</td>
<td>2</td>
<td>300</td>
<td>0.5</td>
</tr>
<tr>
<td>Catchment CSS22</td>
<td>243.4</td>
<td>0.58</td>
<td>8</td>
<td>900</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**SUM** 3577.6
- **CSO parameters**
  Table 4.9 lists calibrated parameters $V_{\text{MAX}}, Q_{\text{E,MAX}}$ for all combined sewer overflows in Ljubljana CITY DRAIN model.

<table>
<thead>
<tr>
<th>CSO ID</th>
<th>$V_{\text{MAX}}$</th>
<th>$Q_{\text{E,MAX}}$</th>
<th>CSO ID</th>
<th>$V_{\text{MAX}}$</th>
<th>$Q_{\text{E,MAX}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSO QC V01</td>
<td>7.54</td>
<td>0.04</td>
<td>CSO QC V11</td>
<td>49</td>
<td>2.5</td>
</tr>
<tr>
<td>CSO QC V02</td>
<td>16.11</td>
<td>0.3</td>
<td>CSO QC V12</td>
<td>129</td>
<td>2.28</td>
</tr>
<tr>
<td>CSO QC V03</td>
<td>7.63</td>
<td>0.08</td>
<td>CSO QC V13</td>
<td>3.27</td>
<td>0.2</td>
</tr>
<tr>
<td>CSO QC V04</td>
<td>35</td>
<td>0.45</td>
<td>CSO QC V14</td>
<td>5</td>
<td>0.15</td>
</tr>
<tr>
<td>CSO QC V05</td>
<td>46.4</td>
<td>0.26</td>
<td>CSO QC V15</td>
<td>34.62</td>
<td>0.80</td>
</tr>
<tr>
<td>CSO QC V06</td>
<td>12.56</td>
<td>0.37</td>
<td>CSO QC V16</td>
<td>34</td>
<td>0.05</td>
</tr>
<tr>
<td>CSO QC V07</td>
<td>28.4</td>
<td>0.55</td>
<td>CSO QC V17</td>
<td>95.5</td>
<td>2</td>
</tr>
<tr>
<td>CSO QC V08</td>
<td>35</td>
<td>0.27</td>
<td>CSO QC V18</td>
<td>34.23</td>
<td>1.5</td>
</tr>
<tr>
<td>CSO QC V09</td>
<td>129</td>
<td>9.2</td>
<td>CSO QC V19</td>
<td>24.87</td>
<td>1.5</td>
</tr>
<tr>
<td>CSO QC V10</td>
<td>129</td>
<td>1.22</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **River parameters**
  Table 4.10 lists calibrated parameters $N$, $K$, $X$ for each river branch in Ljubljana CITY DRAIN model.

<table>
<thead>
<tr>
<th>River block ID</th>
<th>N</th>
<th>K</th>
<th>X</th>
<th>River block ID</th>
<th>N</th>
<th>K</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Musk sM Q201</td>
<td>1</td>
<td>300</td>
<td>0.3</td>
<td>Musk sM Q238</td>
<td>1</td>
<td>300</td>
<td>0.3</td>
</tr>
<tr>
<td>Musk sM Q1</td>
<td>1</td>
<td>400</td>
<td>0.3</td>
<td>Musk sM Q237</td>
<td>7</td>
<td>800</td>
<td>0.3</td>
</tr>
<tr>
<td>Musk sM Q202</td>
<td>2</td>
<td>500</td>
<td>0.3</td>
<td>Musk sM Q227</td>
<td>2</td>
<td>300</td>
<td>0.3</td>
</tr>
<tr>
<td>Musk sM Q207</td>
<td>6</td>
<td>800</td>
<td>0.3</td>
<td>Musk sM Q228</td>
<td>3</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>Musk sM Q208</td>
<td>8</td>
<td>500</td>
<td>0.1</td>
<td>Musk sM Q230</td>
<td>1</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Musk sM Q210</td>
<td>4</td>
<td>300</td>
<td>0.1</td>
<td>Musk sM Q232</td>
<td>1</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Musk sM Q212</td>
<td>5</td>
<td>600</td>
<td>0.2</td>
<td>Musk sM Q233</td>
<td>1</td>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>Musk sM Q213</td>
<td>5</td>
<td>600</td>
<td>0.2</td>
<td>Musk sM Q235</td>
<td>1</td>
<td>300</td>
<td>0.1</td>
</tr>
</tbody>
</table>
5 Results of CD Model and Assessment

Ljubljana CITY DRAIN model has been set up step by step, and rainfall event of April 24, 1995 to April 26, 1995 was used for calibrating. Discharges of overflows and WWTP effluent generated by MOUSE and CITY DRAIN are compared in this chapter. As for river network calibration, comparisons are between discharges of corresponding river branches from two models. Besides, the prepared model is used to predicate system performance regarding to different situations in the future for the sake of assisting strategic planning in this chapter.

5.1 Comparison between overflows

In CITY DRAIN sewer network, 12 main combined sewer overflows were modelled. The following figures (from figure 5.1 to figure 5.12) are the comparisons of corresponding overflows in MOUSE and CITY DRAIN.

As mentioned before, simulation duration is from 00:00:00 of April 24, 1995 to 00:00:00 of April 26, 1995. However in order to have a clear picture for comparison, figure 5.1 to 5.2 are enlarging graphs from 20:40:15 of April 24, 1995 to 12:25:15 of April 25, 1995. For the rest of time, there is no overflow.

Figure 5.1 is the comparison between overflow0, which locates in the upstream part of river Ljubljanica. The red line stands for discharge of overflow0 in MOUSE model and blue line stands for that in CD model. These two lines match each other very well. Root Mean Square Error (RMSE) was used to evaluate the result, and it equals to 0.007.

Fig. 5.1: Comparison between discharges of overflow0
Figure 5.2 shows the comparison between overflow1, which goes into the most upstream part of river Ljubljanica (small). The same with figure 5.1, red line and blue line stand for discharge of overflow1 in MOUSE model and in CD mode respectively. These two lines also match each other very well. RMSE equals to 0.012.

\[ \text{Fig. 5.2: Comparison between discharges of overflow1} \]

Figure 5.3 compares discharge of overflow2 in MOUSE model and in CD model. Overflow 2 has very small discharge compared with other overflows. RMSE was calculated as 0.0005 approximately which indicates a good fitting.

\[ \text{Fig. 5.3: Comparison between discharges of overflow2} \]

Figure 5.4 compares discharge of overflow3. Red line is the result from MOUSE and blue line is from CD. RMSE was calculated as 0.016 which is small enough to prove a qualified calibrated result.

\[ \text{Fig. 5.4: Comparison between discharges of overflow3} \]
Figure 5.5 compares discharge of overflow4. RMSE was calculated as 0.043. There is a little increase of the error compared with the above 3 overflows. However, RMSE = 0.043 is still quite small error. It is acceptable.

Figure 5.6 is the comparison between overflow6. Still, red line stands for discharge from MOUSE model and blue line stands for that from CD model. RMSE equals to 0.0012. The error is acceptable.

Figure 5.7 compares overflow8 in MOUSE and in CD. It is easy to notice, they don’t match each other very well. RMSE is equal to 0.124, which is quite big. The reason will be explained later.
Figure 5.8 reveals a good match between overflow9. RMSE equals to 0.0004 approximately.

![Fig. 5.8: Comparison between discharges of overflow9](image)

Figure 5.9 reveals a good match between overflow10. RMSE equals to 0.023.

![Fig. 5.9: Comparison between discharges of overflow10](image)

In Figure 5.10 discharges of overflow11 from MOUSE and from CD have apparent difference between each other. RMSE was calculated as 0.07.

![Fig. 5.10: Comparison between discharges of overflow11](image)

In addition, discharge of overflow 5 and overflow 7 equals to 0 m³/s both in CD and MOUSE model.
**Assessment of overflow**

As mentioned earlier, to evaluate the quality of overflow result, quality indicator – Root Mean Square Error (see table 5.1) – was used to compare simulated data (results from CITY DRAIN) with MOUSE data.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Mathematical equation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>$\sum_{i=1}^{N} \frac{\sqrt{(M_i - S_i)^2}}{N}$</td>
<td>$[0, +\infty]$</td>
</tr>
</tbody>
</table>

Where $S_i$ element in the time series of simulated data, $M_i$ element in the time series of MOUSE data, $N$ number of elements.

Table 5.2 lists RMSE of 12 overflows.

<table>
<thead>
<tr>
<th>Location</th>
<th>RMSE</th>
<th>Location</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>overflow0</td>
<td>0.007</td>
<td>overflow6</td>
<td>0.012</td>
</tr>
<tr>
<td>overflow1</td>
<td>0.012</td>
<td>overflow7</td>
<td>0.000</td>
</tr>
<tr>
<td>overflow2</td>
<td>0.0005</td>
<td>overflow8</td>
<td>0.124</td>
</tr>
<tr>
<td>overflow3</td>
<td>0.016</td>
<td>overflow9</td>
<td>0.0004</td>
</tr>
<tr>
<td>overflow4</td>
<td>0.043</td>
<td>overflow10</td>
<td>0.023</td>
</tr>
<tr>
<td>overflow5</td>
<td>0.000</td>
<td>overflow11</td>
<td>0.070</td>
</tr>
</tbody>
</table>

According to table 5.2, RMSE of overflow 0 to 7 and overflow 9 to 11 are all smaller than 0.07, which shows a good fitting with MOUSE data. However, RMSE of overflow 8 equals to 0.124, compared with other overflows, the error is quite large.

The reason for that is CITY DRAIN can not simulate flooding condition (pressurized flow). In CITY DRAIN, Muskingum method is used to calculate flow routing process, which can only applied to kinematic wave. Regarding to MOUSE result, there is a flooding manhole in front of overflow 8 (see figure 5.11 and 5.12).

![Fig. 5.11: Flooded manhole before overflow 8 in Mouse](image)
Results of CD Model and Assessment

Since CITY DRAIN can not simulate flooding condition, surcharge water in MOUSE comes out of sewer system in the form of extra discharge added to overflow8 in CITY DRAIN. That’s why when compared with MOUSE result, overflow8 has more volume (surcharge water) in CD (see figure 5.7). Large error (RMSE = 0.124) can be reasonable explained.

5.2 Comparison between WWTP effluent

Figure 5.13 compares WWTP effluent with CD effluent. RMSE equals to 0.25, which is comparably large.

Error of effluent is related to water balance of entire system.

The water balance equation, inflow volume (runoff discharge and DWF) $\approx$ outflow volume (overflow, effluent and flood), is valid in individual CD and MOUSE model. And under the condition there is equal inflow volume (runoff discharge and DWF) in MOUSE and CD. The following equation can be derived.

$$\sum_{i=0}^{i=11} V_M(\text{overflow}_i) + V_M(\text{effluent}) = \sum_{i=0}^{i=11} V_{CD}(\text{overflow}_i) + V_{CD}(\text{effluent})$$
Which means volume of water coming out from 11 overflows and WWTP in MOUSE should equal to total volume of overflows and effluent in CD.

Since differences between discharges of overflow0 to overflow7 and overflow9 to overflow11 in MOUSE and in CD are quite small. We can assume volume of water coming out of sewer system from these 11 overflows is the same compared MOUSE with CD. Hence, factors determining water balance become volume of overflow8, volume of effluent and inflow volume.

As for overflow8, the discharge difference between two models is the volume of flood water. To get the volume balance, the difference between WWTP effluents should also be the volume of flood. And this can be reasonably explained. Since surcharge water in MOUSE will gradually flow back into sewer system and come out from effluent. While, surcharge water in CD just come out of the system from overflow8 and will never come back.

However, $V_{\text{effluent}}^{\text{MOUSE}} - V_{\text{effluent}}^{\text{CD}} = 33045$ m$^3$, $V_{\text{flood}} = V_{\text{CD overflow8}} - V_{\text{MOUSE overflow8}} = 25390$ m$^3$

They are not equal to each. The difference is 7655 m$^3$. That’s because a few run off coefficients were slightly changed in CD to have a better fitting of the result due to different routing processes within CD and MOUSE. This leads to the difference of total system inflow volume.

### 5.3 Comparison between discharge of river

The discharges of certain locations in the river from upstream to downstream were compared.

Figure 5.14 shows discharge of river1 in MOUSE and CD. Since it is the most upstream part of river Ljubljanica, discharge is equal to upstream boundary condition, which was set exactly the same in MOUSE and CD.

![Fig. 5.14: Comparison between discharges of location river1](image)

In figure 5.15, red line stands for discharge of river3 in MOUSE, and blue line stands for that in CD. The trends of these two lines are the same.
Figure 5.15 compares discharge of river3 in MOUSE and in CD. There is a large error at the beginning. However, two lines meet together very soon, and then have a good fitting with each other.

Figure 5.16 shows discharge of river6. Since it is the most upstream part of river Ljubljanica, discharge is equal to boundary condition, which is the same in MOUSE and CD.

Figure 5.17 compares discharge of riverL2. Large error appears at the beginning. And a good fitting for the rest of time.
Figure 5.19 compares discharge of riverL4. Similar to riverL2, large error appears at the beginning. For the rest of time, they math each other quite well.

![Figure 5.19: Comparison between discharges of location riverL4](image)

Figure 5.20 compares discharge of river outlet. Still, large error appears at the beginning. For the rest of time, they math each other quite well.

![Figure 5.20: Comparison between discharges of outlet of the river](image)

**Assessment of river**

RMSE was also calculated for 6 locations in river and outlet (see table 5.3).

<table>
<thead>
<tr>
<th>Location</th>
<th>RMSE</th>
<th>Location</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>river1</td>
<td>0.015</td>
<td>riverL3</td>
<td>1.151</td>
</tr>
<tr>
<td>river3</td>
<td>0.448</td>
<td>riverL4</td>
<td>1.906</td>
</tr>
<tr>
<td>river6</td>
<td>0.981</td>
<td>outlet</td>
<td>1.973</td>
</tr>
<tr>
<td>riverL1</td>
<td>0.019</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RMSE is increased compared with that of overflows, except two locations (river 1 and river 6) in the most upstream part. Although RMSE is larger, when referred to graphs, main difference always appeared at the beginning, and they matched with each other very soon. The trend of two lines is the same as well as the variation of peak value. So, errors are acceptable.

Further more, the accuracy of discharge in river will directly affect simulation of pollutant in river. Figure 5.21 and figure 5.22 give the comparison of ammonia concentration in river branch 230 and in the downstream part of river (branch 210). According to these two graphs, CITY DRAIN provided a good simulation of pollutant concentration at the peak value which is important to water quality analysis and management. This further proves errors appear at the beginning of discharge can not disturb dominating simulation results.
5.4 Verification of Ljubljana CD model

Rainfall event June 5, 1995 to June 7, 1995 was used for verifying calibrated parameters. Figure 5.23 to figure 5.26 show comparisons between discharge of overflow0, overflow1, overflow8 and effluent. Comparison of the rest overflows are put in appendix 1.

In figure 5.23, red line and blue line represent discharge of overflow0 in MOUSE and CD respectively. It is obvious they match each other quite well.
Similar to figure 5.23, red line in figure 5.24 shows discharge of overflow 1 in MOUSE, while the blue indicates that in CD. There is perfect match between them.

![Fig. 5.24: Comparison between discharges of overflow1](image1)

According to figure 5.25 and figure 5.26, it can be concluded that similar to calibration results, large errors appear in overflow 8 and effluent. The same reason is responsible for explanation.

![Fig. 5.25: Comparison between discharges of overflow8](image2)

![Fig. 5.26: Comparison between discharges of effluent](image3)

RMSE is also used as quality indicator (see table 5.4). Similar to calibrated results, overflow 8 and effluent give large errors. The reason for that is also because of flooding condition appeared in front of overflow 8 and slightly modification of runoff coefficients. In general, results of validation are good, which can further prove the quality of calibration.
### Table 5.4 RMSE for 12 overflows and effluent

<table>
<thead>
<tr>
<th>Location</th>
<th>RMSE</th>
<th>Location</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>overflow0</td>
<td>0.010</td>
<td>overflow7</td>
<td>0.007</td>
</tr>
<tr>
<td>overflow1</td>
<td>0.022</td>
<td>overflow8</td>
<td>0.106</td>
</tr>
<tr>
<td>overflow2</td>
<td>0.002</td>
<td>overflow9</td>
<td>0.009</td>
</tr>
<tr>
<td>overflow3</td>
<td>0.033</td>
<td>overflow10</td>
<td>0.026</td>
</tr>
<tr>
<td>overflow4</td>
<td>0.045</td>
<td>overflow11</td>
<td>0.084</td>
</tr>
<tr>
<td>overflow5</td>
<td>0.000</td>
<td>effluent</td>
<td>1.281</td>
</tr>
<tr>
<td>overflow6</td>
<td>0.014</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 5.5 Long term simulation of different scenarios

As a conceptual model with reasonable accuracy, Ljubljana CD model have the advantage to support long term simulation of different scenarios. Each run can finish in a short time and present results regarding to different conditions.

As for Ljubljana model, we can easily change rainfall input data to predict system behaviour in terms of different storm events or climate change (see figure 5.23). And we can also increase run off coefficients of some CAs to various extend to indicate a deduction of pervious area (urbanization) in different time period (see figure 5.24). Beside, DWF can be modified in relation to PE, when regarding to population growth.

#### 5.5.1 Prediction of system performance for climate change

Figure 5.27 shows the prediction of system performance regarding to climate change. The blue line stands for discharge of WWTP effluent when running rainfall event between Feb 1, 1995 and Feb 28, 1995. The red line stands for that in 2050 with the assumption rainfall amount will be doubled because of climate change. It is shown clearly CD model provides us a reasonable result indicating a large increase of the discharge.

![Fig. 5.27: Comparison of WWTP effluent under climate change](image_url)
5.5.2 Prediction of system performance for urbanization

Figure 5.28 presents comparison between discharge of overflow8 in terms of urbanization in 2015 and before urbanization in 1995. In order to simulate the situation, rainfall amount was considered not change in February 2015 compared with in February 1995, however, runoff coefficients (proportion between impervious area and whole area) of some CAs were increased (see table 5.4).

The red line in figure 5.28 presents discharge of overflow8 in February 2015. The blue presents discharge of overflow8 in February 1995. The result shows a slightly rise because of the increase in runoff coefficient caused by urbanization.

<table>
<thead>
<tr>
<th>Catchment ID</th>
<th>Runoff coefficient in 1995</th>
<th>Runoff coefficient after urbanization in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS02</td>
<td>0.11</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS03</td>
<td>0.12</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS05</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS09</td>
<td>0.067</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS10</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS15</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS16</td>
<td>0.27</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS18</td>
<td>0.27</td>
<td>0.8</td>
</tr>
<tr>
<td>CSS19</td>
<td>0.18</td>
<td>0.8</td>
</tr>
</tbody>
</table>

In conclusion, all these predictions of system behaviour are essential references for decision maker to give an efficient and holistic responding to future requirements, helping them find the right balance between the systems needs, environment and stakeholders’ interests, Thus, CD model can act as effective tool for strategic planning.
6 Development and Application of RTC Blocks

As stated in introduction chapter, the advantage of integrated model is a good simulation and management of interactions between different components. In Ljubljana CITY DRAIN model, sewer network, river network and WWTP were set up on the same platform, and ran simultaneously, which provided an environment to realise real time control of their interactions. And on the basis of a good simulation approved in chapter 5, RTC application seems quite meaningful for CD model.

Consequently, in this chapter additional RTC blocks were developed and applied. The basic idea is controlling discharge of overflows and WWTP effluent depending on the environmental requirement in target river location by sending control signals to WWTP and corresponding CSO (weirs).

6.1 Development of RTC blocks

RTC blocks were developed as a package, which is composed of two blocks – RTC_forecast_river and RTC_splitter. The basic idea is by controlling the discharge of overflows or effluent through time, dynamic concentrations of target river location always remain within the limitation.

6.1.1 Two blocks of RTC

RTC_forecast_river

Figure 6.1 shows the mask of RTC_forecast_river block. Limitation of pollutant concentration (Cr) should be set first.

![RTC_forecast_river](image)

Where
- R1 – Flow of target river location;
- Qw – Controlled overflow to river;
- Q1 – Upstream sewer outflow;
- Qfr – Upstream sewer outflow with forecast rainfall;
- Q2 – Q2 from Splitter (refer to Q2 in RTC_splitter);
- Qr – flow diverted to a storage (control signal to splitter).
**RTC_splitter**

Figure 6.2 shows the mask of RTC_splitter block.

![RTC_splitter mask](image)

Fig. 6.2: Mask of RTC_splitter block

Where

- \( Q_i \) – Upstream sewer outflow;
- \( Q_r \) – Control signal from RTC_forecast_river block;
- \( Q_1 \) – flow diverted to an extra storage;
- \( Q_2 \) – flow goes to downstream sewer network.

### 6.1.2 Theoretical basis underlying

Figure 6.3 is the schematic illustration of RTC application – feed back/forward control with P controller. The control signal is how much inflow should be diverted to a storage, and controlled overflow decreased with the deduction of inflow. Control objective is concentration of target river location \((C_R)\) always remain within the limitation \((C_t)\).

![Schematic illustration of RTC](image)

Fig. 6.3: Schematic illustration of RTC—deed backward control with P controller

Where

- \( R_1 \) – Flow of target river location;
- \( Q_W \) – Controlled overflow to river;
- \( Q_i \) – Upstream sewer outflow;
- \( Q_{if} \) – Upstream sewer outflow with forecast rainfall;
- \( Q_r \) – flow diverted to a storage (control signal to splitter);
- \( Q_1 \) – flow diverted to an extra storage \((Q_1 = Q_r)\);
- \( Q_2 \) – flow goes to downstream sewer network.

Figure 6.4 shows processes underlying RTC_forecast_river block, RTC_splitter block.
Fig. 6.4: Processes underlying two main RTC blocks

Three S_functions underlying RTC blocks were compiled based on MATLAB (see Appendix 1)

CD2_sfun_compare
CD2_sfun_ControllerRiver
CD2_sfun_splitter_controller
Control without forecasting – feed backward control with P controller

First consider control without forecasting, which means there is no ‘compare block’ within controller. The process underlying RTC_forecast_river block becomes figure 6.5.

Fig. 6.5: Processes underlying ‘controller’ without forecast

R1 is a vector including \([Q_{R}, C_{R1}, C_{R2}, \ldots]\);
R1,i-1 is a vector including \([Q_{R,i-1}, C_{R1,i-1}, C_{R2,i-1}, \ldots]\);
Q_{W} is a vector including \([q_{w}, C_{w1}, C_{w2}, \ldots]\);

Where (refer to figure 6.6)

- \(Q_{R}\) is the discharge of target river location;
- \(Q_{R,i-1}\) is the discharge of river branch in front of target river location;
- \(C_{R1}, C_{R2}\) are concentrations of pollutants of target river location;
- \(C_{R1,i-1}, C_{R2,i-1}\) are concentrations of river branch in front of target river location;
- \(q_{w}\) is discharge of controlled overflow;
- \(C_{w1}, C_{w2}\) are concentration of pollutants in controlled overflow.

**Fig. 6.6: Illustration of target river location**

- If upstream river branch \((Q_{R,i-1})\) in front is before river location receiving controlled overflow (figure 6.6), \(Q_{R} = Q_{R,i-1} + q_{w}\). For time step \(t\), \(C_{R1} = (q_{w} \cdot C_{w1} + Q_{R,i-1} \cdot C_{R1,i-1}) / Q_{R}\) (calculated in river system, read directly by controller).

- If \(Q_{R,i-1}\) is behind controlled overflow, \(Q_{R} = Q_{R,i-1}\). For time step \(t\), \(C_{R1} = (Q_{R,i-1} \cdot C_{R1,i-1}) / Q_{R}\) (calculated in river system, read directly by controller).

The basic control theory is (In this research one dominating pollutant is considered):

\[
E^{t} = C_{R1} \cdot C_{r}
\]

If \(E^{t} > 0\) then \(Q^{t} = (E^{t} \cdot Q_{R}) / C_{w1}\)

If \(E^{t} < 0\) then \(Q^{t} = 0\)

Where

\(Q_{r}\) is flow diverted to a storage (control signal);
\(C_{r}\) is concentration limitation of pollutant (refer to figure 6.1).

And then Discrete State-Space function is used to make \(Q^{t}\) one time step further \(Q^{t+1}\) \((Q^{t} = Q^{t+1})\) and goes into RTC_splitter block. Figure 6.7 shows the processes under RTC_splitter.
Fig. 6.7: Processes underlying RTC_splitter

Where

- $Q_{i}^{t+1}$ – upstream sewer outflow for the next time step;
- $Q_{1}$ – flow diverted to an extra storage;
- $Q_{2}$ – flow goes to downstream sewer network;
- $Q_{W}$ – Controlled overflow to river
- $Q_{rt+1}$ – flow diverted to a storage

The functions are:

$$Q_{1}^{t+1} = Q_{rt+1}$$
$$Q_{2}^{t+1} = Q_{i}^{t+1} - Q_{1}^{t+1} (Q_{2}^{t+1} \geq 0)$$

And then $Q_{W}^{t+1}$ is calculated by CSO block

According to control process, $Q_{r}^{t}$ is equal to $Q_{r}^{t+1}$, which means control signal $Q_{r}^{t}$ generated at time step $t$ is used to control inflow $Q_{i}^{t+1}$ for the next time step. Since CITY DRAIN using discrete computation, $Q_{1}^{t}$ and $Q_{i}^{t+1}$ can be quite different from each other. Besides, $Q_{r}^{t}$ also subjects to $C_{w1}^{t}$ (concentration in controlled overflow), pollutant mass from upstream at time step $t$ ($M_{R,i-1}^{t} = Q_{R,i-1}^{t} * C_{R1,i-1}^{t}$). These parameters can be quite different at time step $t+1$. Thus, $C_{R}^{t+1}$ may large than $C_{r}$ if at time step $t+1$, $Q_{r}^{t+1} = Q_{r}^{t}$ is divert to a storage. In conclusion, the above control may fail because of control time lag.

Control with forecasting – feed back/forward control with P controller

As mentioned above, because of control time lag, feed backward control can fail. A combination of feed forward and feed backward control is needed, which take rainfall forecasting into consideration.

The basic idea is to calculate the difference between $Q_{i}$ (upstream sewer outflow, see figure 6.8) and $Q_{if}$ (upstream sewer outflow with forecast rainfall, see figure 6.7) before sending control signal, which is also an important factor in calculating control signal (feed forward control).

Fig. 6.8: Upstream outflow with forecast rainfall and regular rainfall
In figure 6.8 every parameter and input data of two catchments are the same except rainfall data. In terms of rain forecast, it means at time step \( t \) in CITY DRAIN model, rainfall amount for the next time step is used as input data value. Thus, the difference between \( Q_i \) and \( Q_{if} \) is caused by rainfall, not DWF or inflow from upstream sewer network.

Figure 6.9 shows the underlying processes of RTC_forecast_river block (controller with forecast). Compared with figure 6.5, a ‘compare’ is used to implement feed forward control.

Explanations of each parameter can refer to figure 6.3 and 6.5.

Functions under ‘compare block’ are:

- If \( Q_i \geq Q_{if} \geq Q_2 \) then \( Q_C = Q_{if} - Q_2 \);  
- If \( Q_{if} < Q_2 \) then \( Q_C = 0 \);  
- If \( Q_{if} > Q_i \) then \( Q_C = Q_{if} - Q_i \).

Control signal \( Q_r \) is calculated in a different way from the one without forecast.

\[
E^t = C_{R1}^t - C_r \\
\text{If } E^t > 0 \text{ then } Q_r^t = (E^t * Q_{Rr}^t) / C_{w1}^t + Q_C^t \\
\text{If } E^t < 0 \text{ then } Q_r^t = Q_C^t
\]

And then Discrete State-Space function is used to make the \( Q_r^t \) one time step further \( Q_{r+1}^t (Q_r^t = Q_{r+1}^t) \) and goes into RTC_splitter block (for the rest processes Feed back/forward control is the same as feed backward control).

It is easy to find that with the help of ‘compare’, the difference between \( Q_i \) and \( Q_{i+1} \) which caused by rainfall is compensated. However the difference caused by DWF and upstream sewer inflow cannot be compensated as well as the difference between \( M_{R_i-1}^t \) and \( M_{R_i-1}^{t+1} \).

Figure 6.10 is an example interface of RTC with feed back/forward control.
Integrated Urban Wastewater System Modelling with Conceptual Surrogate Models

Fig. 6.10: Example interface of RTC
Fig. 6.11: Overview of Ljubljana CD model with RTC application

Control of overflow 4

Control of effluent
6.2 Application of RTC blocks in Ljubljana case

In Ljubljana model, overflow 4 and effluent were controlled by RTC blocks. Figure 6.11 shows the overview of Ljubljana CD model with RTC application.

6.2.1 Control of overflow 4

For control of overflow 4, extra overflow discharge is diverted to storage according to the dynamic concentration of ammonia in river branch 230 (see figure 6.12).

Since only discharge of overflow 4 can be influenced by control process, limitation of pollutant concentration in river branch 230 (Cr) should large than maximum value of original river concentration, i.e. the maximum concentration of river branch 230 without receiving overflow 4 (peak value of red line in figure 6.13). In figure 6.13, blue line stands for ammonia concentration of branch 230 after receiving overflow 4, while red line is ammonia concentration of river branch 230 without disturbance of overflow 4. So, C_r was set to 0.6 g/m³.
After setting $C_r$, RTC was applied, and figure 6.14 presents the control results. Blue line and red line stand for ammonia concentration in river branch 230 before control and after control respectively. It is easy to notice that during peak time, for most of time, concentration exceeded 0.6 g/m$^3$ previously were limited within $C_r$, except for two points. Generally speaking, the control effect is good.

The reason for failure is due to control time lag (discrete computation in CD). Although difference between $Q_i^t$ and $Q_{i+1}^{t+1}$ which caused by rainfall is compensated with the help of 'compare' in feed back/forward control, difference caused by DWF and upstream inflow as well as the difference between pollutant mass from upstream $M_{R,i-1}^t$ and $M_{R,i-1}^{t+1}$ can not be compensated as explained in chapter 6.1.2. When there is a sudden change of them, the control impact will be influenced.

In figure 6.14, yellow line represents pollutant mass ($M_{R,i-1}$) from river branch 228 (upstream river branch in front of target river location, see figure 6.12). And around the time of failure points, there is a steep slope of yellow line, which indicates a significant increase between $M_{R,i-1}^t$ and $M_{R,i-1}^{t+1}$. 
In conclusion, significant increase from $M_{R,i-1}t$ to $M_{R,i-1}t+1$ impacted the control effect of overflow 4. However, for most of time RTC blocks provided a satisfying control effect.

### 6.2.2 Control of effluent

According to figure 6.15, effluent from WWTP was discharged into river branch 213 and flowed to river outlet. For effluent control, extra effluent was diverted to storage according to the dynamic ammonia concentration of outflow from river.

**Fig. 6.15: Map of effluent control**

Since only discharge of effluent can be influenced by control process, limitation of pollutant concentration of river outflow ($C_r$) should large than maximum value of original river concentration, i.e. the maximum concentration of outflow without receiving effluent (peak value of red line in figure 6.16). In figure 6.16, blue line stands for ammonia concentration of river outflow after receiving effluent, while red line is ammonia concentration of river outflow without disturbance of effluent. So, $C_r$ was set to $1 \text{ g/m}^3$ in Ljubljana case.

**Fig. 6.16: Ammonia concentration of river outflow before and after receiving effluent**
After setting $C_r$, RTC was applied for effluent, figure 6.17 presents the control results. Blue line and red line stand for ammonia concentration of river outflow before control and after control respectively. A dramatic increase of blue line at the beginning indicates pollutant concentration is much larger than limitation before control. However, when RTC block was applied, concentration exceeded $C_r=1 \text{ g/m}^3$ previously was limited within $1 \text{ g/m}^3$. Thus, the control application succeeded.

![Ammonia conc. of river outflow before/after control & pollutant mass from branch 212](image)

Compared with control of overflow 4, the slope of yellow line (pollutant mass from branch 212 in figure 6.15) around effective controlling time is flat. So it can not disturb control process.

In conclusion, Real Time Control blocks were developed in the research. It is a kind of feed back/forward control with P control which is capable of controlling discharge of overflows and WWTP effluent depending on the environmental requirement in target river location diverting excessive water to a designated storage. Generally speaking, RTC blocks can work effectively, however sometimes failure occurs due to control time lag. The control may fail at $t+1 \ (C_{R,t+1}>C_r)$ when mass of pollutant coming from upstream river branch in front of target river location at time step $t+1 (M_{R,t+1})$ is much larger than that at time step $t \ (M_{R,t+1})$, and meanwhile pollutant concentration of target river at time step $t \ (C_R)$ is very close to limitation \ $(C_r)$. 
7 Conclusions and Recommendations

This chapter lists the conclusions of present research, provides limitations and shows recommendations for future research.

7.1 Conclusions

1. Due to conceptual feature of CITY DRAIN model, it is easy to link different components and simulate urban wastewater system as a comprehensive entity. Different from MOUSE, which is incapable of modelling WWTP, Ljubljana CD model was set up for three main components of urban wastewater system – sewer network, WWTP, and river. Overflows from sewer network are diverted to receiving river from upstream to downstream, and effluent from WWTP is discharged to downstream river branch and then flow out of the catchment. All the processes and interactions are simulated simultaneously.

2. According to the assessment of overflows and effluent, Ljubljana CD model can provide a good simulation of flow routing process in sewer system. However, CITY DRAIN is not good at simulating flood condition, surcharge water goes out of the system form the nearest downstream overflow.

3. Regarding to river network assessment, Ljubljana CD model can simulate discharge and concentration of river with reasonable accuracy, which gives rise to the idea of developing and applying RTC for the integrated urban wastewater system depending on the dominant pollutant concentration in river.

4. Since CITY DRAIN is conceptual model, surface runoff and sewer flow routing process are lumped leading to simplified computation. Computational time is reduced greatly compared with MOUSE which focus on emulating detail physically processes in real system. This feature ensures CITY DRAIN to be an effective tool of providing prediction of system performances for different long term scenarios. By changing input rainfall data, runoff coefficients or PE, CD model can provide reasonable results in terms of climate change, increasing of impervious area or population growth. The results can benefit decision maker for efficient strategic planning.

5. As an integrated model supporting parallel calculation, CITY DRAIN realises a good simulation and management of interactions between different components, especially with the application of RTC. RTC blocks, feed back/forward control with P controller, were developed in CITY DRAIN which are capable of controlling discharge of overflows and WWTP effluent depending on the environmental requirement in target river location by sending control signal to WWTP and corresponding CSO (weirs). Generally speaking, RTC blocks can work effectively, however sometimes failure occurs (control of overflow 4 in Ljubljana CD model) due to control time lag. To be more specific, the control may fail at t+1 (C_{R,t+1} > C_t) when mass of pollutant coming from upstream river branch in front of target river location at time step t+1(M_{R,t+1}^{i+1}) is much larger
than that at time step \( t \) (\( M_{R,t} \)), and meanwhile pollutant concentration of target river at time step \( t \) (\( C_{R,t} \)) is very close to limitation (\( C_r \)).

### 7.2 Limitations of present work and recommendations for future research

1. In case of surface flooding and surcharge conditions (pressurized flow), CITY DRAIN can not perform well due to Muskingum method it used, which mainly calculates kinematic flow.

2. As for RTC application, the difference between pollutant mass from upstream river at time step \( t \) and time step \( t+1 \) can not be compensated due to control time lag and may influence control effect.

3. During RTC process, extra discharge of overflow and effluent is diverted to storage. However, there is no management to decide when and how to empty the storage.

4. For future development, efforts should be placed on advancing RTC by introducing PI or PID controller to reduce error caused by control time lag. And try to develop a program for emptying storage without exceeding concentration limitation of river.

5. For users aiming at obtaining a ‘big overview’ of entire urban wastewater system with relatively less accurate results, and for those who need quick responses of different scenarios from the model, CITY DRAIN model is a decent choice.
References

Achleitner S. (2006). Modular conceptual modelling in urban drainage development and application of CITY DRAIN, a PhD Dissertation, University of Innsbruck, Austria.


APPENDIX 1: Results of Verification

Fig. 1: Comparison between discharges of overflow2

Fig. 2: Comparison between discharges of overflow3

Fig. 3: Comparison between discharges of overflow4

Fig. 4: Comparison between discharges of overflow6
Additionally, discharge of overflow 5 equals to 0 m\(^3\)/s both in MOUSE and CD model.
APPENDIX 2: S_functions developed for RTC blocks in MATLAB

1. CD2_sfun_compare

%===================================================================== 
% File: sfun_cd2_compare.m
% Author: Y.Chen UNESCO-IHE
%===================================================================== 
function [sys, x0, str, ts] = CD2_sfun_compare(t, x, u, flag, n_comp, tstep)
% The following outlines the general structure of an S-function.
switch flag,
    case 0,
        [sys, x0, str, ts]=mdlInitializeSizes(t, x, u, flag, n_comp, tstep);
    case 2,
        sys=mdlUpdate(t, x, u, n_comp,tstep);
    case 3,
        sys=mdlOutputs(t, x, u, n_comp,tstep);
    case {1, 4, 9}
        sys=[];
    otherwise
        error(['Unhandled flag = ', num2str(flag)]);
end
%===================================================================== 
% mdlInitializeSizes
% Return the sizes, initial conditions, and sample times for the S-
% function.
%===================================================================== 
function [sys, x0, str, ts]=mdlInitializeSizes(t, x, u, flag, n_comp, tstep)
sizes = simsizes;
sizes.NumContStates = 0;
sizes.NumDiscStates = 0;
sizes.NumInputs = 3*(n_comp+1);
sizes.NumOutputs = n_comp+1;
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1; % at least one sample time is needed
sys = simsizes(sizes);
x0 = zeros(sizes.NumDiscStates, 1);
str = [];
ts = [tstep 0];
%=====================================================================
% mdlUpdate
% Handle discrete state updates, sample time hits, and major time step
% requirements.
%=====================================================================
function sys=mdlUpdate(t, x, u, n_comp,tstep)
sys=[];
%=====================================================================
% mdlOutputs
% Return the block outputs.
%=====================================================================
function sys=mdlOutputs(t, x, u, n_comp,tstep)
if u(1)>=u(n_comp+2) & u(n_comp+2)>=u(2*(n_comp+1)+1);
    y(1) = u(n_comp+2)-u(2*(n_comp+1)+1);
    y(2:n_comp+1)=u(2:n_comp+1);
end
if u(n_comp+2)<u(2*(n_comp+1)+1);
    y(1) = 0;
    y(2:n_comp+1)=u(2:n_comp+1);
end
if u(n_comp+2)>u(1);
    y(1) = u(n_comp+2)-u(1);
    y(2:n_comp+1)=u(2:n_comp+1);
end
sys=y;
2. CD2\_sfun\_ControllerRiver

```matlab
function \[sys,x0,str,ts\] = CD2\_sfun\_ControllerRiver(t,x,u,flag,n\_comp,Cr,tstep)
% The following outlines the general structure of an S-function.
switch flag,
  case 0,
    [sys,x0,str,ts]=mdlInitializeSizes(n\_comp,tstep);
  case 2,
    sys=mdlUpdate(t,x,u,n\_comp,tstep);
  case 3,
    sys=mdlOutputs(t,x,u,n\_comp,Cr,tstep);
  case \{1,4,9\}
    sys=[];
  otherwise
    error(['Unhandled flag = ',num2str(flag)]);
end

function [sys,x0,str,ts]=mdlInitializeSizes(n\_comp,tstep)

sizes = simsizes;
sizes.NumContStates = 0;
sizes.NumDiscStates = 0;
sizes.NumOutputs = 1;
sizes.NumInputs = 3\*(n\_comp+1);
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1;  % at least one sample time is needed

sys = simsizes(sizes);
x0 = zeros(sizes.NumDiscStates,1);
str = [];
ts = [tstep 0];
```

%=====================================================================  
function sys=mdlUpdate(t,x,u,n_comp,tstep)

sys=[];

%=====================================================================  
function sys=mdlOutputs(t,x,u,n_comp,Cr,tstep)

E=u(n_comp+1)-Cr;
if E<=0
    y=u(2*(n_comp+1)+1);
else
    Value=E*u(1);
    y=u(2*(n_comp+1)+1)+ Value/u(2*(n_comp+1));
end

sys=y;
3. CD2_sfun_splitter_controller

function [sys, x0, str, ts] = CD2_sfun_splitter_controller(t, x, u, flag, n_comp,tstep)

% The following outlines the general structure of an S-function.
switch flag,
    case 0,
        [sys, x0, str, ts]=mdlInitializeSizes(t, x, u, flag, n_comp,tstep);
    case 2,
        sys=mdlUpdate(t, x, u, n_comp,tstep);
    case 3,
        sys=mdlOutputs(t, x, u, n_comp,tstep);
    case {1, 4, 9}
        sys=();
    otherwise
        error(['Unhandled flag = ', num2str(flag)]);
end

% mdlInitializeSizes
% Return the sizes, initial conditions, and sample times for the S- 
% function.
function [sys, x0, str, ts]=mdlInitializeSizes(t, x, u, flag, n_comp,tstep)

sizes = simsizes;
sizes.NumContStates = 0;
sizes.NumDiscStates = 0;
sizes.NumInputs = n_comp+2;
sizes.NumOutputs = 2*(n_comp+1);
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1;  % at least one sample time is needed

sys = simsizes(sizes);
x0 = zeros(sizes.NumDiscStates, 1);
str = [];
hs = [tstep 0];
function sys=mdlUpdate(t, x, u, n_comp,tstep)
sys=[];

function sys=mdlOutputs(t, x, u, n_comp,tstep)
y=[u(1:n_comp+1);u(1:n_comp+1)];
y(1)=u(n_comp+2);
Q =u(1)-u(n_comp+2);
if Q >=0
    y(n_comp+2)=Q;
else
    y(n_comp+2)=0;
end
sys=y;