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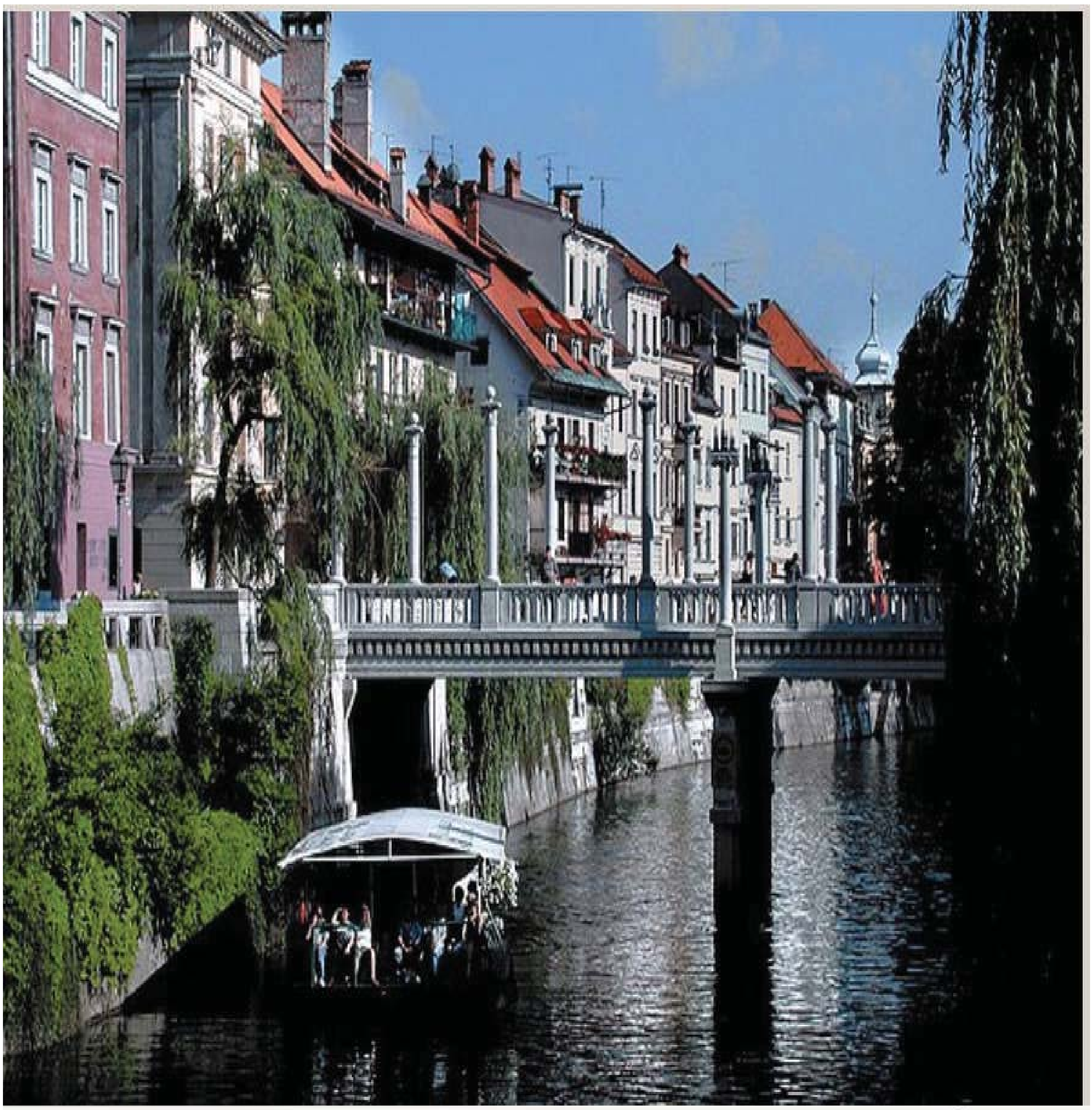

Integrated Urban Wastewater System Modelling with Conceptual Surrogate Models

Ying Chen

MSc Thesis (WSE-HI.09-10)
April 2009

UNESCO-IHE
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SWITCH

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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

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.

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April, 2009

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List of symbols

CA	Sub-catchment
CD	CITY DRAIN
CSO	Combined Sewer Overflow
DWF	Dry Whether Flow
PE	Population Equivalent
RMSE	Root Mean Square Error
RTC	Real Time Control
WWTP	Wastewater Treatment Plant

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.

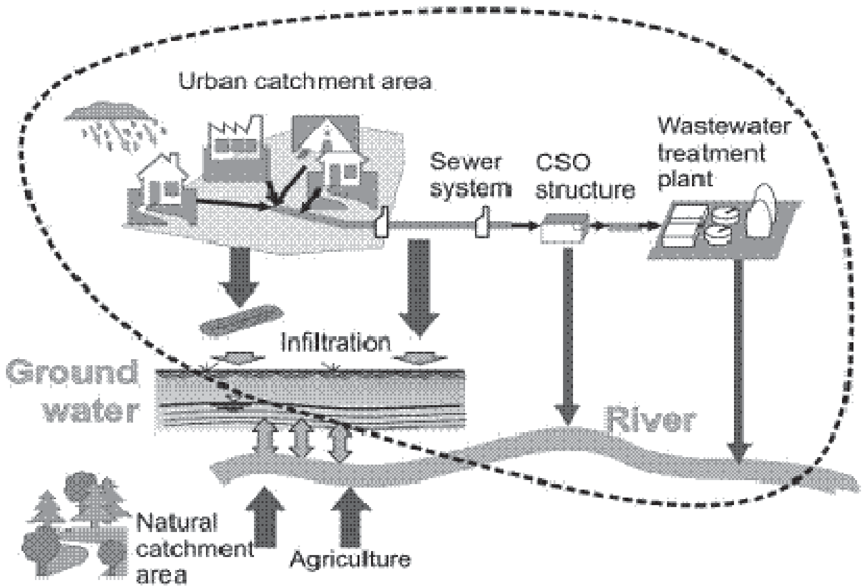

Fig. 1.1: Wastewater cycle in urban environment

[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 waster water 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 sub-system 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 extents the capability of CITY DRIAN software, and can be used to control river pollution by diverting excessive overflows and WWTP effluent in to 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.

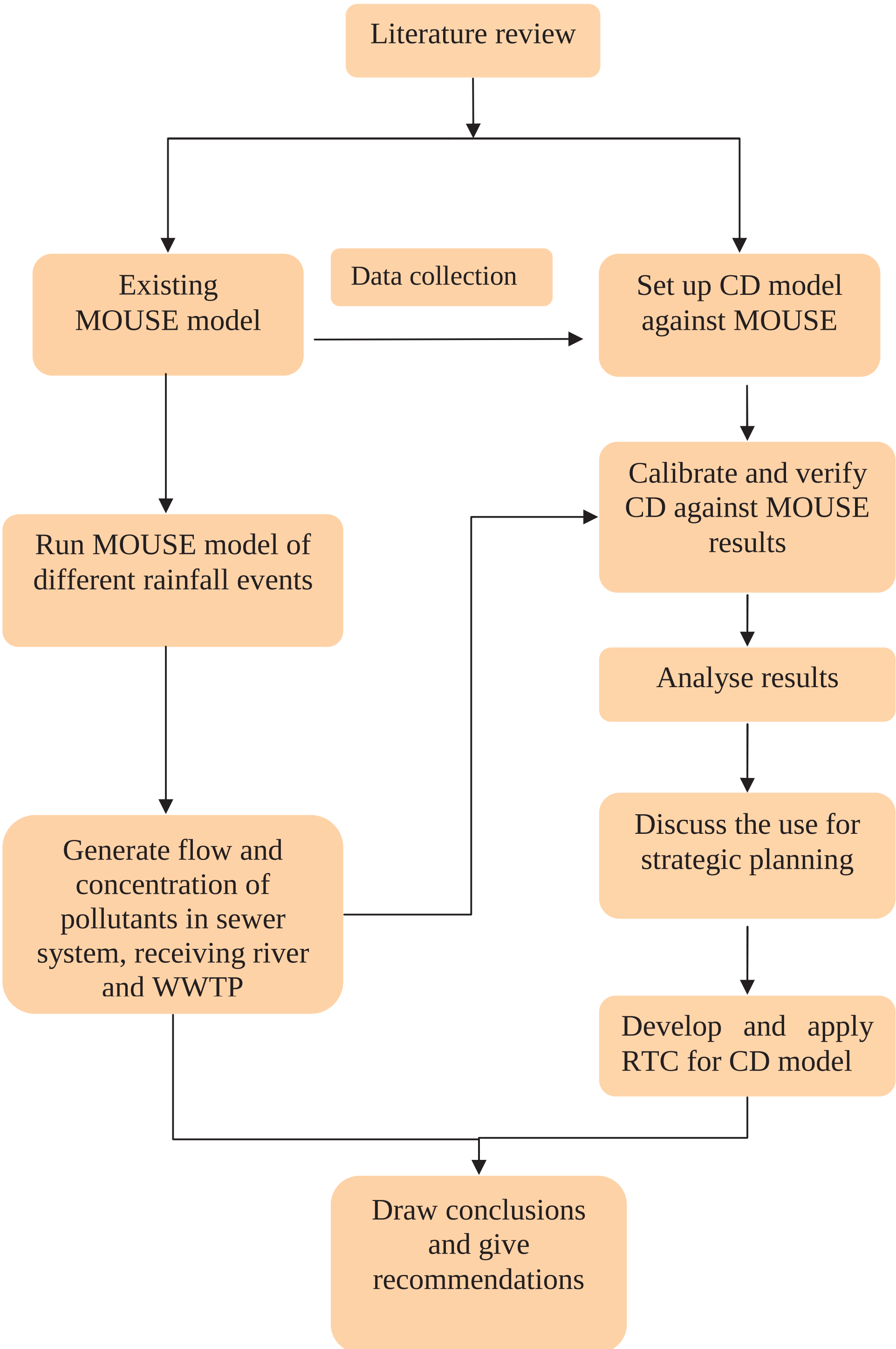

Fig. 1.2: Methodology flow chart

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 sating limitations of exiting research results in chapter1 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 2.1: Comparison of different integrated models

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

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.

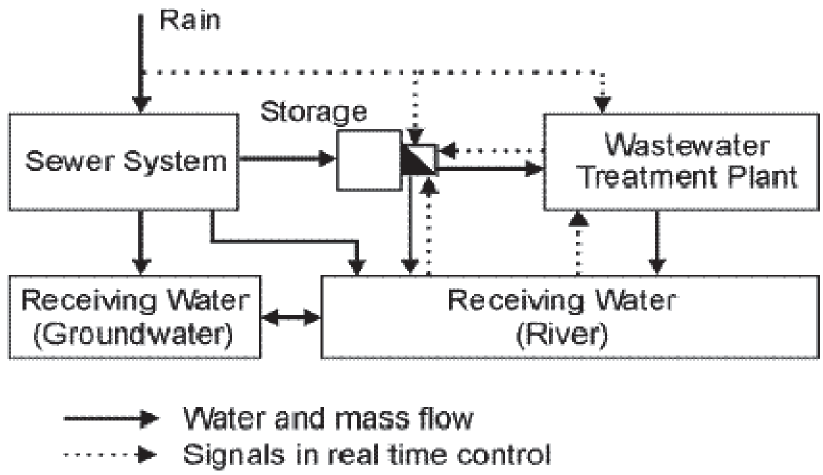

Fig. 3.1: Schematic on the main components and information flow in CITY DRAIN

[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 [m^3/s] – Flow
V [m^3] – Volume
L [m] – Length
t, Δt [s] – Time
C [g/m^3] – 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 list in the library. And they are classified to 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 setting for each simulation.

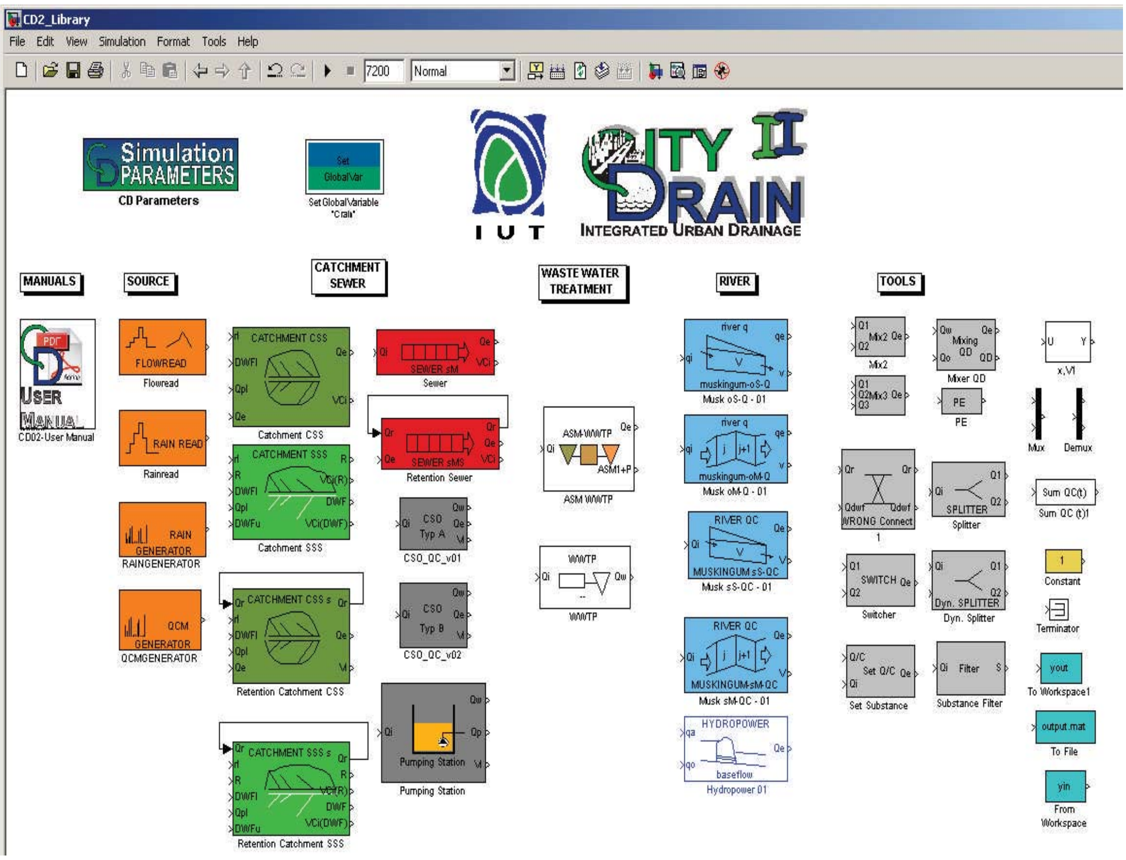

Fig. 3.2: CITY DRAIN library

Core block

Core element of every CITY DRAIN simulation is the block “CD – Simulation Parameters” (see figure 3.3).

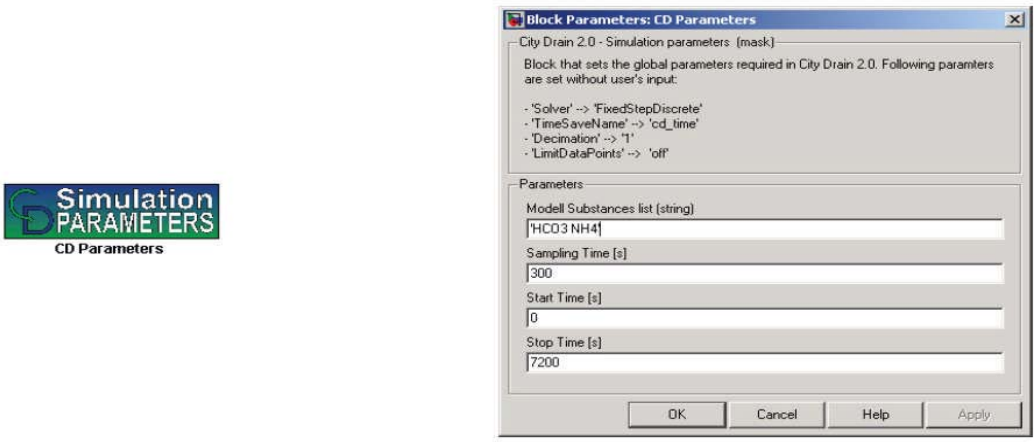

Fig. 3.3 Block of “CD – Simulation parameters”

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.

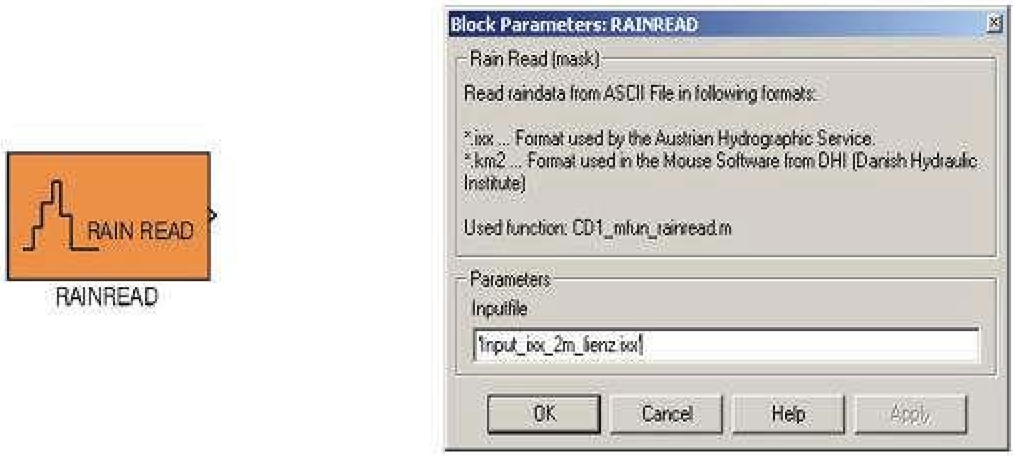

Fig. 3.4: Block of Rainread

- **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.

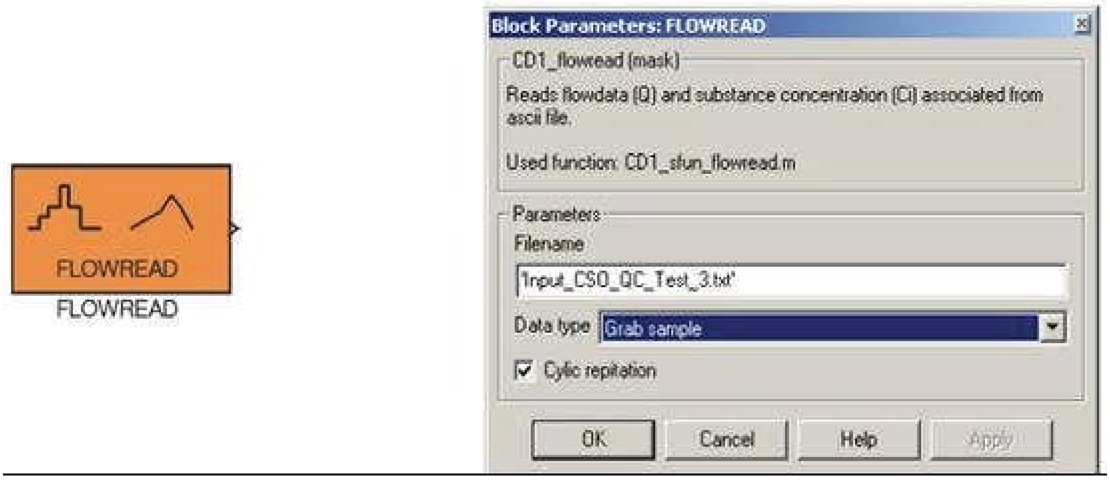

Fig. 3.5: Block of Flowread

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:

r_L – Rain volume per time step [mm/Δt];
$Q_{DWF,L}$ – Dynamic dry weather flow [q(m^3/s) C(g/m^3)];
$Q_{P,L}$ – Dynamic flow parasite warer [q(m^3/s) C(g/m^3)];
Q_e – Waste/storm water from an upstream catchment [q(m^3/s) C(g/m^3)].

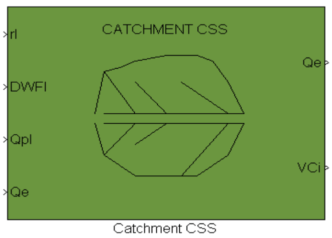

Fig. 3.6: Block of Catchment CSS

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

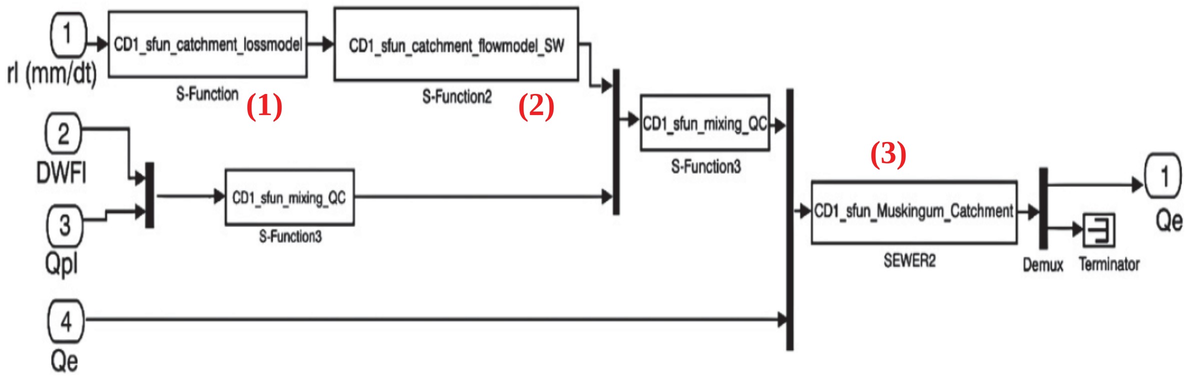

Fig. 3.7: Routing processes under Catchment CSS block

(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.

$$h_e = (r_L - h_i - h_p)\ \varphi$$

$$\varphi = A_e / A$$

where:

h_i – Initial loss;
h_p – Permanent loss;
φ – 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_L – 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;
Δt – time step, inherited from the global setting;
he – 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 ≈ Δt);
X – Dimensionless weighting factor related to the amount of wedge storage.

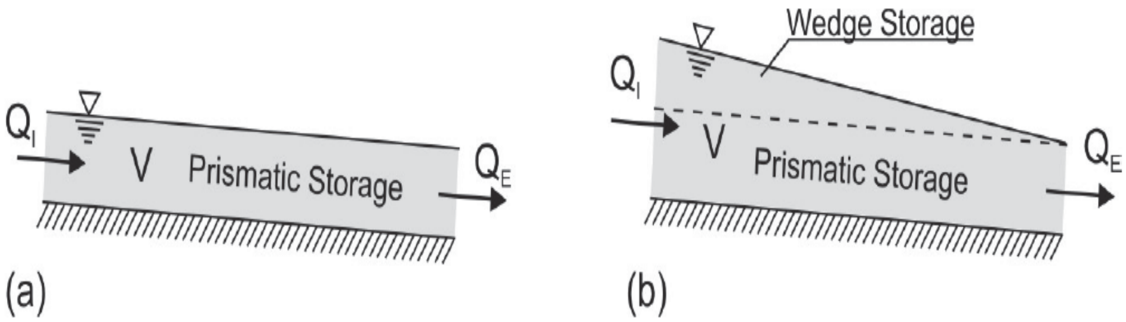

Fig. 3.8: Flow in channels (a) Steady – uniform flow and (b) Flood – wave flow

The first term of the right side represents the prismatic storage where the second represents the wedge storage. Since K ≈ Δt, the term for prismatic storage can be written as:

$$K^* Q_E = \Delta t * Q_E = \Delta t * V * A_0 = L * A_0$$

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 and 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:

$$V_i = K * [X * Q_{I,i} + (1 - X) * Q_{E,i}]$$

$$V_{i+1} = K * [X * Q_{I,i+1} + (1 - X) * Q_{E,i+1}]$$

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

$$Q_{E,i+1} = C_0 * Q_{I,i+1} + C_1 * Q_{I,i} + C_2 * Q_{E,i}$$

The three coefficients are specific for Muskingum Method.

$$C_0 = \frac{0.5 * \Delta t - K * X}{K * (1 - X) + 0.5 * \Delta t} ; \quad C_1 = \frac{0.5 * \Delta t + K * X}{K * (1 - X) + 0.5 * \Delta t} ; \quad C_2 = \frac{K * (1 - X) - 0.5 * \Delta t}{K * (1 - X) + 0.5 * \Delta t}$$

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, C1, $C_2 \geq 0$ (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 Δt:

$$\frac{1}{2(1 - X)} \leq \frac{K}{\Delta t} \leq \frac{1}{2X}$$

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).

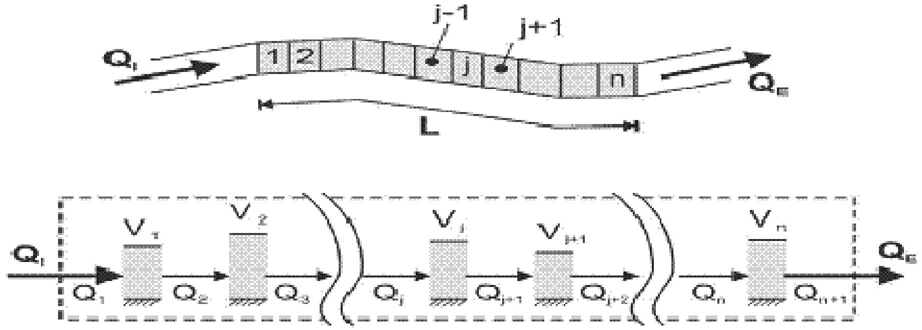

Fig. 3.9: Schematic on nomenclature for multiple sub-reaches

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':

$$K' = K / n$$

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

$$Q_{i+1}^{j+1} = C_0 * Q_{i+1}^{j} + C_1 * Q_i^j + C_2 * Q_i^{j+1}$$

Using

$$C_0 = \frac{0.5*\Delta t - K'*X}{K'*(1-X)+0.5*\Delta t} \quad C_1 = \frac{0.5*\Delta t + K'*X}{K'*(1-X)+0.5*\Delta t} \quad C_2 = \frac{K'*(1-X)-0.5*\Delta t}{K'*(1-X)+0.5*\Delta t}$$

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

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

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.

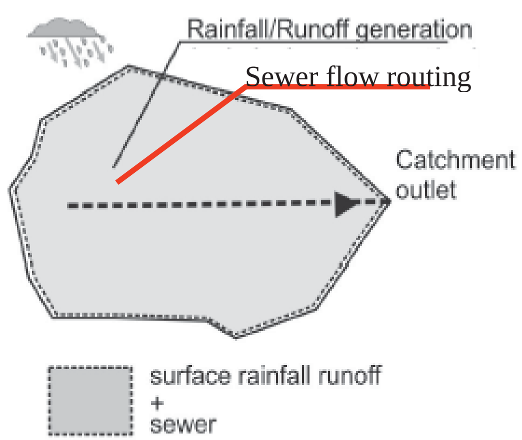

Fig. 3.10: Schematic on nomenclature for multiple sub-reaches

[Adopted from Achleitner, 2006]

- **CSO**

CSO (see figure 3.11) is used for simulation of an overflow structure for either combined or separate sewer. Inflow (Qi) 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).

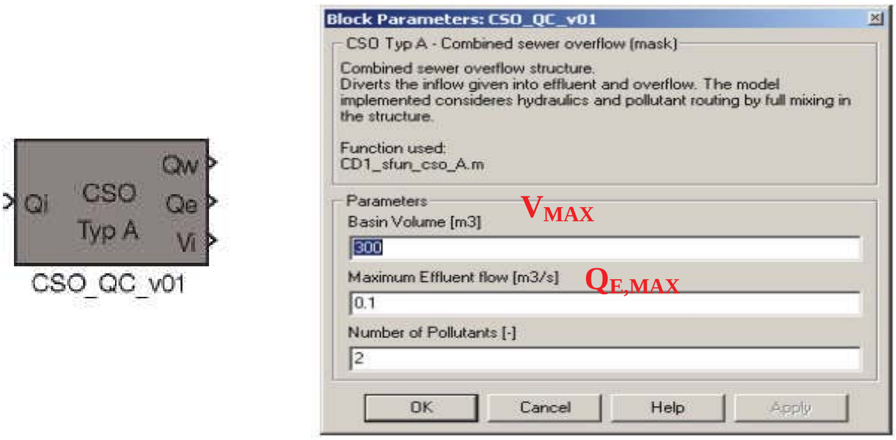

Fig. 3.11: Block of CSO

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

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

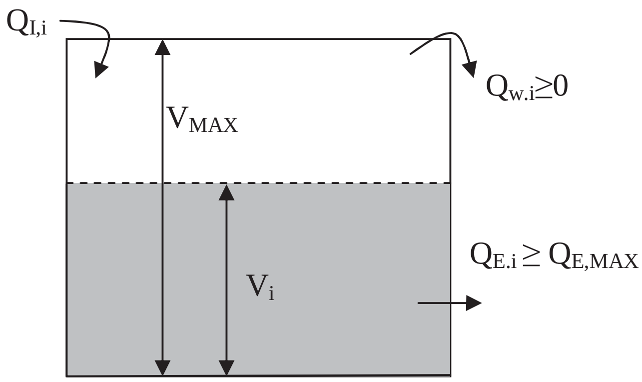

Fig. 3.12: Variable definitions of discrete CSO model

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

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

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 $Q_{I,i}$ 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

$$V_i' = (Q_{I,i} - Q_{E,MAX})*\Delta t + V_{i-1}$$

Case 1

If $V_i' \leq 0$

Then $V_i = 0$; $Q_{E,i} = V_{i-1}/\Delta t + Q_{I,i} \leq Q_{E,MAX}$; $Q_{W,i} = 0$;

Case 2

If $V_i' \geq V_{MAX}$

Then $V_i = V_{MAX}$; $Q_{E,i} = Q_{E,MAX}$; $Q_{W,i} = Q_{I,i} - Q_{E,MAX} - (V_{MAX} - V_{i-1})/\Delta t$;

Case 2

If $0 < V_i' < V_{MAX}$

Then $V_i = (Q_{I,i} - Q_{E,MAX})\,\Delta t + V_{i-1}$; $Q_{E,i} = Q_{E,MAX}$; $Q_{W,i} = 0$;

- **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.

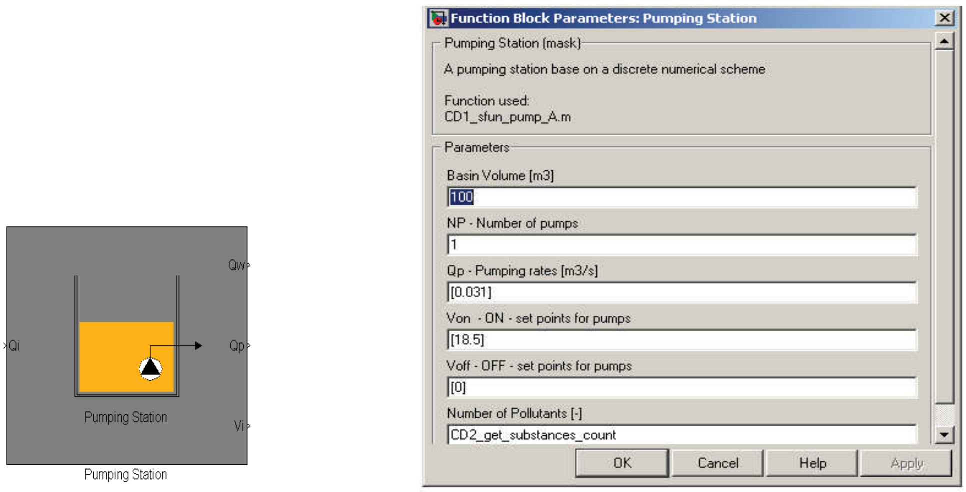

Fig. 3.13: Block of Pumping station

WWTP block

The block (see figure 3.14) models a WWTP that is considered to fulfil predefined requirements of

-- removal efficiency $R_{E,MIN}$ and

-- maximum effluent concentration $C_{E,MAX}$

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

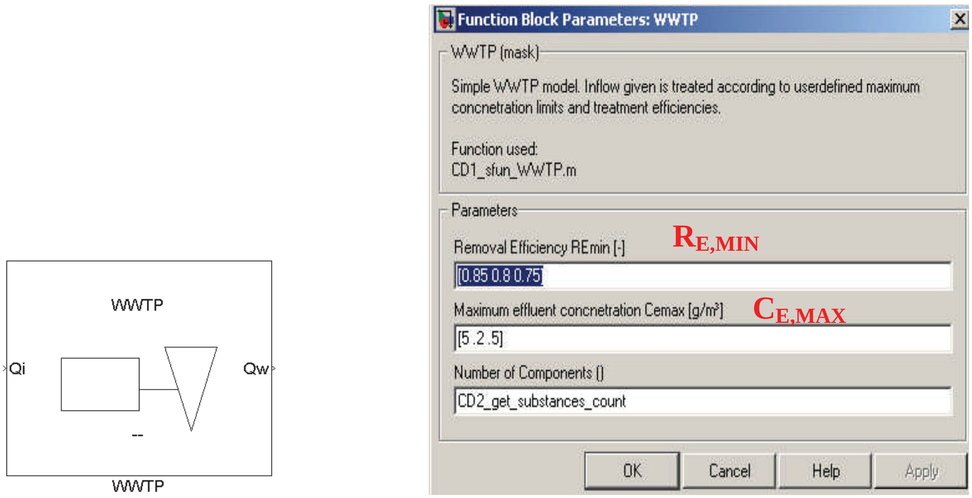

Fig. 3.14: Block of WWTP

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.

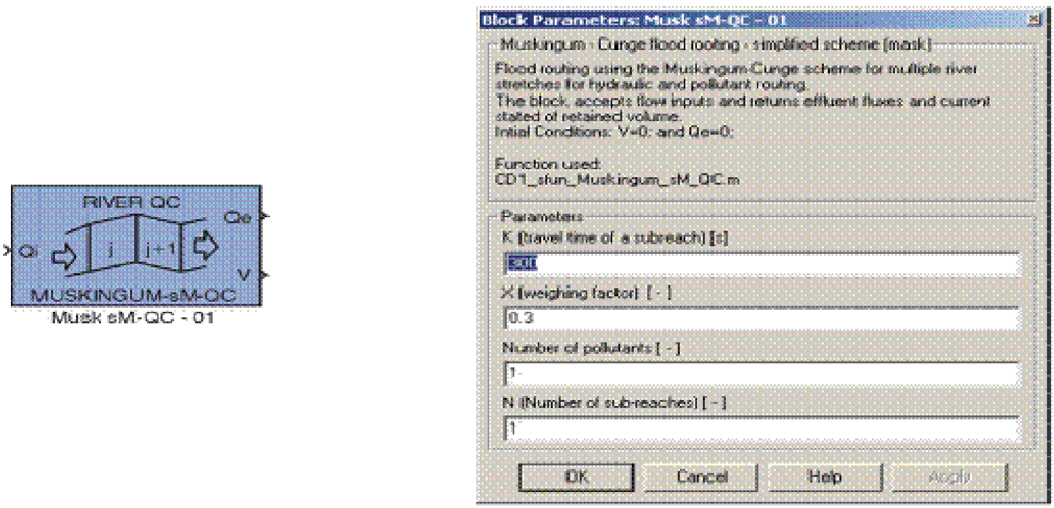

Fig. 3.15: Block of Muskingum_sM_QC

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)

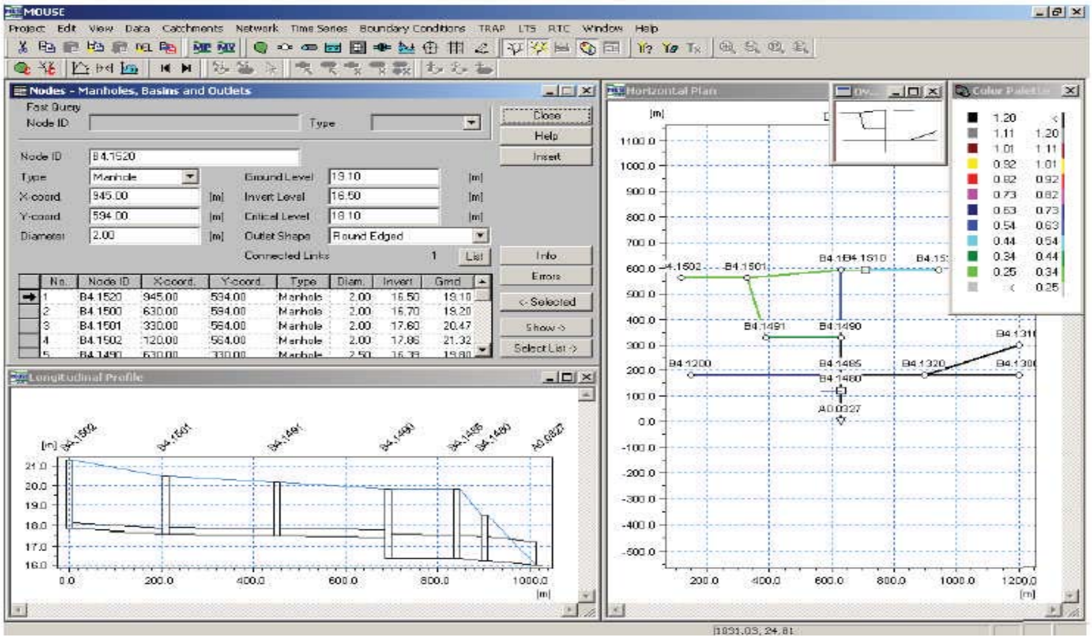

Fig. 3.16: Graphic interface of MOUSE

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 MOUSR 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.

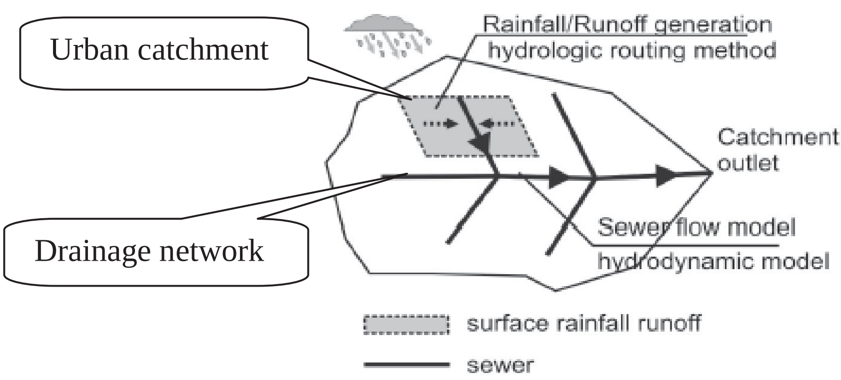

Fig. 3.17: Schematic computation processes in MOUSE

[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.

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.

Fig. 4.1: Location of Ljubljana

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.

Fig. 4.2: Map of Ljubljana

4.2 Preparation of input data

CITY DRAIN model was built against exiting 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.

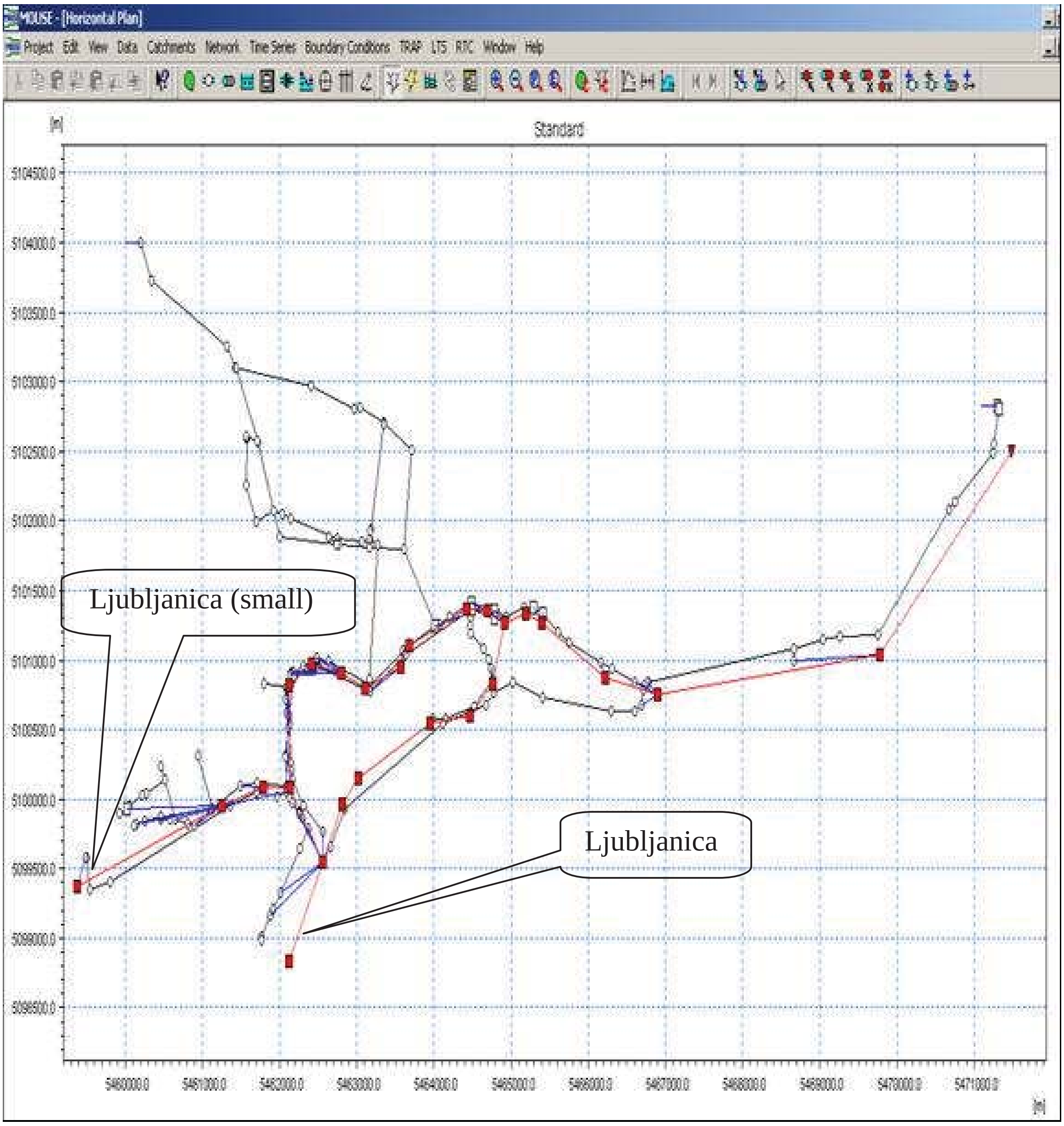

Fig. 4.3: MOUSE model of Ljubljana

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

Table 4.1 Data required from MOUSE

Sub-catchments (CA)			
PE	Population equivalents	[-]	Parameter Values
t_f*	Time of concentration in CA	[s]	
A	Sub-catchment area	[ha]	
φ	Run-off coefficient	[-]	
h_i	Initial loss	[mm]	
h_p	Permanent loss	[mm/ Δt]	
CSO			
V_{MAX}	Basin volume of CSO	[m^3]	
$Q_{E,MAX}$	Maximum effluent flow	[m^3/s]	
Pumping stations			
V	Basin volume of Pumping station	[m^3]	
Q_p	Mean pumping rate	[m^3/s]	
h_{on}	Water level of ON set point	[m]	
h_{off}	Water level of Off set point	[m]	
Rain data			Time Series
r	Accumulate rainfall height in Δt	[mm]	
Flow data			
DWF	Dry weather flow hydrograph	[m^3/s] and [g/m^3]	
River	Boundary condition of River	[m^3/s] and [g/m^3]	

(* 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

CD parameters	
Model substance list (pollutant simulated)	ammonia
Sample time (time step)	300 sec
Start time (1995,4,24)	0 sec
Stop time (1995,4,26 two days)	172800 sec

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 φ, 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_{MAX} and $Q_{E,MAX}$ 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 4.3 Pumping station parameters

Basin Volume	1260 m^3
Number of pumps	2
Pumping rate	[0.078 0.01]
Volume on	[644 32900]
Volume off	[400 644]

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.

$$\frac{\text{Average value } m^3/\text{PE/day}}{\text{Total seconds of a day}} * \text{ PE } * \text{Diurnal hourly factor} = \text{CD Value}$$

Among which

$$\frac{\text{Average value } m^3/\text{PE/day}}{\text{Total seconds of a day}} = 0.182 / (24*3600) = 2.1 * 10^{-6} \ m^3/\text{PE/s}$$

PE of each sub-catchment (see table 4.4)

Table 4.4 Data required from MOUSE

Catchment ID	PE	Catchment ID	PE
Catchment CSS01	3938	Catchment CSS12	5568
Catchment CSS02	17113	Catchment CSS13	7416
Catchment CSS03	18202	Catchment CSS14	3654
Catchment CSS04	2767	Catchment CSS15	5691
Catchment CSS05	8856	Catchment CSS16	643
Catchment CSS06	3436	Catchment CSS17	9346
Catchment CSS07	983	Catchment CSS18	1056
Catchment CSS08	39433	Catchment CSS19	15928
Catchment CSS09	3952	Catchment CSS20	10535
Catchment CSS10	164919	Catchment CSS21	3080
Catchment CSS11	6855	Catchment CSS22	10535
		SUM	**343906**

Diurnal hourly factor (see table 4.5)

Table 4.5 Diurnal hourly factor

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

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/m^3).

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 4.6 Diurnal hourly factor

river	Discharge (constant value)	Concentration (ammonia constant value)
Ljubljanaica	20	0.45
Ljubljanica (small)	5	0.1

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/m^3

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.

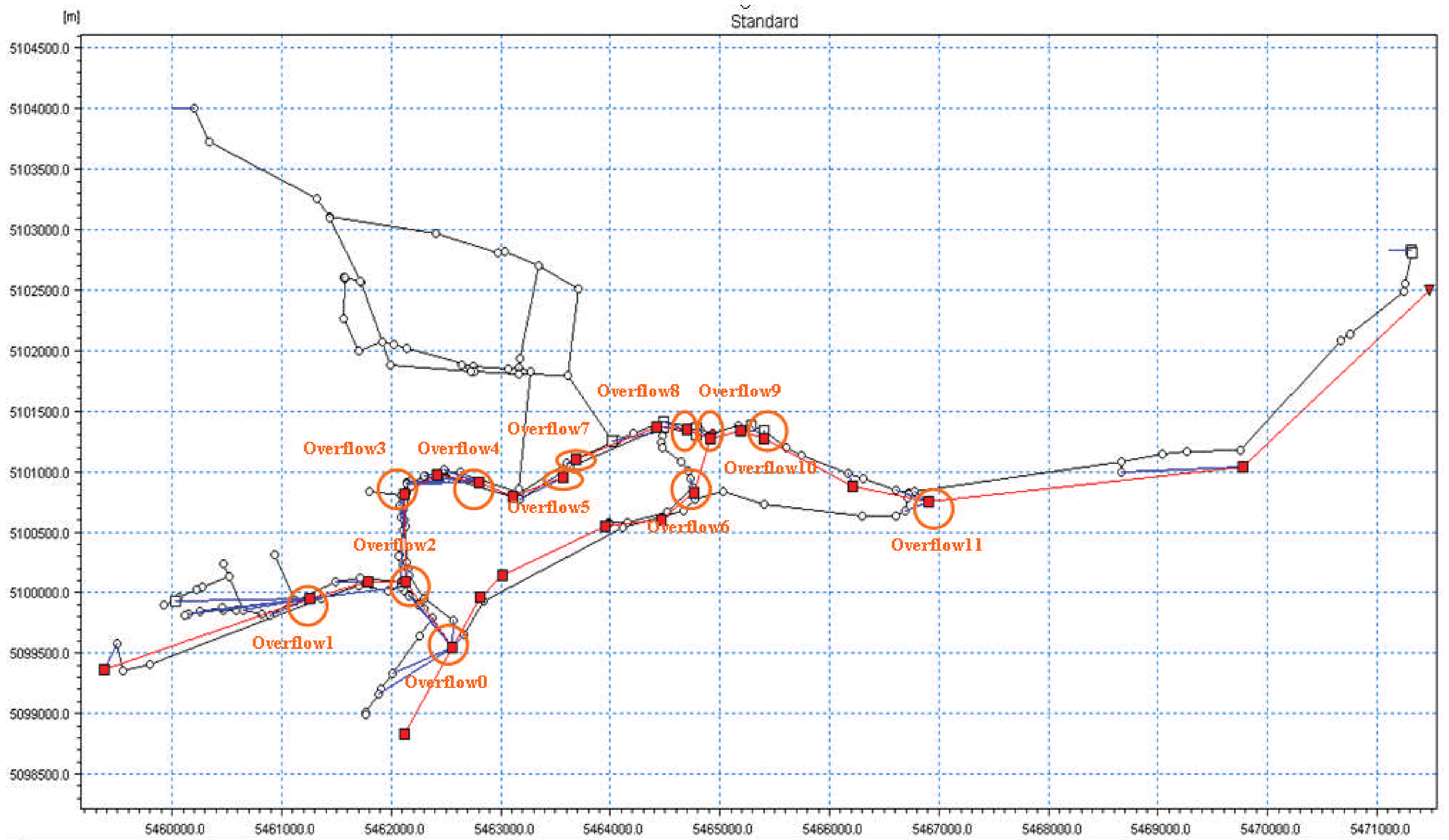

Fig. 4.4: River nodes which receive overflow from sewer system

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.

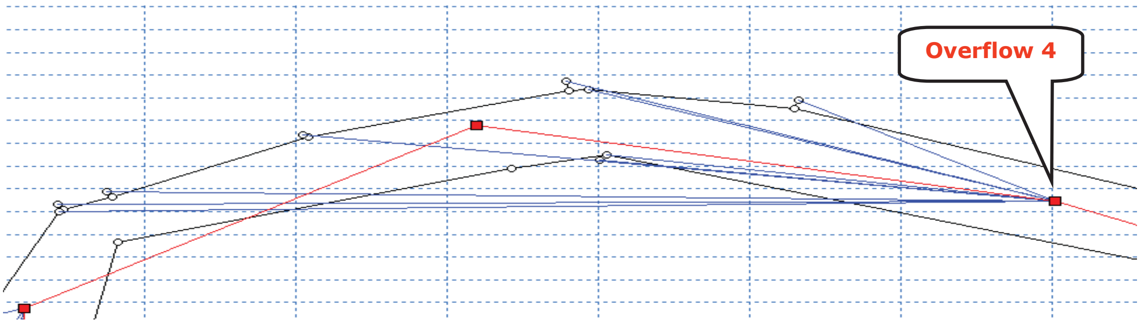

Fig. 4.5: Enlarge map of receiving river node (overflow 4) and surrounding sewer network

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.

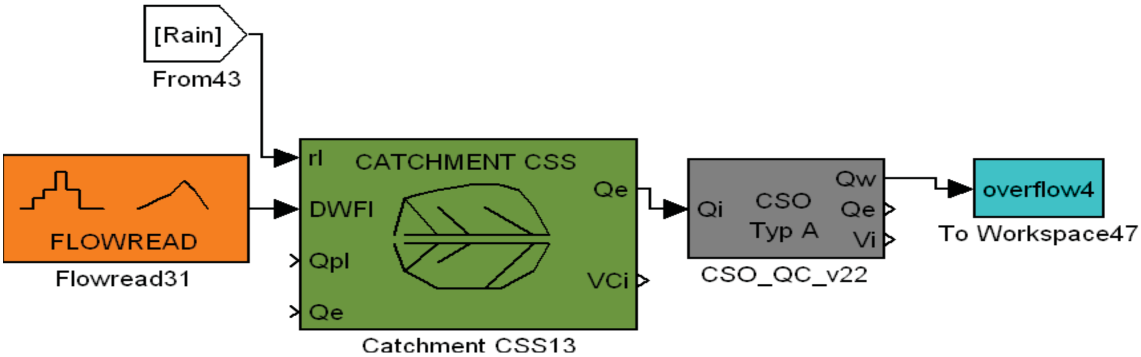

Fig. 4.6: CA in CITY DRAIN sewer network (example of overflow 4)

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.

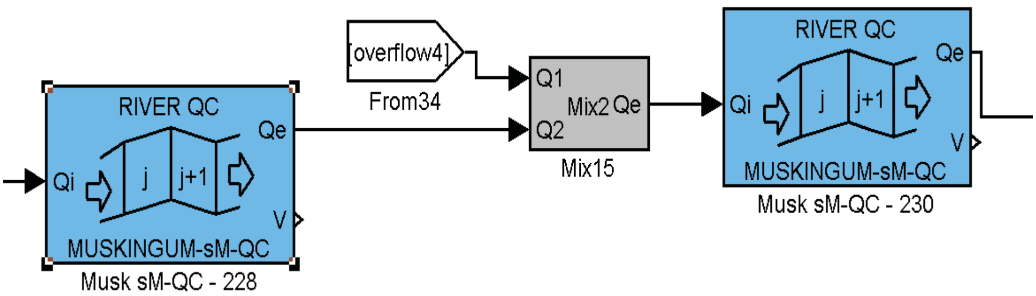

Fig. 4.7: River network of CITY DRAIN (example of overflow 4)

4.4 Overview of Ljubljana CD model

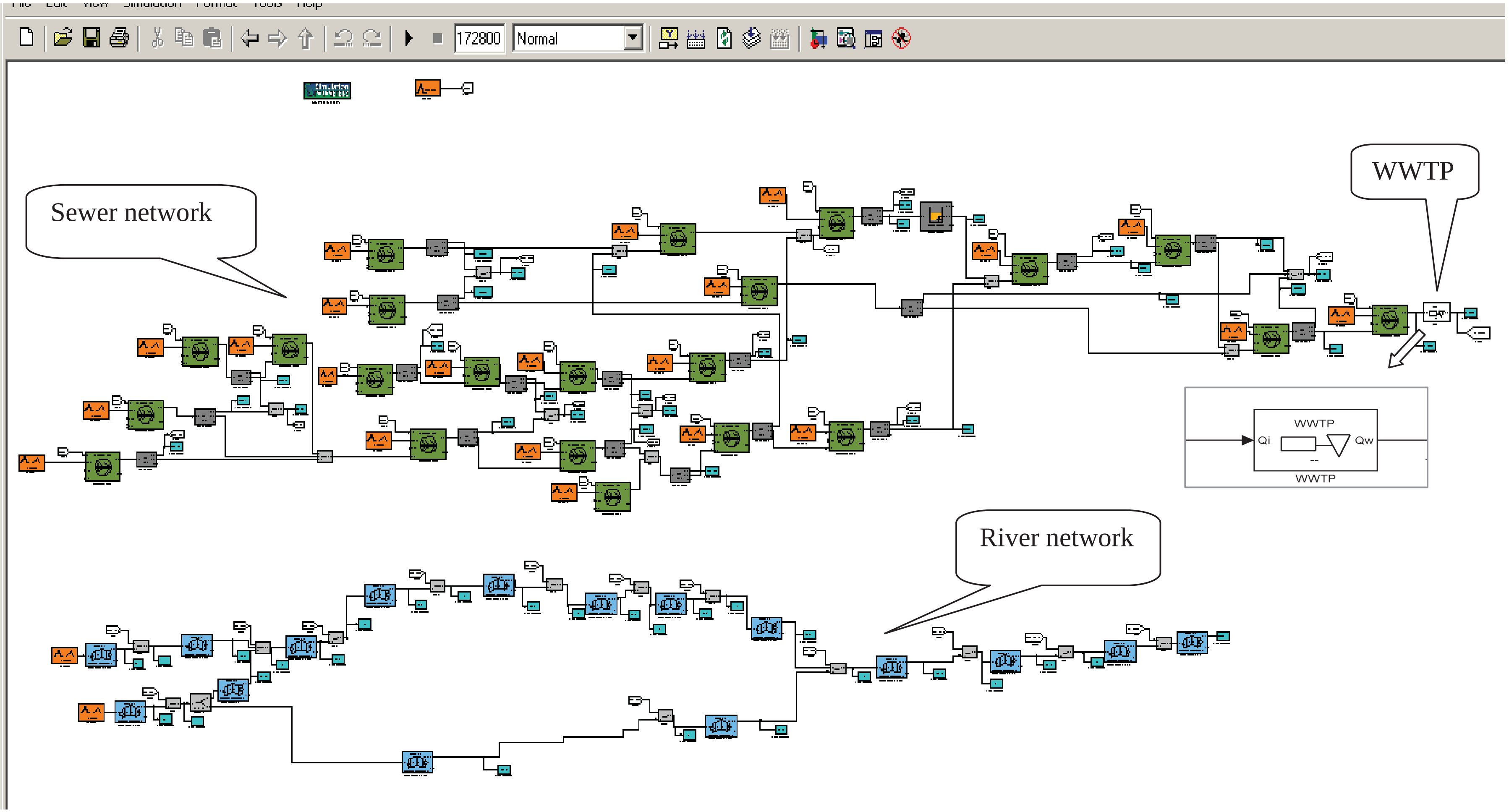

Fig. 4.8: Overview of Ljubljana CITY DRAIN network

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 different 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 = patternsearch(@fun,x0). In which function (@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 4.7 Parameters calibrated in CITY DRAIN.

Catchments Block		
K	time for a unit discharge wave travelling through a sub-reach of a CA	[s]
N	number of sub-reaches of one CA	[-]
X	weighting factor for the amount of wedge storage	[-]
φ	Run-off coefficient	[-]
CSO Block		
V_{MAX}	Basin volume of CSO	[m^3]
$Q_{E,MAX}$	Maximum effluent flow	[m^3/s]
River Block		
K	time for a unit discharge wave travelling through a sub-reach of a CA	[s]
N	number of sub-reaches of one CA	[-]
X	weighting factor for the amount of wedge storage	[-]

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_{MAX}, $Q_{E,MAX}$ were estimated from MOUSE, but calibrated regarding to the fitness of the result. Usually because V_{MAX} is too small to affect Q_W and Q_E, it is not an important factor.
- For most CAs, φ 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 4.8 Catchment parameters

Catchment ID	Area (copied from MOUSE)	φ	N	K	X
Catchment CSS01	49.4	0.32	2	300	0.2
Catchment CSS02	309.5	0.11	5	300	0.2
Catchment CSS03	232	0.12	2	300	0.4
Catchment CSS04	41.7	0.67	1	300	0.5
Catchment CSS05	81.6	0.20	1	300	0.3
Catchment CSS06	24.7	0.55	1	300	0
Catchment CSS07	7.8	0.334	1	300	0.2
Catchment CSS08	99	0.45	1	300	0.4
Catchment CSS09	15.3	0.067	1	300	0.2
Catchment CSS10	1522.4	0.10	5	420	0.2
Catchment CSS11	54.7	0.20	2	300	0.1
Catchment CSS12	55.4	0.32	1	300	0.1
Catchment CSS13	89	0.47	7	300	0.1
Catchment CSS14	46.5	0.50	4	300	0.2
Catchment CSS15	127.2	0.10	9	420	0.1
Catchment CSS16	6.7	0.27	1	300	0.1
Catchment CSS17	64.9	0.50	10	300	0.2
Catchment CSS18	11.1	0.27	1	300	0.1
Catchment CSS19	272.1	0.18	1	300	0.3
Catchment CSS20	99.7	0.70	8	300	0.3
Catchment CSS21	123.2	0.2	2	300	0.5
Catchment CSS22	243.4	0.58	8	900	0.3
SUM	**3577.6**				

- CSO parameters

Table 4.9 lists calibrated parameters V_{MAX}, $Q_{E,MAX}$ for all combined sewer overflows in Ljubljana CITY DRAIN model.

Table 4.9 CSO parameters

CSO ID	**V_{MAX}**	**$Q_{E,MAX}$**	**CSO ID**	**V_{MAX}**	**$Q_{E,MAX}$**
CSO_QC_V01	7.54	0.04	CSO_QC_V 11	49	2.5
CSO_QC_V02	16.11	0.3	CSO_QC_V 12	129	2.28
CSO_QC_V03	7.63	0.08	CSO_QC_V 13	3.27	0.2
CSO_QC_V04	35	0.45	CSO_QC_V 14	5	0.15
CSO_QC_V05	46.4	0.26	CSO_QC_V 15	34.62	0.80
CSO_QC_V 06	12.56	0.37	CSO_QC_V 16	34	0.05
CSO_QC_V 07	28.4	0.55	CSO_QC_V 17	95.5	2
CSO_QC_V 08	35	0.27	CSO_QC_V 18	34.23	1.5
CSO_QC_V 09	129	9.2	CSO_QC_V 19	24.87	1.5
CSO_QC_V 10	129	1.22			

- River parameters

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

Table 4.10 River parameters

River block ID	N	K	X	River block ID	N	K	X
Musk_sM_Q201	1	300	0.3	Musk_sM_Q238	1	300	0.3
Musk_sM_Q1	1	400	0.3	Musk_sM_Q237	7	800	0.3
Musk_sM_Q202	2	500	0.3	Musk_sM_Q227	2	300	0.3
Musk_sM_Q207	6	800	0.3	Musk_sM_Q228	3	500	0.1
Musk_sM_Q208	8	500	0.1	Musk_sM_Q230	1	300	0.1
Musk_sM_Q210	4	300	0.1	Musk_sM_Q232	1	300	0.1
Musk_sM_Q212	5	600	0.2	Musk_sM_Q233	1	300	0.1
Musk_sM_Q213	5	600	0.2	Musk_sM_Q235	1	300	0.1

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.

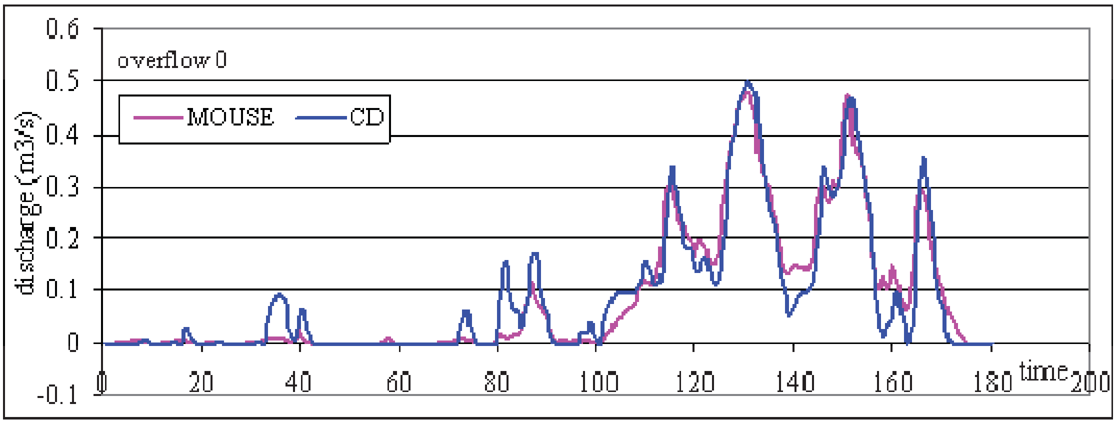

Fig. 5.1: Comparison between discharges of overflow0

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.

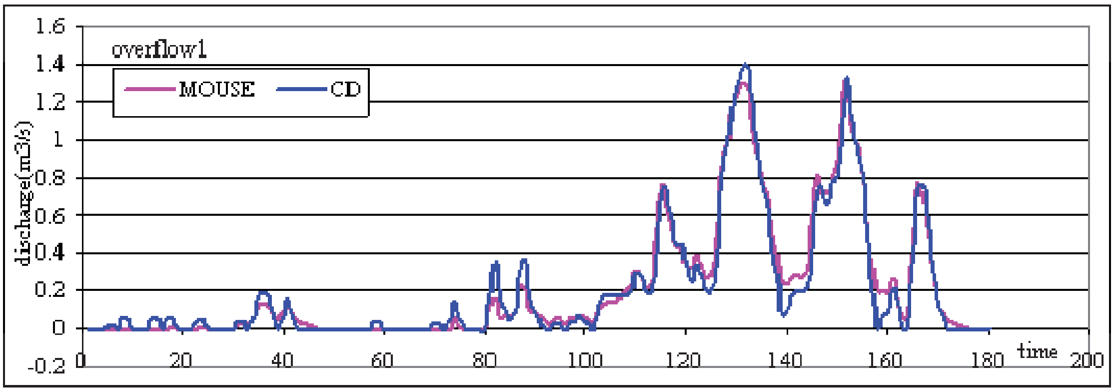

Fig. 5.2: Comparison between discharges of overflow1

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.

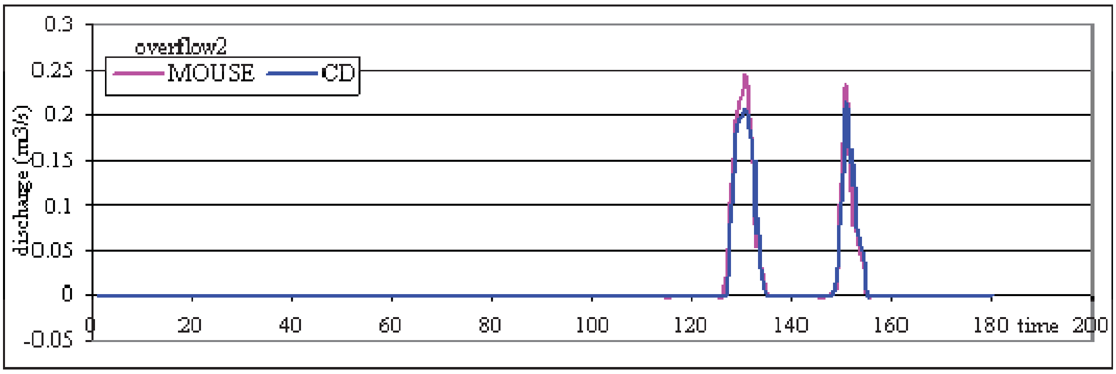

Fig. 5.3: Comparison between discharges of overflow2

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.

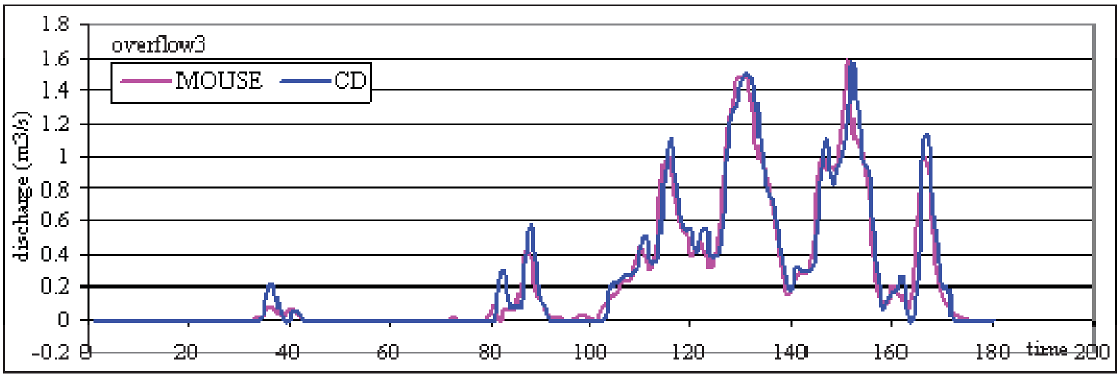

Fig. 5.4: Comparison between discharges of overflow3

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.

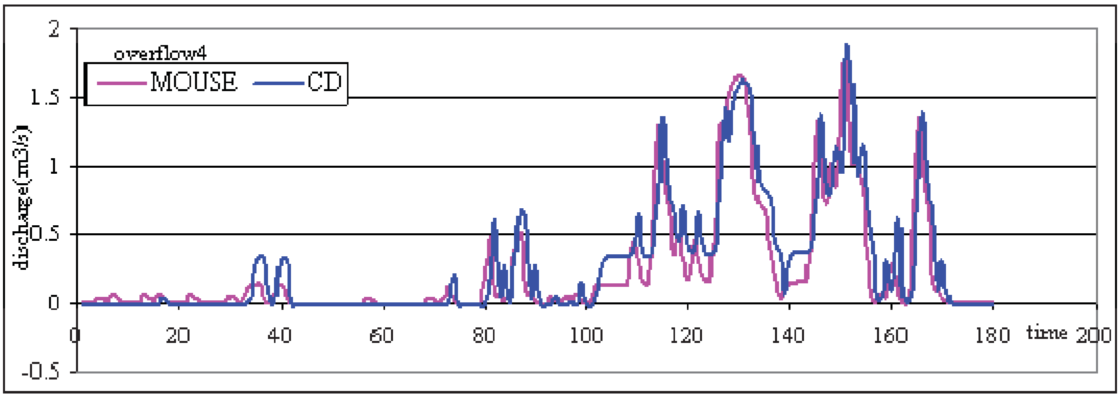

Fig. 5.5: Comparison between discharges of overflow4

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.

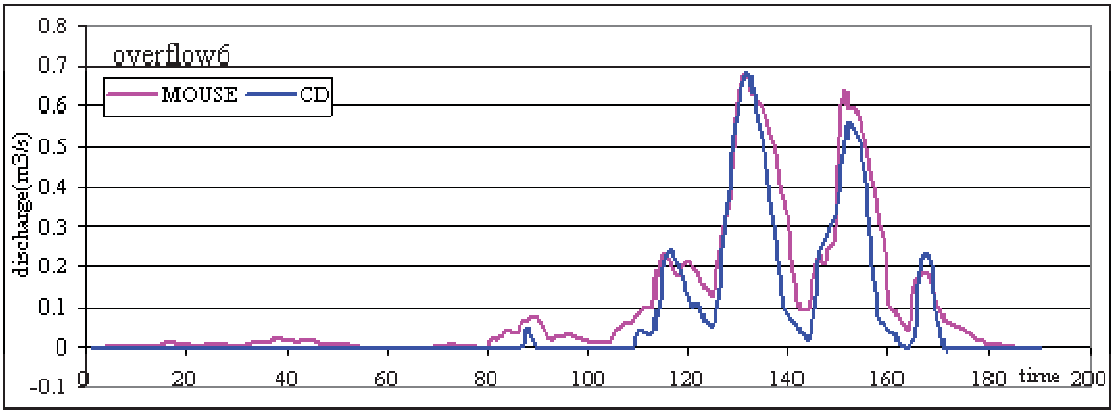

Fig. 5.6: Comparison between discharges of overflow6

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.

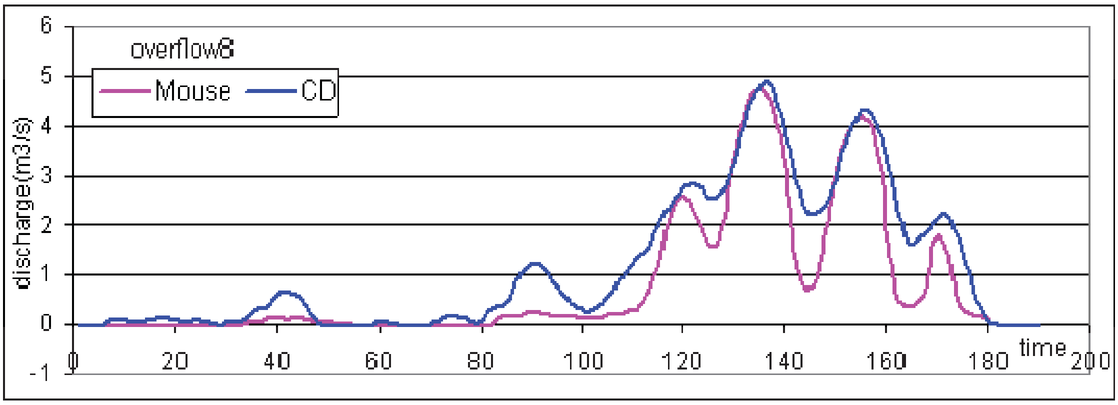

Fig. 5.7: Comparison between discharges of overflow8

Figure 5.8 reveals a good match between overflow9. RMSE equals to 0.0004 approximately

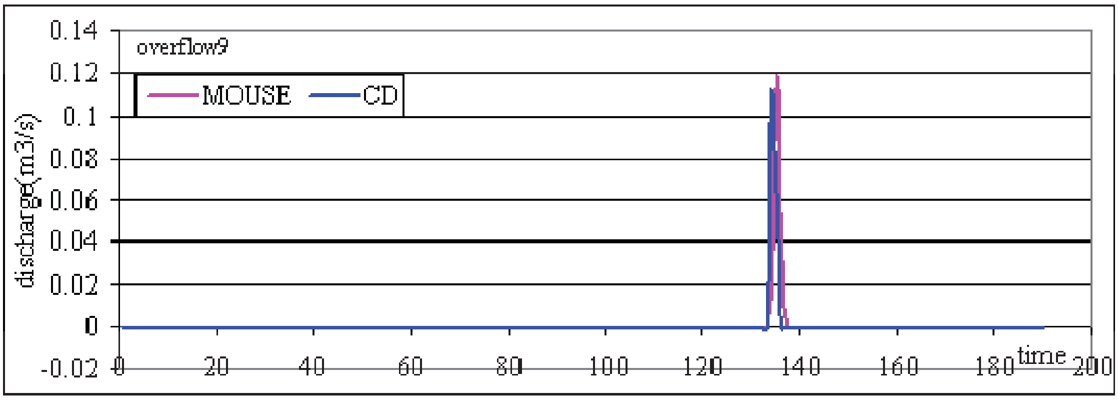

Fig. 5.8: Comparison between discharges of overflow9

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

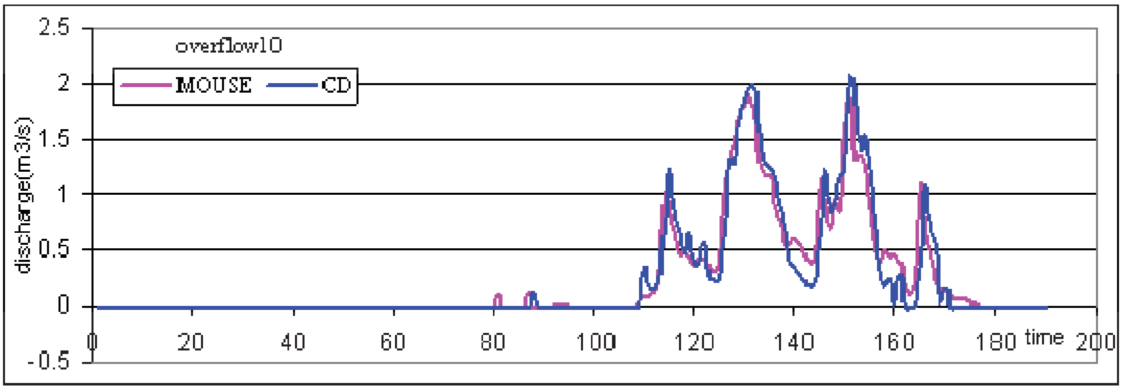

Fig. 5.9: Comparison between discharges of overflow10

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

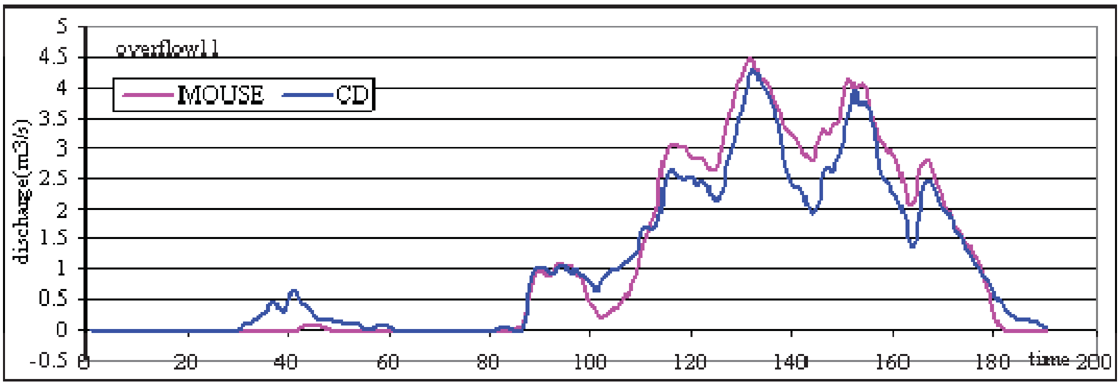

Fig. 5.10: Comparison between discharges of overflow11

In addition, discharge of overflow 5 and overflow 7 equals to $0m^3/s$ 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 5.1 Quality indicator

Indicator		Mathematical equation	Range
RMSE	Root Mean Square Error	$$\frac{\sum_{i=1}^{N}\sqrt{(M_i - S_i)^2}}{N}$$	[0 +∞]
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			

E is in the range of [0 +∞], small value tending towards 0 indicates a good fitting. Table 5.2 lists RMSE of 12 overflows

Table 5.2 RMSE for 12 overflows

Location	RMSE	Location	RMSE
overflow0	0.007	overflow6	0.012
overflow1	0.012	overflow7	0.000
overflow2	0.0005	overflow8	0.124
overflow3	0.016	overflow9	0.0004
overflow4	0.043	overflow10	0.023
overflow5	0.000	overflow11	0.070

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).

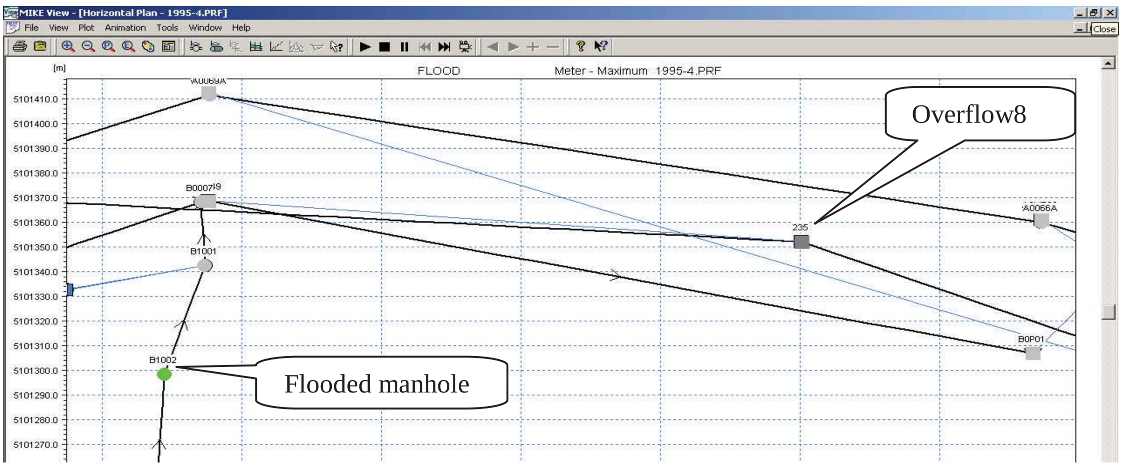

Fig. 5.11: Flooded manhole before overflow 8 in Mouse

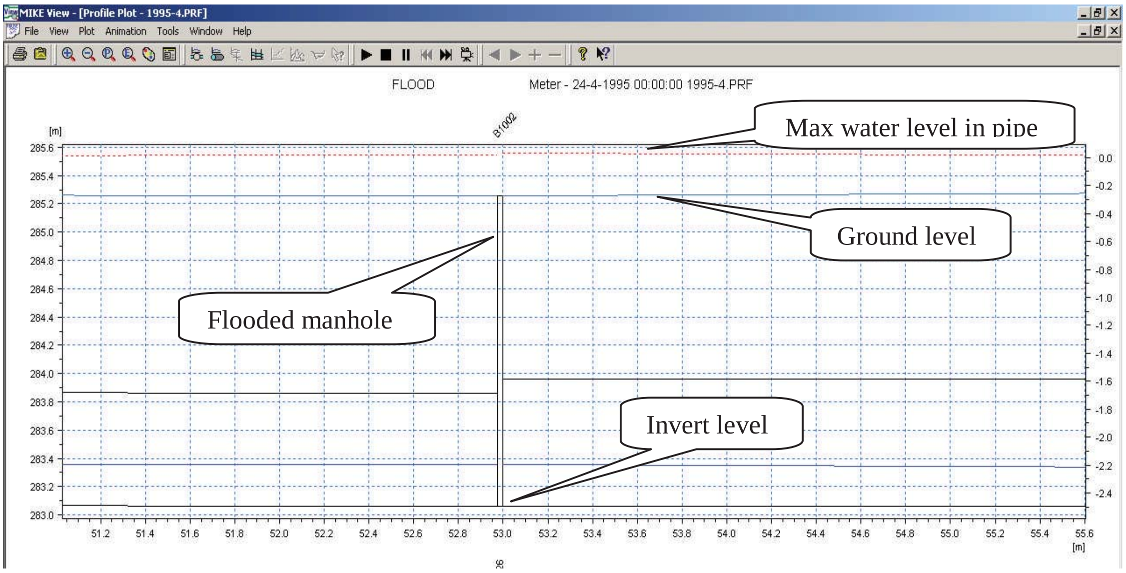

Fig. 5.12: Profile of flooded manhole before overflow 8 in MOUSE

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.

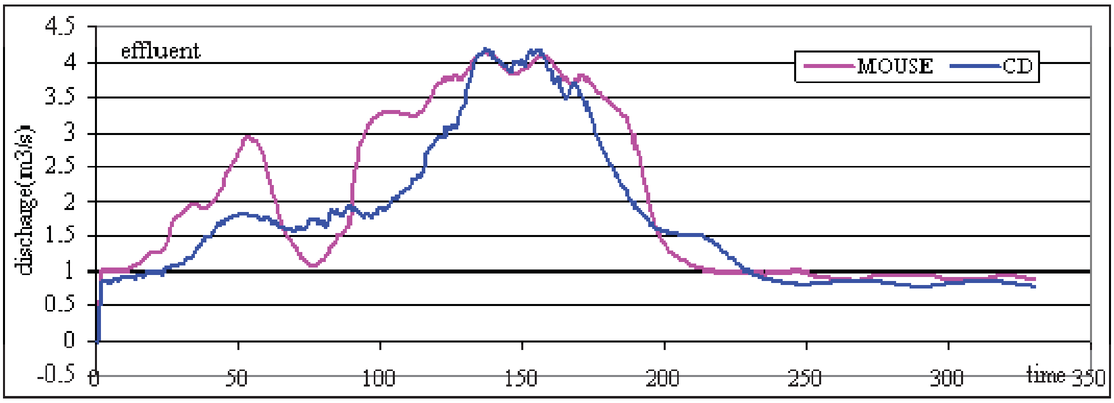

Fig. 5.13: Comparison between discharges of effluent

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

The water balance equation, inflow volume (runoff discharge and DWF) ≈ 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.

$$\sum_{i=0}^{i=11} V_M(\text{overflowi}) + V_M(\text{effluent}) = \sum_{i=0}^{i=11} V_{CD}(\text{overflowi}) + V_{CD}(\text{effluent})$$

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, $V^{M}_{effluent} - V^{CD}_{effluent} = 33045m^3$,

$$V_{flood} = V^{CD}_{overflow8} - V^{MOUSE}_{overflow8} = 25390m^3$$

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(small), discharge is equal to upstream boundary condition, which was set exactly the same in MOUSE and CD.

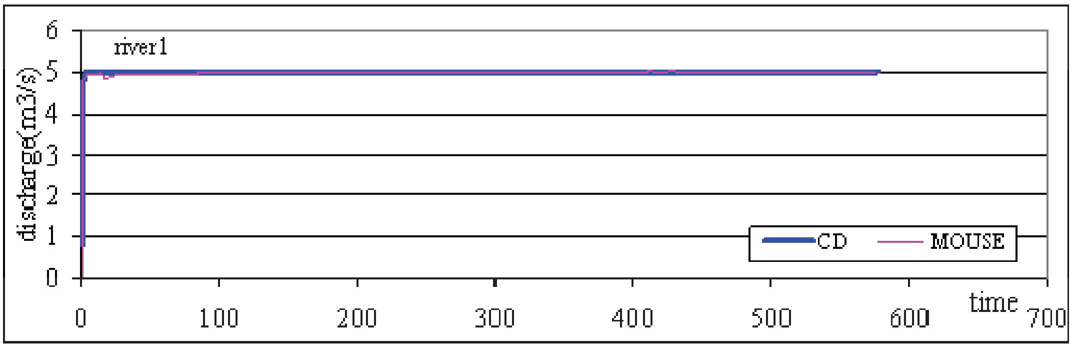

Fig. 5.14: Comparison between discharges of location river1

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.

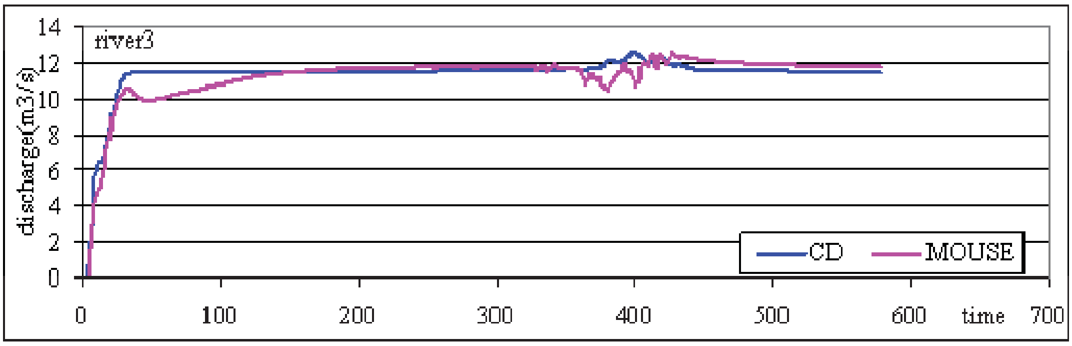

Fig. 5.15: Comparison between discharges of location river3

Figure 5.16 compares discharge of river6 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.

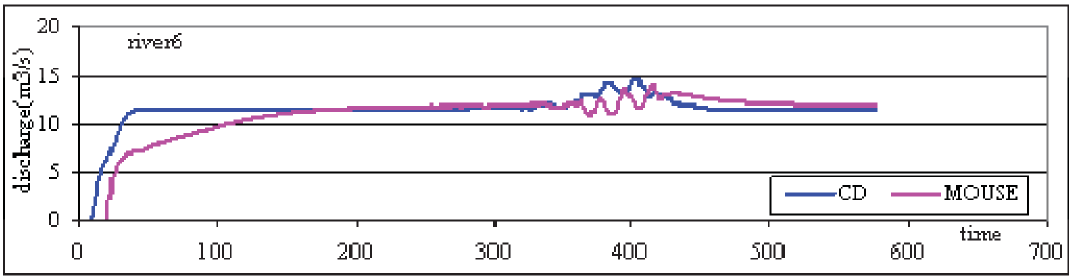

Fig. 5.16: Comparison between discharges of location river6

Figure 5.17 shows discharge of riverL1. Since it is the most upstream part of river Ljubljanica, discharge is equal to boundary condition, which is the same in MOUSE and CD.

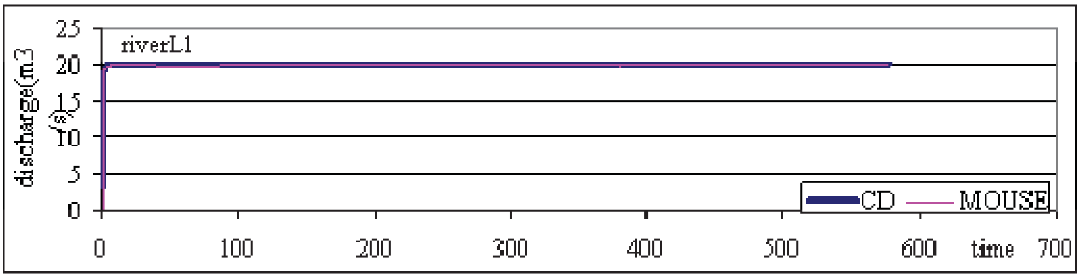

Fig. 5.17: Comparison between discharges of location riverL1

Figure 5.18 compares discharge of riverL2. Large error appears at the beginning. And a good fitting for the rest of time.

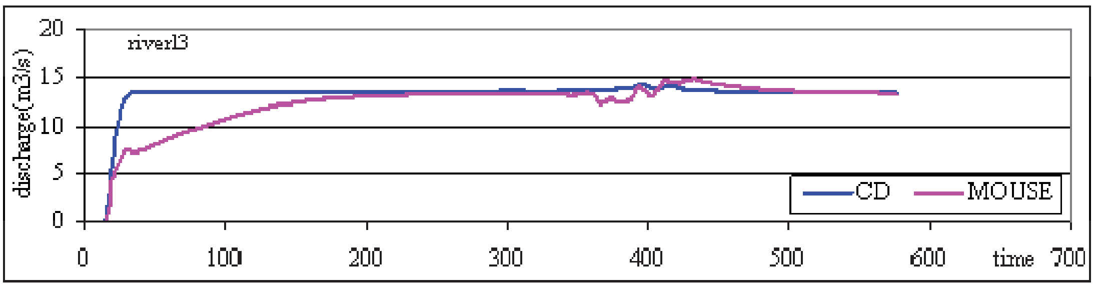

Fig. 5.18: Comparison between discharges of location riverL2

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.

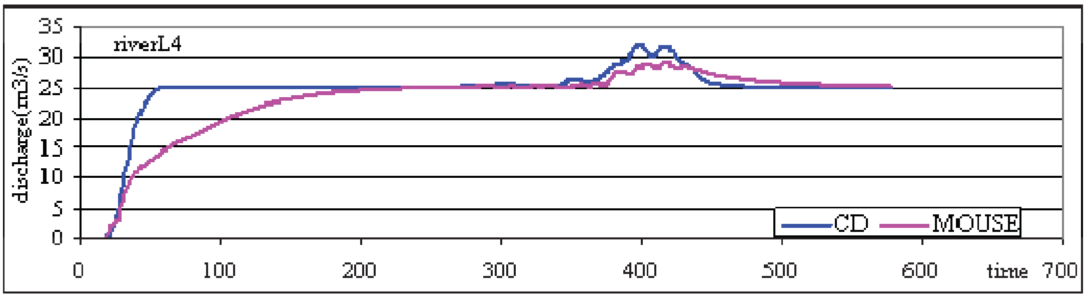

Fig. 5.19: Comparison between discharges of location riverL4

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.

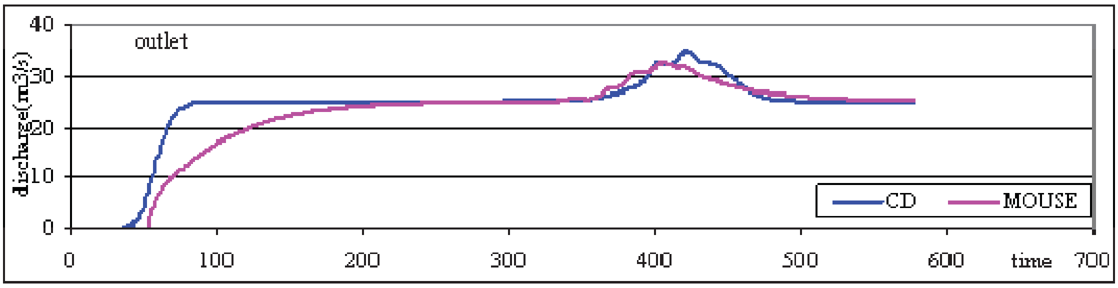

Fig. 5.20: Comparison between discharges of outlet of the river

Assessment of river

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

Table 5.3 RMSE for 6 locations in river and outlet

Location	RMSE	Location	RMSE
river1	0.015	riverL3	1.151
river3	0.448	riverL4	1.906
river6	0.981	outlet	1.973
riverL1	0.019		

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.

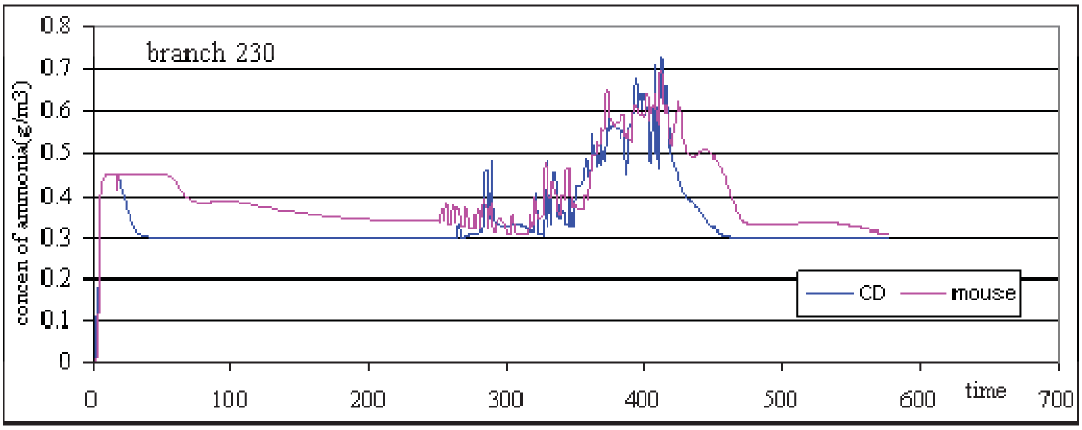

Fig. 5.21: Comparison between concentrations of ammonia in river branch 230

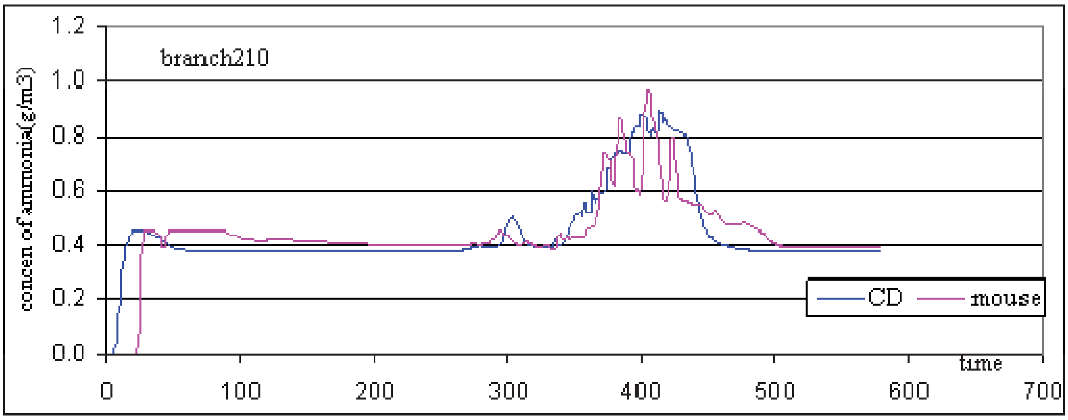

Fig. 5.22: Comparison between concentrations of ammonia in river branch 210

5.4 Verification of Ljubljana CD model

Rainfall event June 5, 1995 to June 7, 1995 was used for verifying calibrated parameters. Figure5.23 to figure5.26 show comparisons between discharge of overflow0, overflow1, overflow8 and effluent. Comparison of the rest overflows are put in appendix 1.

In figure5.23, red line and blue line represent discharge of overflow0 in MOUSE and CD respectively. It is obvious they match each other quite well.

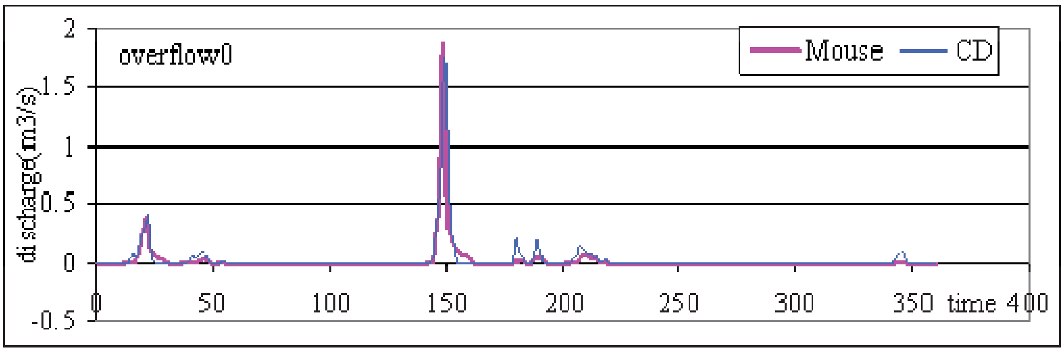

Fig. 5.23: Comparison between discharges of overflow0

Similar to figure5.23, red line in figure5.24 shows discharge of overflow1 in MOUSE, while the blue indicates that in CD. There is perfect match between them.

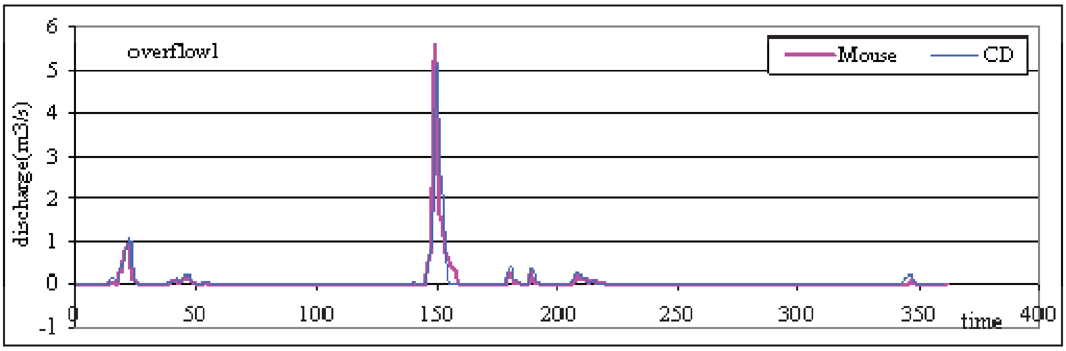

Fig. 5.24: Comparison between discharges of overflow1

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.

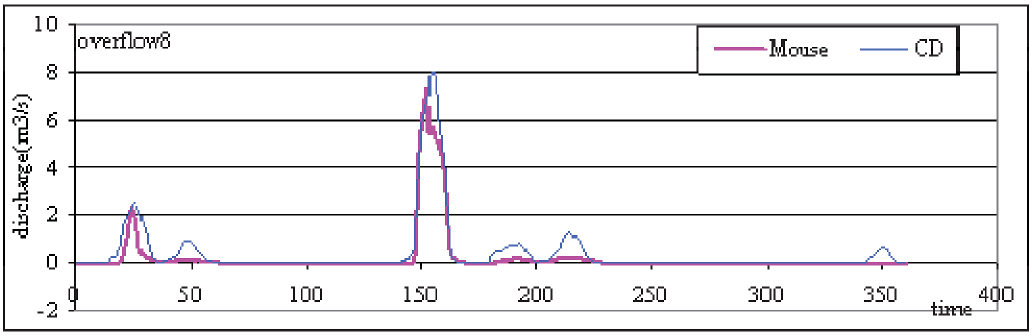

Fig. 5.25: Comparison between discharges of overflow8

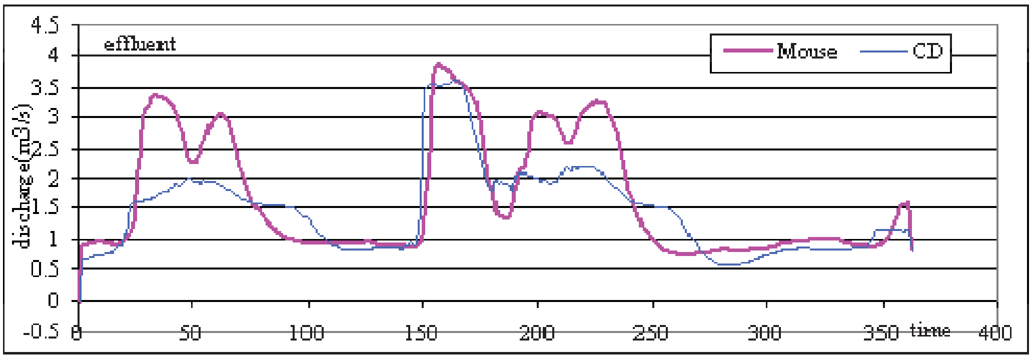

Fig. 5.26: Comparison between discharges of effluent

RMSE is also used as quality indicator (see table 5.4). Similar to calibrated results, overflow8 and effluent give large errors. The reason for that is also because of flooding condition appeared in front of overflow8 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

Location	RMSE	Location	RMSE
overflow0	0.010	overflow7	0.007
overflow1	0.022	overflow8	0.106
overflow2	0.002	overflow9	0.009
overflow3	0.033	overflow10	0.026
overflow4	0.045	overflow11	0.084
overflow5	0.000	effluent	1.281
overflow6	0.014		

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.

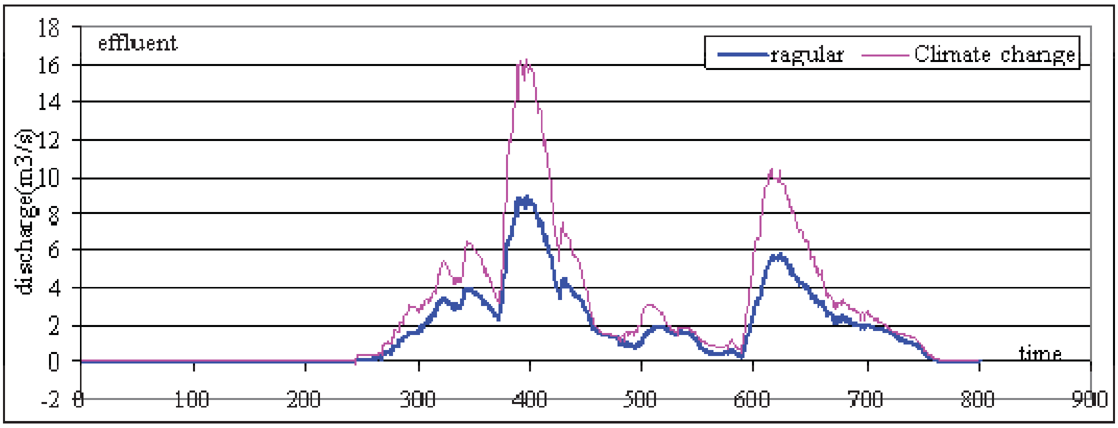

Fig. 5.27: Comparison of WWTP effluent under climate change

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).

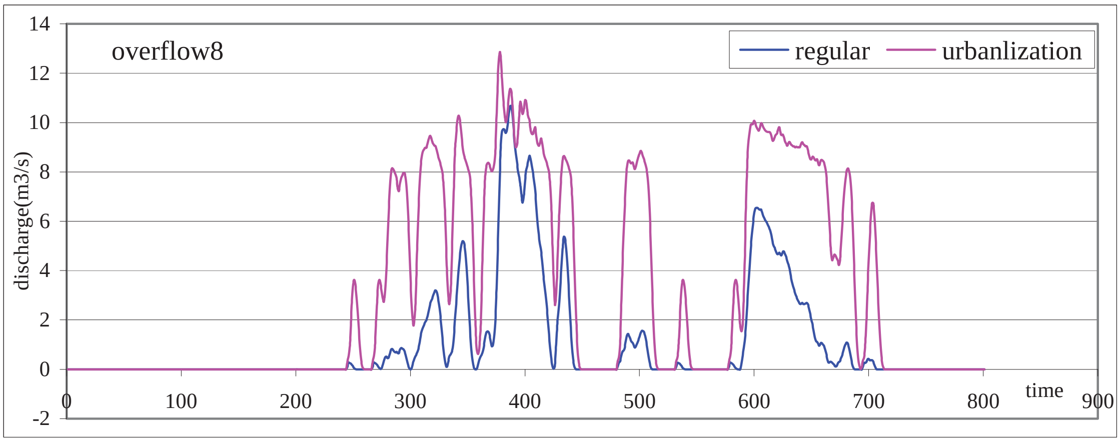

Fig. 5.28: Comparison of overflow8 in terms of urbanization

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 5.5 Change of runoff coefficients due to urbanization

Catchment ID	Runoff coefficient In 1995	Runoff coefficient after urbanization in 2015
Catchment CSS02	0.11	0.8
Catchment CSS03	0.12	0.8
Catchment CSS05	0.2	0.8
Catchment CSS09	0.067	0.8
Catchment CSS10	0.1	0.8
Catchment CSS15	0.1	0.8
Catchment CSS16	0.27	0.8
Catchment CSS18	0.27	0.8
Catchment CSS19	0.18	0.8

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.

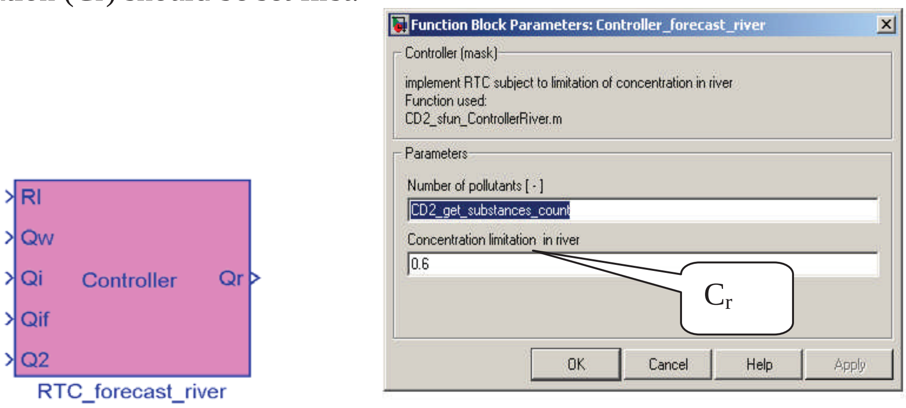

Fig. 6.1: Mask of RTC_forecast_river

Where

R1 – 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_2 – Q_2 from Splitter (refer to Q_2 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.

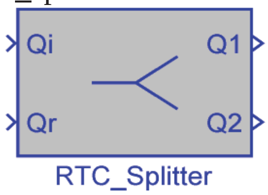

Fig. 6.2: Mask of RTC_splitter block

Where

Q_i – Upstream sewer outflow;
Qr – 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_r).

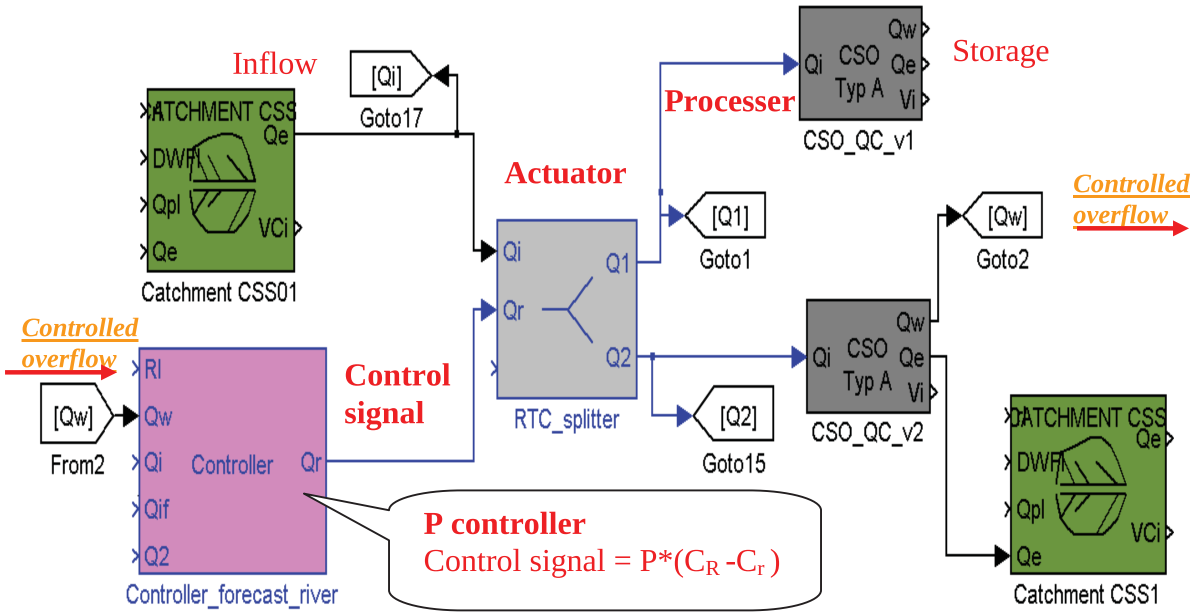

Fig. 6.3: Schematic illustration of RTC—deed backward control with P controller

Where

R1 – Flow of target river location;
Q_W – Controlled overflow to river;
Q_i – Upstream sewer outflow;
Q_{if} – Upstream sewer outflow with forecast rainfall;
Qr – 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_spliter block.

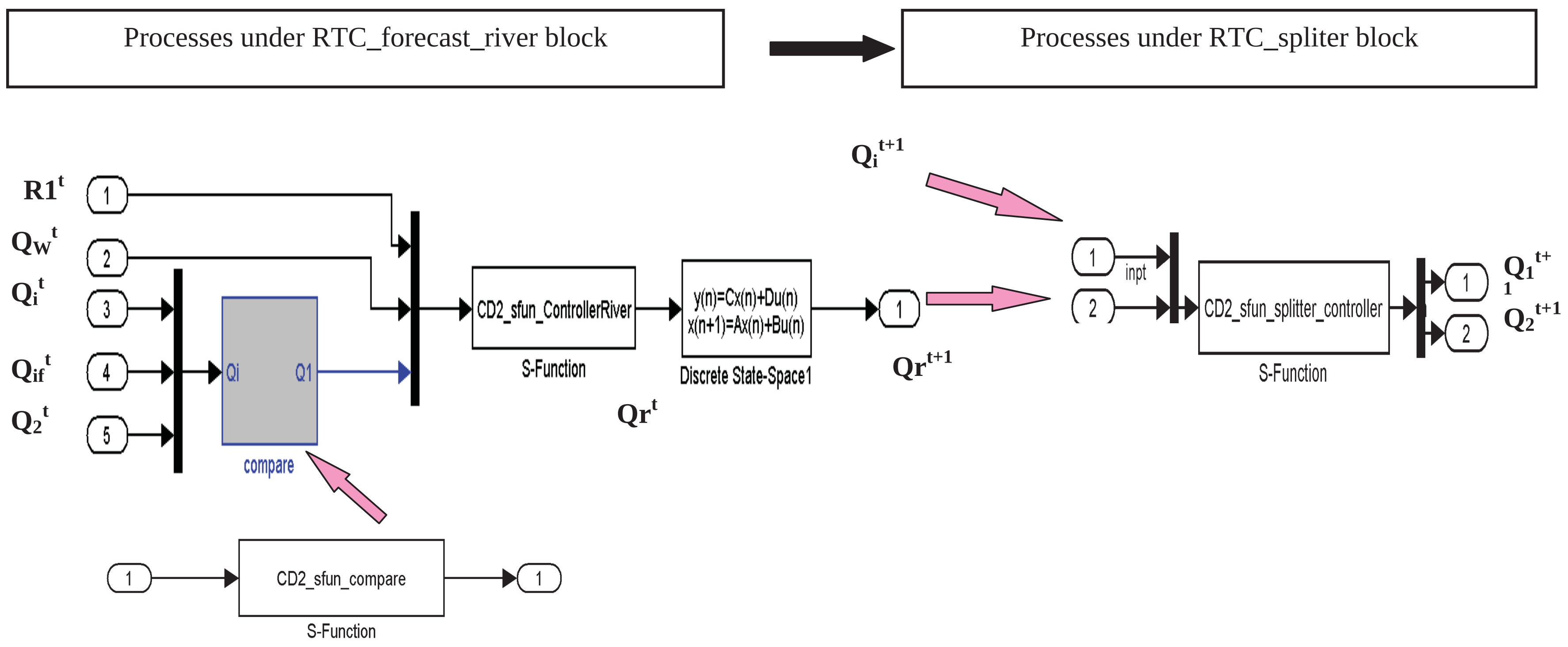

Fig. 6.4: Processes underlying two main RTC blocks

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.

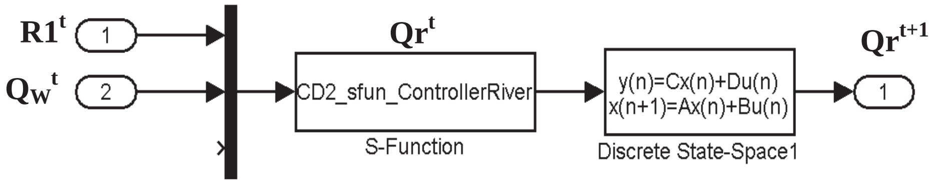

Fig. 6.5: Processes underlying 'controller' without forecast

R1 is a vector including [Q_R C_{R1} C_{R2} …];
$R1_{i-1}$ is a vector including [$Q_{R,i-1}$ $C_{R1,i-1}$ $C_{R2,i-1}$ …];
Q_W is a vector including [q_w C_{w1} C_{w2} …];
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.

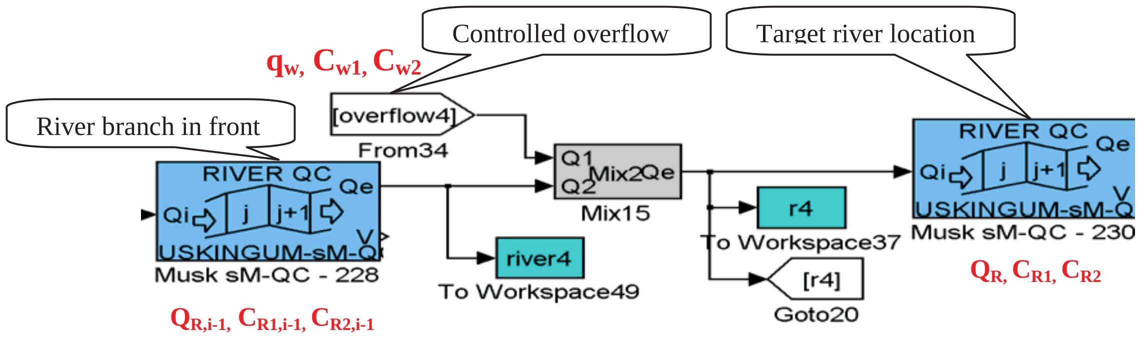

Fig. 6.6: Illustration of target river location

- 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, $C_{R1}{}^t = (q_w{}^t * C_{w1}{}^t + Q_{R,i-1}{}^t * C_{R1,i-1}{}^t) / Q_R{}^t$ (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, $C_{R1}{}^t = (Q_{R,i-1}{}^t * C_{R1,i-1}{}^t) / Q_R{}^t$ (calculated in river system, read directly by controller).

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

$E^t = C_{R1}{}^t - C_r$
If $E^t > 0$ then $Qr^t = (E^t * Q_R{}^t) / C_{w1}{}^t$
If $E^t < 0$ then $Qr^t = 0$

Where

Qr 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 $Q_r{}^t$ one time step further $Q_r{}^{t+1}$ ($Q_r{}^t = Q_r{}^{t+1}$) and goes into RTC_splitter block. Figure 6.7 shows the processes under RTC_splitter.

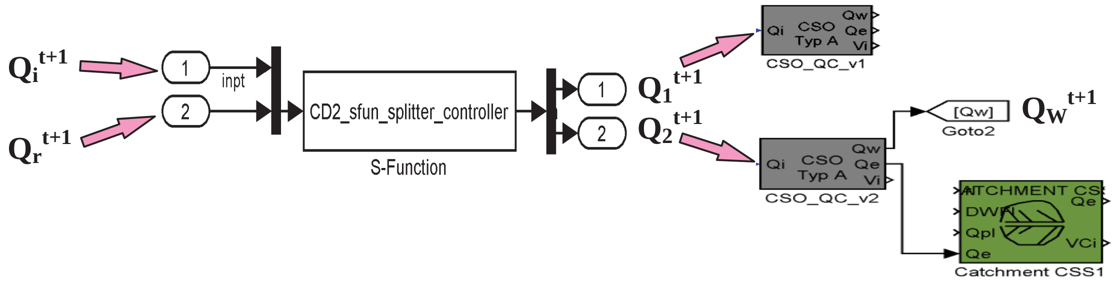

Fig. 6.7: Processes underlying RTC_splitter

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
Qr^{t+1} – flow diverted to a storage

The functions are:

$$Q_1^{t+1} = Qr^{t+1}$$

$$Q_2^{t+1} = Q_i^{t+1} - Q_1^{t+1} \; (Q_2^{t+1} \geq 0)$$

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_i^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).

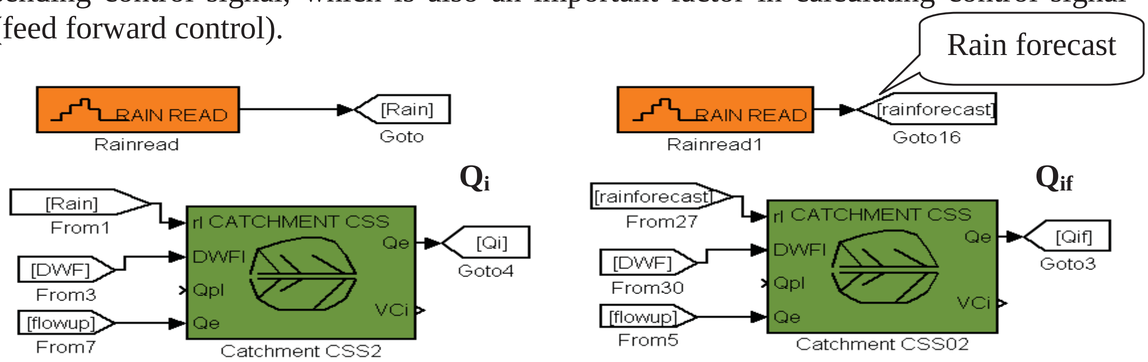

Fig. 6.8: Upstream outflow with forecast rainfall and regular rainfall

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.

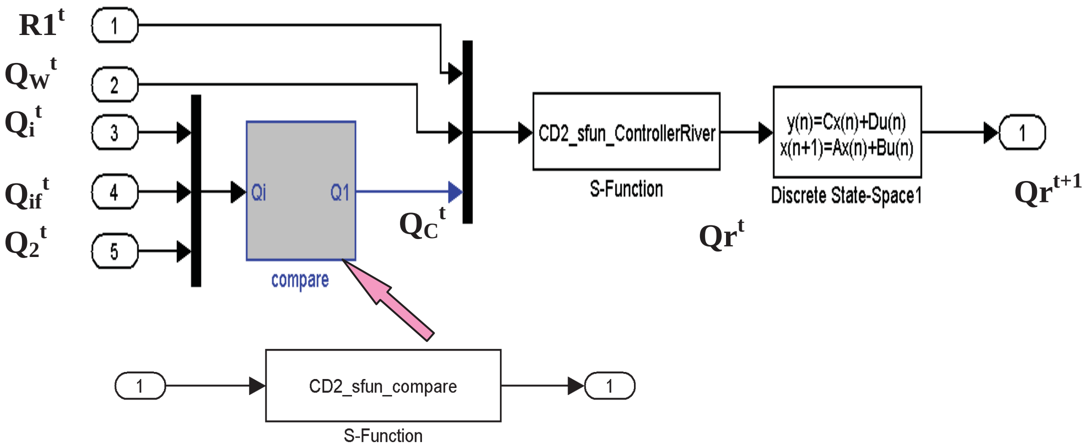

Fig. 6.9: Processes underlying RTC_forecast_ river block

Explanations of each parameter can refer to figure 6.3 and 6.5.
Functions under 'compare block' are:

If $Q_i^t \geq Q_{if}^t \geq Q_2^t$ then $Q_C^t = Q_{if}^t - Q_2^t$;

If $Q_{if}^t \leq Q_2^t$ then $Q_C^t = 0$;

If $Q_{if}^t \geq Q_i^t$ then $Q_C^t = Q_{if}^t - Q_i^t$;

Control signal Q_r is calculated in a different way from the one without forecast

$E^t = C_{R1}^t - C_r$

If $E^t > 0$ then $Qr^t = (E^t * Q_R^t) / C_{w1}^t + Q_C^t$

If $E^t < 0$ then $Qr^t = Q_C^t$

And then Discrete State-Space function is used to make the Q_r^t one time step further Q_r^{t+1} (Q_r^t = Q_r^{t+1}) 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^t and Q_i^{t+1} which caused by rainfall is compensated. However the difference caused by DWF and upstream sewer inflow can not 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.

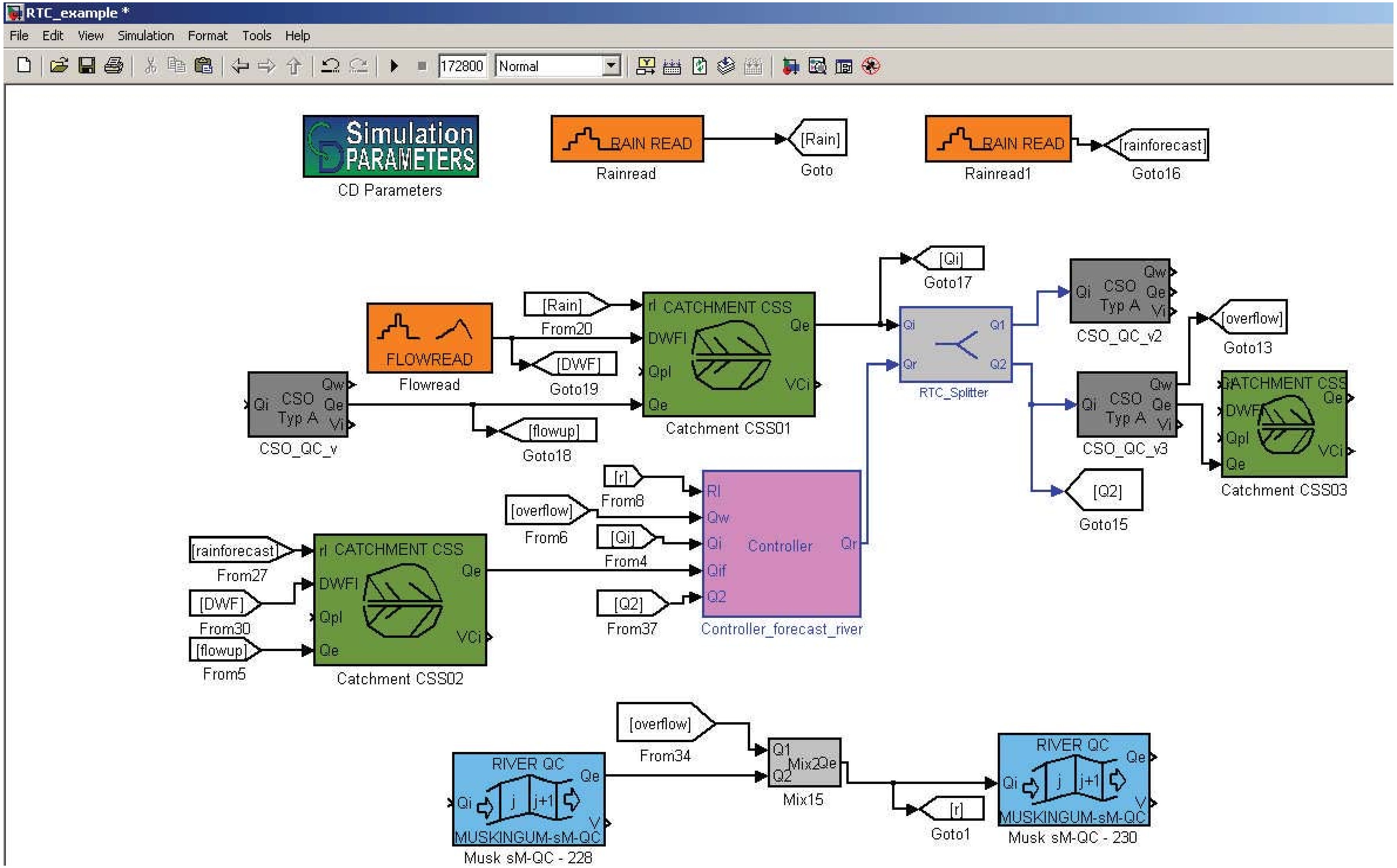

Fig. 6.10: Example interface of RTC

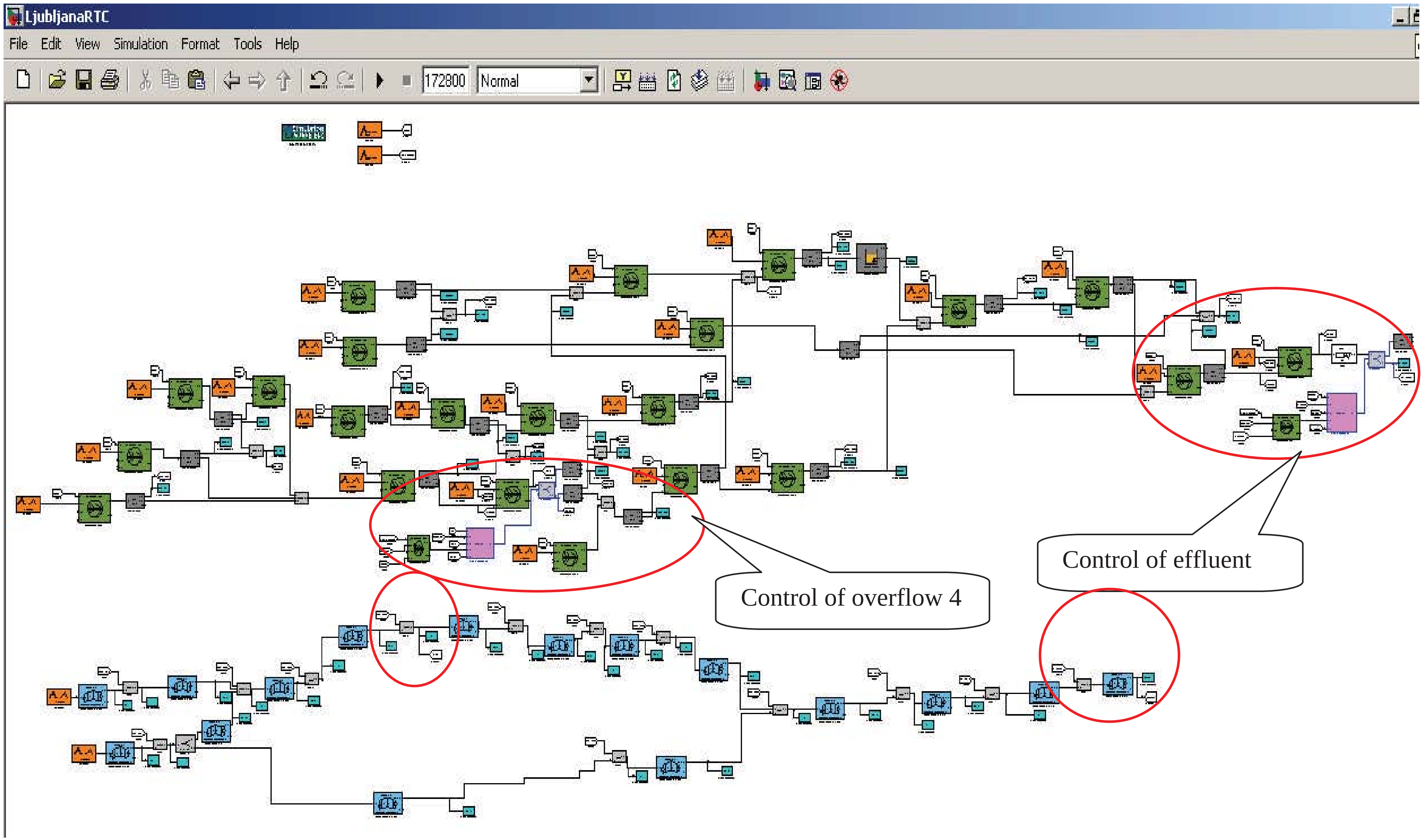

Fig. 6.11: Overview of Ljubljana CD model with RTC application

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 overflow4

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).

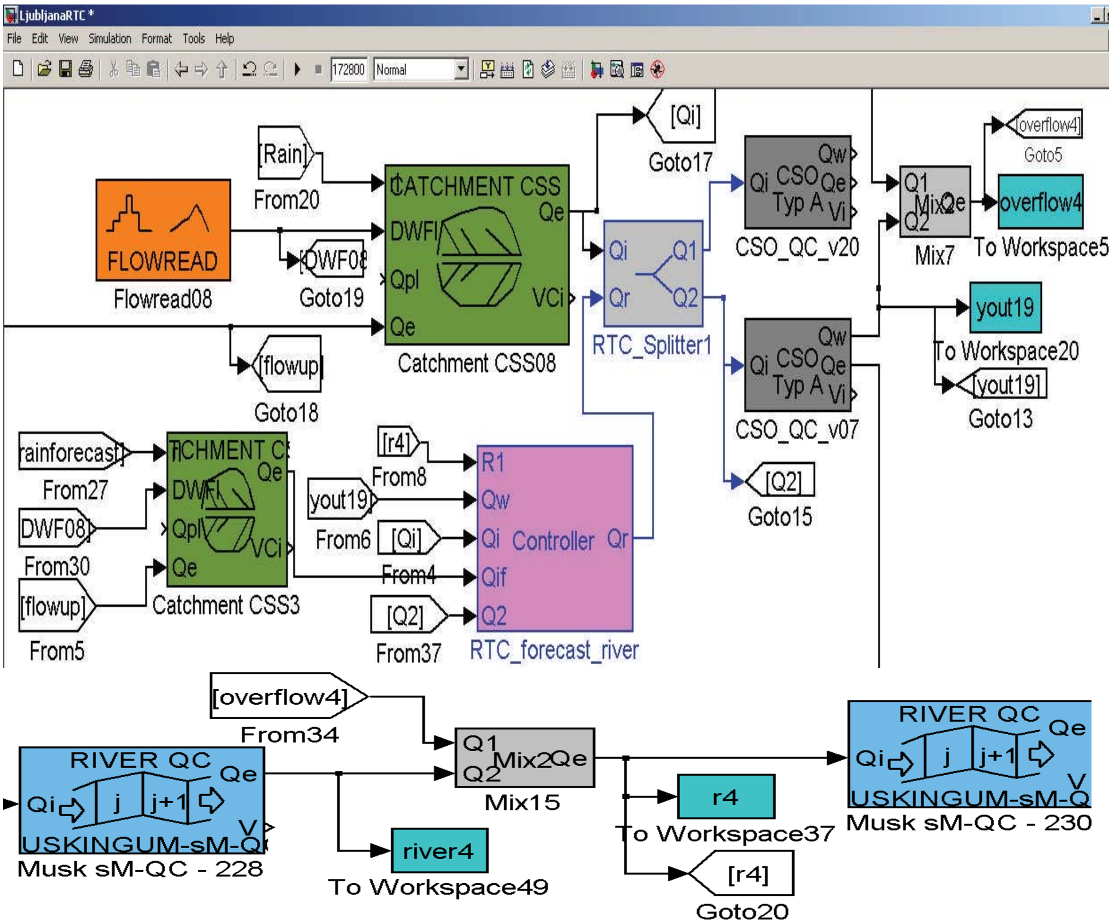

Fig. 6.12: Map of overflow 4 control

Since only discharge of overflow4 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/m^3.

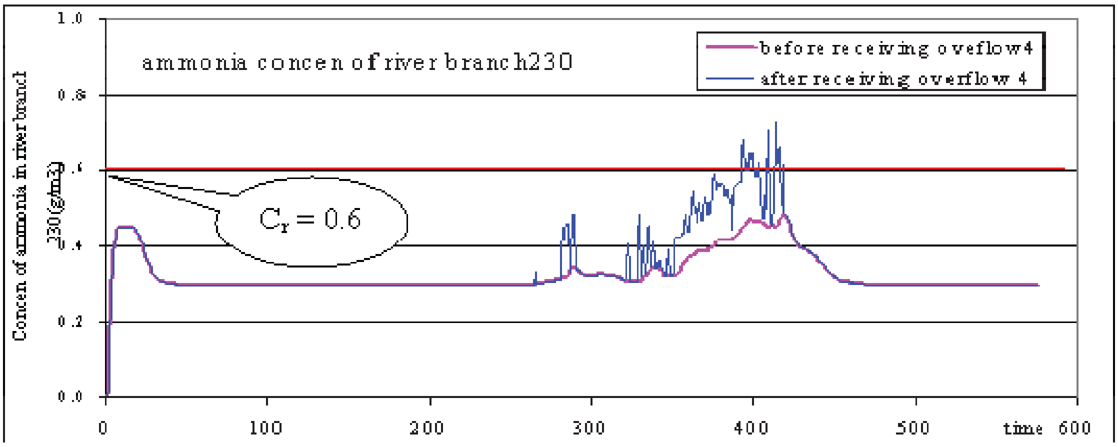

Fig. 6.13: Ammonia concen in river branch 230 before and after receiving overflow4

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 Cr, except for two points. Generally speaking, the control effect is good.

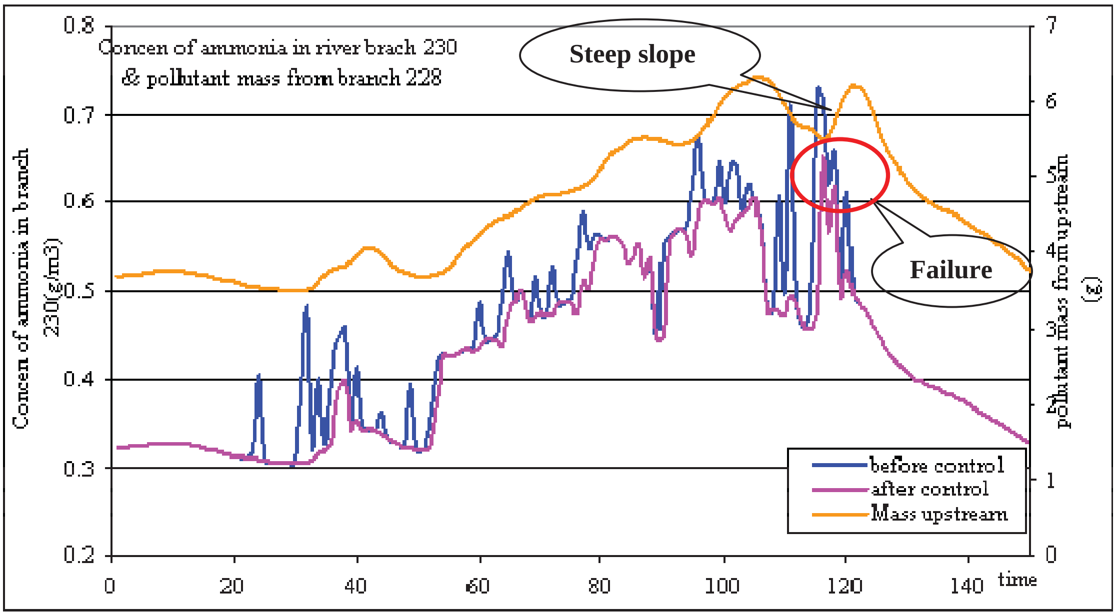

Fig. 6.14: Ammonia concen in branch 230 before/after control & pollutant mass from branch 228

The reason for failure is due to control time lag (discrete computation in CD). Although difference between Q^t_i and Q_i^{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 $M_{R,i\text{-}1}{}^{t}$ to $M_{R,i\text{-}1}{}^{t+1}$ 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.

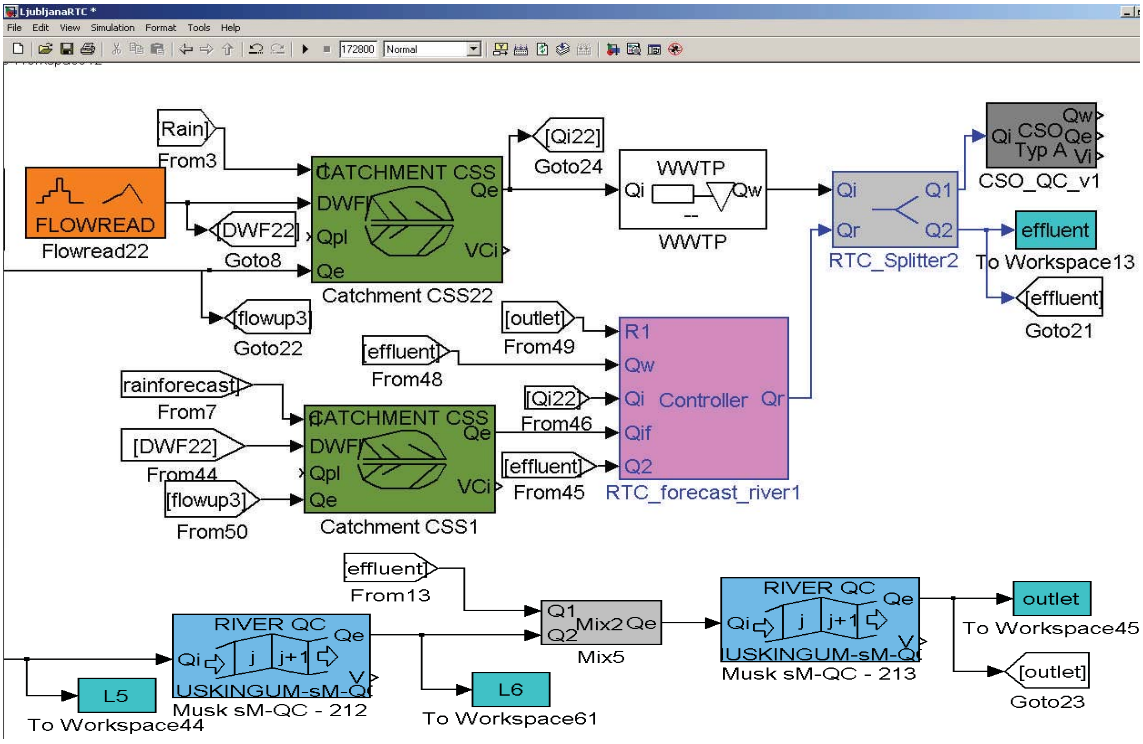

Fig. 6.15: Map of effluent control

Since only discharge of effluent can be influenced by control process, limitation of pollutant concentration of river outflow (Cr) 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 g/m^3 in Ljubljana case.

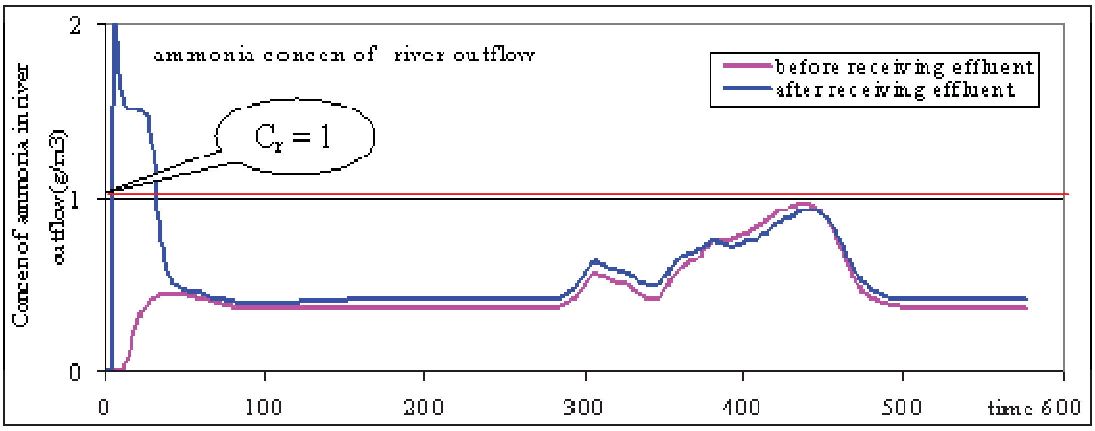

Fig. 6.16: Ammonia concentration of river outflow before and after receiving effluent

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 Cr=1 g/m^3 previously was limited within 1 g/m^3. Thus, the control application succeeded.

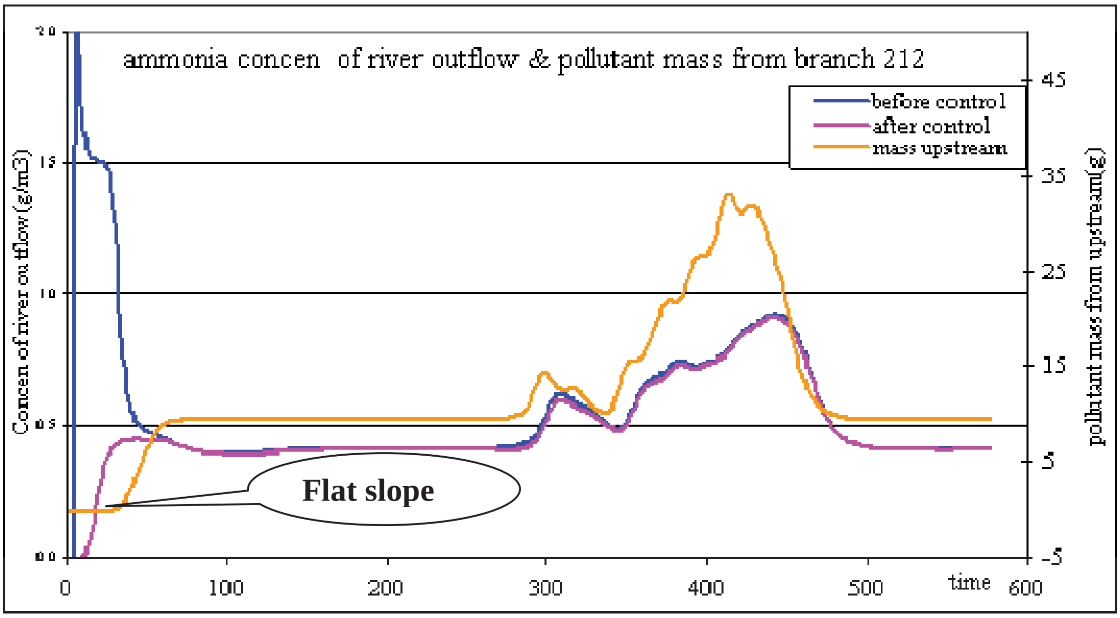

Fig. 6.17: Ammonia conc. of river outflow before/after control & pollutant mass from branch 212

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($M_{R,i-1}^{t+1}$) is much larger than that at time step t ($M_{R,i-1}^{t}$), and meanwhile pollutant concentration of target river at time step t (C_R^t) 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 ($C_R^{t+1}>C_r$) when mass of pollutant coming from upstream river branch in front of target river location at time step t+1($M_{R,i-1}^{t+1}$) is much larger

than that at time step t ($M_{R,i-1}^{t}$), 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.

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APPENDIX 1: Results of Verification

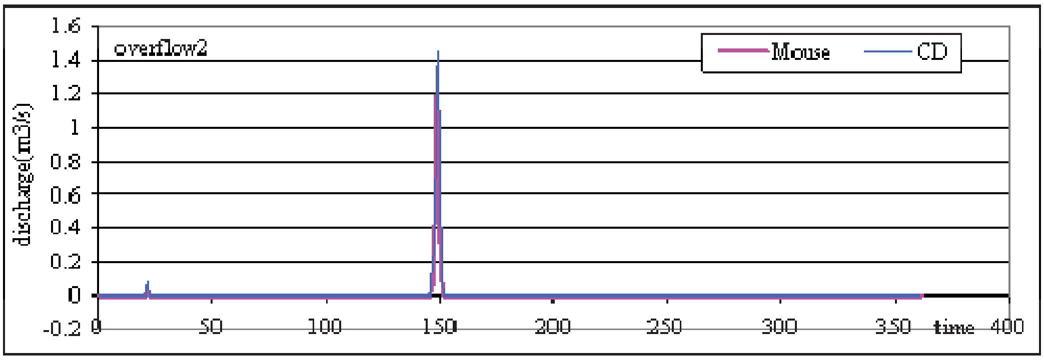

Fig. 1: Comparison between discharges of overflow2

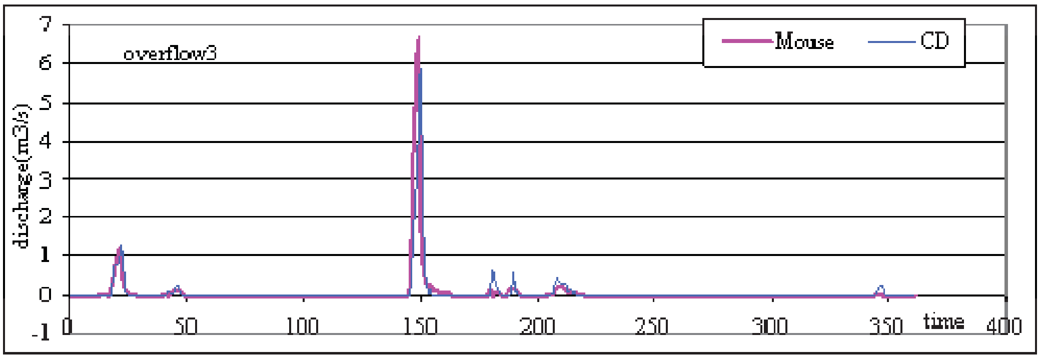

Fig. 2: Comparison between discharges of overflow3

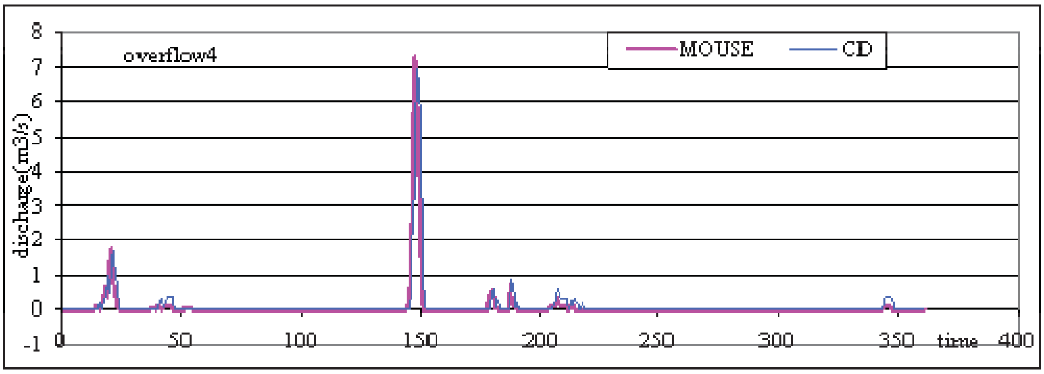

Fig. 3: Comparison between discharges of overflow4

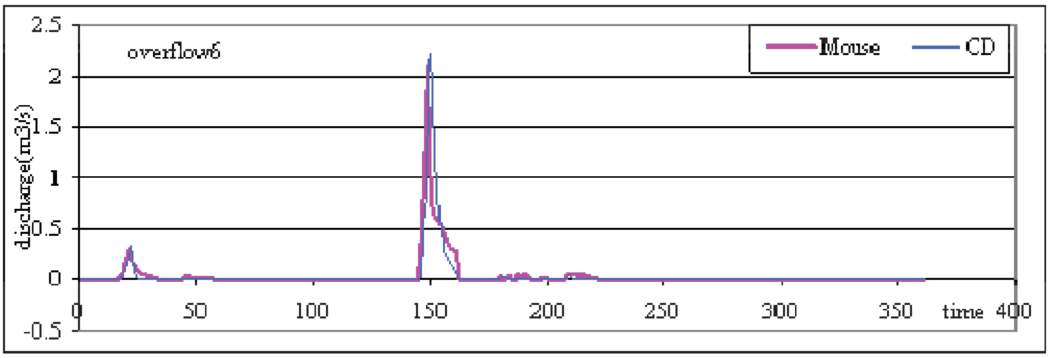

Fig. 4: Comparison between discharges of overflow6

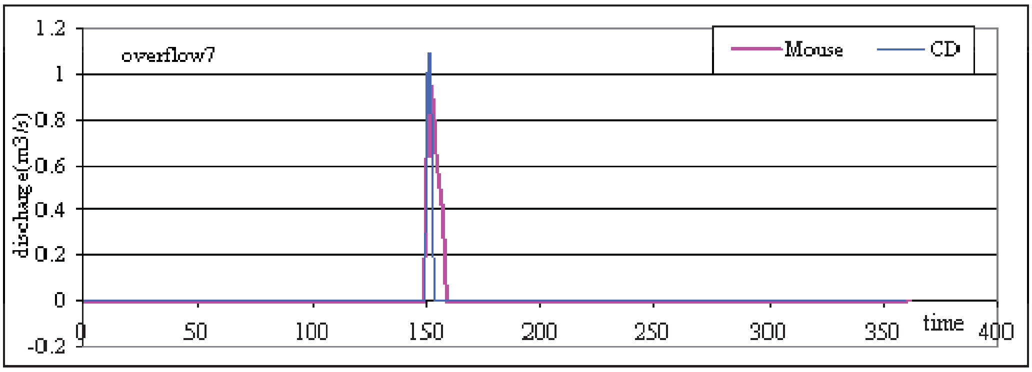

Fig. 5: Comparison between discharges of overflow7

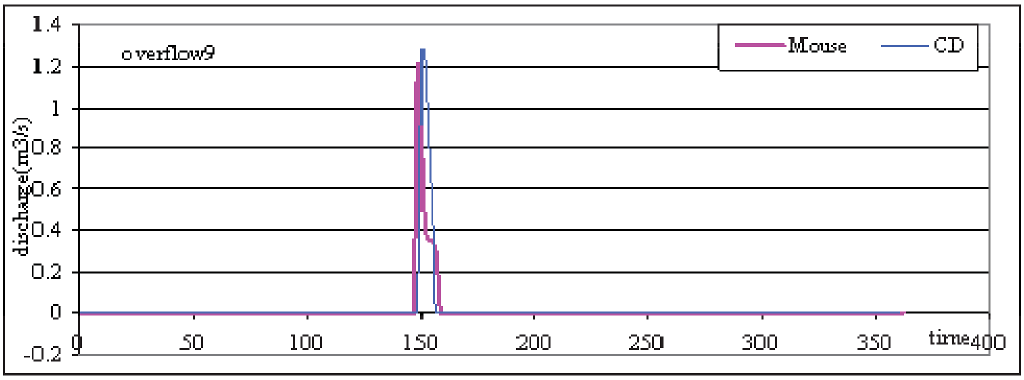

Fig. 6: Comparison between discharges of overflow9

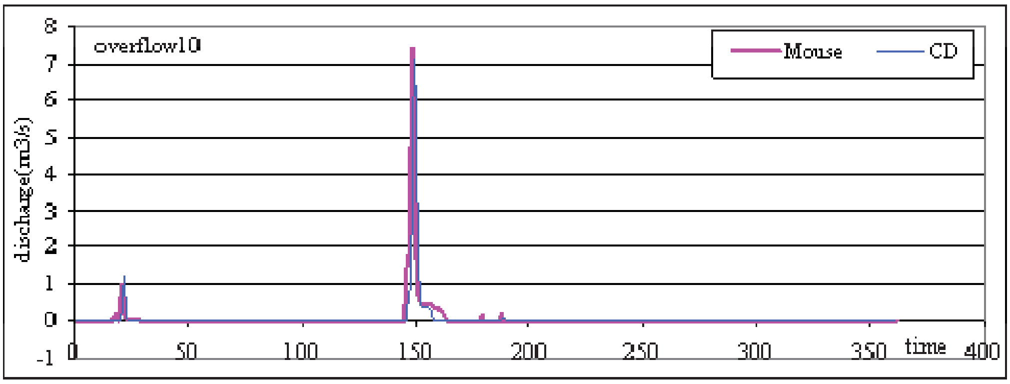

Fig. 7: Comparison between discharges of overflow10

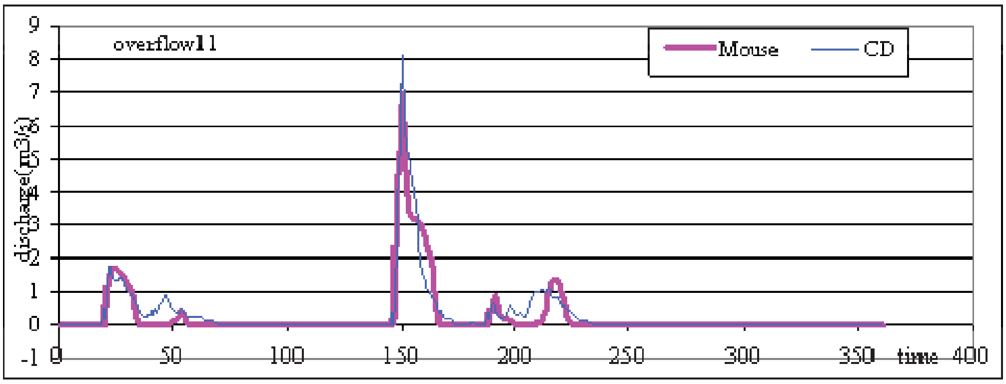

Fig. 8: Comparison between discharges of overflow11

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

```
%=================================================================
========
% File:         CD2_sfun_ControllerRiver
% Author:       Y.Chen UNESCO-IHE
%=================================================================
========
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

%=================================================================
========
% mdlInitializeSizes
% Return the sizes, initial conditions, and sample times for the S-
function.
%=================================================================
========
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];



%=================================================================
========
% 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,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

```
%=====================================================================
========
% File:          sfun_cd2_splitter_controller.m
% Author:        Y.Chen UNESCO-IHE
%=====================================================================
========

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 = [];
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)
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;
```