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Flooding Analysis of Urban Drainage Systems

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FLOODING ANALYSIS OF URBAN DRAINAGE SYSTEMS

By

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ABSTRACT

– Description of the problems

Throughout history floods have been one of the most severe natural catastrophes, which brought about loss of lives and huge economic losses in addition to the influence on community activities and adverse effects on the environment. We have witnessed enormous flood events almost all over the world, even in the early years of 21st century. The cruel lesson learnt is that we have not coped well with floods.

Studying the risk of flooding is the goal of this thesis. The focus is given to flooding of urban drainage systems. Urban climate, human activities and land use vary quickly and greatly with time. These variations modify the features of both urban hydrology and hydraulics, and change the distribution of water. It may lead to dual adverse effects in one region: the severe water shortage in one period and the increasing risk of flooding in another period. Therefore, finding appropriate solutions for these problems has been being a great challenge for the whole world.

- Aims of this study

This study aims to contribute ideal approaches and models to understand deeply urban flooding problems, i.e. to find the causes of flooding, to analyze their propagations and on this basis to evaluate the risk of flooding, and finally to search for solutions for flood mitigation.

- Study contents and methodologies

Distinguishing the potential hazards of urban flooding, delineating the changes of urban lands, developing models to simulate flooding and examining different measures to mitigate the risk of flooding constitute the main contents of this study. It is carried out by both qualitative analysis and quantitative simulations in a stepwise manner.

Regarding the stochastic characteristics of flooding, a risk analysis initiates the study, which aims to formulate flooding scenarios in general urban environment through procedures of system definition, hazard identification, causal analysis, frequency analysis, consequence estimation and mitigation. A Norwegian case study illustrates the whole process.

Following the risk analysis, GIS technology is introduced to delineate the variation of topography. GIS hydrological modeling is applied to delineate the basic hydrological elements from a Digital Elevation Model (DEM). The accuracy of grid DEM and the influence of buildings are studied.

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Two urban flooding models, the "basin" model and the dual drainage model, are developed on the basis of the MOUSE program (DHI, 2000). The three models, i.e. the MOUSE model, the “basin” model and the dual drainage model, are examined through two case studies, and the flow capacities of the existing sewers in these two case studies are then checked. Following the flooding simulation, the effectiveness of four flooding mitigation measures is tested.

- **Main results**

Sixty-eight (68) potential flooding hazards are identified by risk analysis in Chapter three. In combination with Trondheim case study, the frequencies of several flooding scenarios are studied, and it is indicated that the flooding of urban drainage systems happens more frequently than river flooding. When it happens, urban flooding disturbs very much the activities in flooding areas. Therefore management attentions should be paid to urban flooding in addition to large river flooding.

GIS is used as a bridge between digital data and numerical flooding simulation. Two important hydrological elements, watersheds and surface stream networks, are derived from grid DEM in Chapter four. The preliminary flood risk zones are delineated in combination with two case studies. They provide useful information for flood management.

The three flooding models are calibrated through two case studies: Trondheim-Fredlybekken catchment in Norway and Beijing-Baiwanzhuang (BWZ) catchment in China. Flooding checking of the existing sewer systems in these two case studies indicates that the current flow capacities of sewers are less than the designed capacities. Consequently, flood mitigation measures are examined in the following Chapter six. The study indicates that the combination of structural and non-structural flood mitigation measures are regarded as the comprehensive solution for flood control.

- **Restrictions of the developed models**

The developed flood models are restricted to summer and autumn flooding situations. In other words, the snowmelt routine is not included in the hydrological model applied. However, if a hydrological model that is able to simulate snowmelt could be connected to the developed models, then the hydraulic analysis would be carried out similarly.

PREFACE AND ACKNOWLEDGEMENT

The present study was initiated in 1998 when the author visited Norwegian University of Science and Technology (NTNU) under the Cultural Exchange Program between Norway and China. It was carried out in the period of 1999-2003 as a doctoral engineer at Department of Hydraulic and Environmental Engineering, Faculty of Engineering Science and Technology, Norwegian University of Science and Technology (NTNU). The Faculty of Engineering Science and Technology financed the first three years' study and the Department of Hydraulic and Environmental Engineering (IVM) supported for the last year.

First of all, I would like to express my sincere thanks to my supervisor Prof. Dr. Wolfgang Schilling for providing this study opportunity. Thanks for his perceptive insight in the research direction, for his patience while I entered to a new research field and for his interest, encouragement and critical discussions through the study period. In addition, I thank to him helping me while I contact with outside for this study purposes. His working enthusiasm is also a motivation of my study.

During the study period, I was involved in an international research project "Risk Management for Urban Drainage Systems - Simulation and Optimization" (RisUrSim). I benefit from the discussions of the project meetings. In addition, "RisUrSim" supported me attending Mike11 GIS intensive training course and the 29th Congress of International Association and Hydraulic Research (IAHR). Herein, I would like to express my heartfelt thanks to the project leader, Prof. Dr. Sveinung Sægrov, not only for the financial support, but also for his co-supervisor and personal understanding. Ingrid Selseth at SINTEF also kindly helped me in many ways.

The Department of Hydraulic and Environmental Engineering provided friendly and opened work environment. Prof. Ånund Killingtveit contributed his time on the discussions of my study. He also developed my knowledge in hydrological modeling. His patience and attitude on research are of great inspiration in my career. In addition, Associate Prof. Sveinn Thorolfsson also gave me very valuable suggestions. Jon Røstum, Lars Petter Risholt, Yngve Robertsen, Brit Ulfsnes, Ragnhild Sundem, Prof. Hallvard Ødegaard and Prof. Liv Fiksdal and other Ph.D. students at IVM gave me their hands. Dr. Matthew Poulton provided assistant with my English.

As all we know, data collection is a tedious work but indispensable for study and research. I received extensive help from Astrid Sofie Øie and Bard Andresen at the Map Department of Trondheim municipality, from Olav Nilssen and Vidar Kristiansen at the Water and Wastewater Department of Trondheim municipality, from Ingebrit Bævre at middle regional office of NVE. Their kind help made Trondheim case study in Norway possible. In addition, Prof. Dr.

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I am grateful to DHI Water and Environment for providing me with a free license to run DHI software. I also appreciate the technical support from DHI staff: Susanne Kallemose, Fin Hansen and Tomas Eidsmo.

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Finally but not least, this work can be regarded as a reward for the support from my family. The persistence in my study, I believe, originated family education from my parents although they passed away twenty years ago. My thesis is a reward for their donation. It is also a reward to the contribution of my parents-in-law. No doubt, I appreciate the support from my husband Zhiheng Sun and my lovely daughter Xinwei. It is not adequate to say thanks for their contributions and understanding. I hope that my experience is not only enriching to myself but to them also.

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NOTATION

E_i	Flooding event i
$P_{flooding}$	Probability of flooding
$f_{s.b.}$	Frequency of sewer blocking
f_m	Frequency of manhole incidents
q_L	Lateral inflow rate per unit length, [m^3/s-m]
Q	Flow discharge, [m^3/s]
A	Flow area, [m^2]
P	Wetted parameter, [m]
R	Hydraulic radius, [m]
Y	Flow depth, [m]
x	Distance in the flow direction, [m]
g	Acceleration of gravity, [m/s^2]
α	Velocity distribution coefficient
S_0	Bottom slope
S_f	Friction slope
τ_0	Mean boundary shear stress, [N/m^2]
n	Roughness coefficient
ρ	Density of water, [kg/m^3]
a	The speed of sound in water, [m/s]
b_{slot}	The width of fictive slot, [m]
D	The diameter of pipe, [m]
H	Elevation, [m]
A_C	Cross section area of node, [m^2]
A_S	Surface area of basin, [m^2]
K	Outlet shape of manhole
ζ	Head loss coefficient through a node

ABBREVIATION

ALARP	As Low As Reasonably Practical
ATV	Hydraulic Calculation and Verification of Drainage System for Outdoor Buildings (Abwassertechnische Vereinigung), Germany standard
BMP	Best Management Practice
ESRI	The Environmental System Research Institute
CEN	European Committee for Standardization
DEM	Digital Elevation Model
DHI	Danish Institute of Water and Environment
DWF	Dry Weather Flow
EN752	European Standard 752
EN752-4	European Standard 752, part 4.
GIS	Geographical Information System
HEC	Hydrological Engineering Center of American
HES	Health, Environment and Safety
IDNDR	The International Decade for Natural Disaster Reduction
IDF	Intensity-Duration-Frequency curve
RAC	Risk Acceptance Criteria
SWMM	Storm Water Management Model
TIN	Triangular Irregular Networks

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Chapter 1

Introduction

"Earthquake and volcano are among the most dramatic natural hazards. ***But*** *with water-related disasters affect more people and cause more damage than any other disasters. It is time to put the spotlight on the socio-economic impact of floods and drought, and what we can do is to prevent such disasters."*

—The International Decade for Natural Disaster Reduction (IDNDR)
(1990-1999)

1. INTRODUCTION

Chapter one describes flooding-related problems: the global flood damage and the increasing risk of flooding both in river basins and in urban areas. Then, the objectives of flood management are discovered, where emphasis is given to urban flooding control. On these bases, the aims of the present study are promoted and the major study procedures and corresponding objectives are illustrated. The organization of the thesis is introduced in the last part of this chapter.

1.1 Study Background: Flooding Related Problems

Water is the necessity of life. It has decided the economic basis for most of the societies. However, it can also be a threat to those who rely on it when its excessive force invades in habited areas. Therefore, water not only provides for life, but also turns out to be the source of catastrophes. Compared with the other natural disasters, floods are regarded as the most frequent events and cause the most economic losses (Fig.1.1). Few countries in the twentieth century were spared the impacts of floods (Fig.1.2). Frequently, we hear reports of submerged catchments or regions, lives that have been lost, properties flushed away, traffic halted, electricity cut, community activities disrupted, environment deteriorated, health state faced severely treated and people in flood-prone areas suffer psychological stress from current and continuing flood. Moreover, floods may even affect places, which at other times are prone to drought (Hossain**,** Saha and Islam**,** 1987; Blaikie and Cannon et. al, 1994; IDNDR, 1997; Smith and Ward, 1998; MWR, 1999; Parker[1], 2000; Christie and Hanlon, 2001). Some flood events are displayed in Appendix A.

Floods are triggered by many causes. Heavy rainfall, tropical storms, snow or ice melt, dam break, mudslide, insufficient capacity of transportation and storage are all among the major flooding origins. Geographically, there are three main types of flooding. ***Riverine flooding*** happens when extreme rainfall attacks a river basin (Mississippi, 1993; Miller, 1997; Changman, 1998; Li and Guo et al., 1999; NVE, 2000; Meade, 2002). ***Urban flooding*** is triggered when surface runoff exceeds the capacity of drainage systems, which happens when heavy rainfall pours on sewers with the limited capacity, or even medium rainfall falls on poorly planned or operated drainage systems (Kamal and Rabbi, 1998; Arambepola, 2002). ***Coastal flooding*** takes place when heavy rainfall on inland encounters storm surges from the sea (Miller, 1997; Barry, 1997; Smith and Ward, 1998; Parker[1], 2000; Pilarczyk and Nuoi, 2002). Therefore, flood control has to do with different situations. In addition, many floods have been caused by combined causes (Milina, 1999; Rafiqul and Rumi, 2002). Therefore, we should prepare to withstand such floods if the possibility exists.

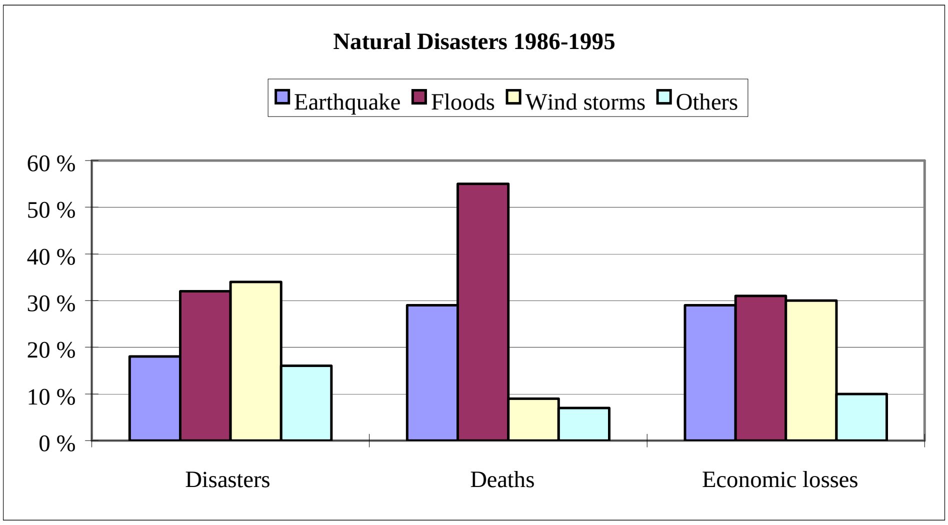

Figure 1.1 Casualties and losses caused by natural hazards in 20th century (Miller, 1997; Wang, Jiang, et.al, 2000; Jiang, Wang and King, 2002)

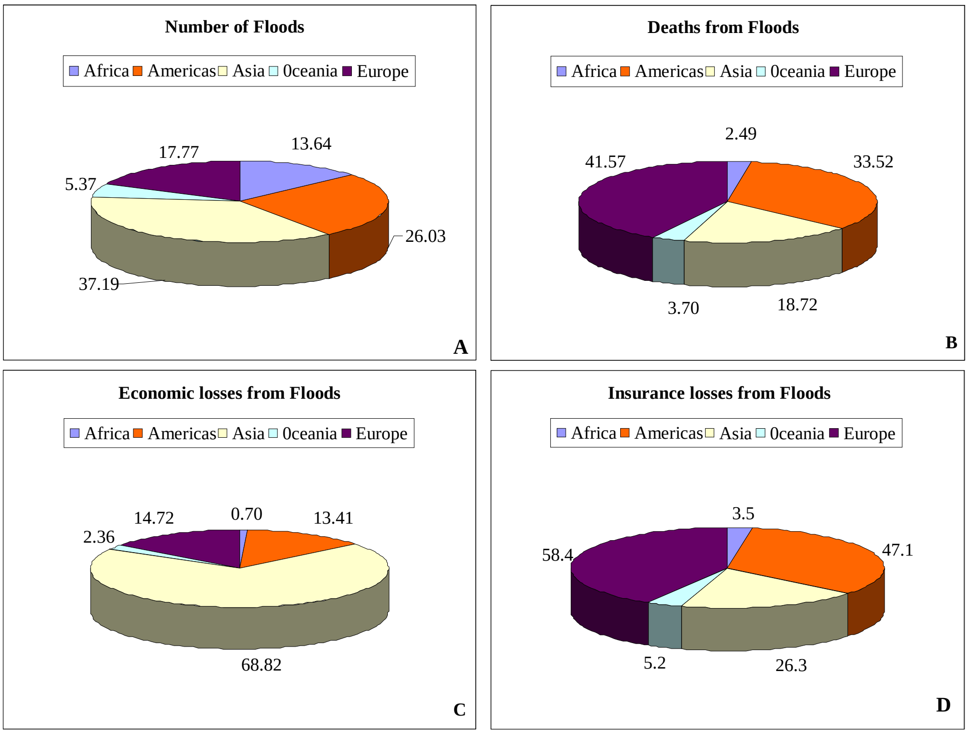

Figure 1.2 Continental distributions of global natural disasters 1950-1999 (Miller, 1997; Smith and Ward, 1998)

Human activities and livelihoods lead to people living alongside of rivers or coastal areas, which are easily prone to flooding. In some cases, the floodplain ways and river storage capacities are occupied by dwellings, cultivated lands and factories, which reduce the capacity of transporting and storing flood water, and consequently increase the frequency of flooding and the number of vulnerable people and the amount of prone assets. As a result, the risk of river flooding is increasing. In the mean time, people are crowding into urban areas, so that the city centers become more densely populated and developed. During urbanization, on one hand, the urban areas are enlarged, which increases the contributing areas to generate runoff. In addition, green lands are replaced by impervious roofs, roads and parking lots, which reduce the capacity of surface to absorb water and decreases the concentration time of surface runoff. Accordingly, both runoff volume and peak discharge in urban catchment are increased (Gardiner, Starosolszky and Yevjevich, 1995; Rosenthal and Hart, 1998; Hu and Guo et. al, 1999; Ahmed, 1999). On the other hand, however, the rehabilitation of rivers, channels and sewers lags far behind the development of municipal constructions. Consequently, the existing drainage capacities are not enough to drain away the runoff discharge and the risk of flooding is accordingly increasing.

In short, rapid development is deteriorating natural ecosystems, reducing their capacity of infiltrating, conveying and retaining water, and consequently increasing the risk of floods. The lessons from floods tell us that economic development, flood defense, conservation of water resources and the environmental protection must be taken into consideration as a whole.

1.2 Objectives of Flood Management

Protection of human beings, material properties, business and social activities from flooding is the aim and major challenge of flood control. Earlier emphasis was placed on floods in rivers, and reliance was on engineering measures to control the volume of floodwater until 60s; then, policies were made combining structural and non-structural measures; in the last decades, the awareness of living with flooding has been perceived. Consequently, flood management is very comprehensive. It addresses a wide spectrum of flood forecasting and warning, flood evacuation, flood protection and mitigation and recovery from floods.

1.2.1 Flood Forecasting and Warning

The accurately and timely forecasting and warning of likable floods is extremely important for flood protection and mitigation. The reliability of forecasting greatly depends on the understanding of hydrological process, the data collection and processing, as well as telecommunication systems. As the use of radar technology, satellite imagery and GIS increase, the accuracy of flood forecasting and warning improves.

1.2.2 Flood Control and Mitigation

Reducing the risk of floods, minimizing the magnitude of floods and alleviating the consequences from floods are the objectives of flood control. In engineering practice, flood defense mainly relied on capital works and control structures in a direct physical attempt to protect vulnerable objects in floodplains and to reduce the greatest damage from floods. In recent decades, the flood abatement approach, i.e. living with flood measure, has been used as an additional solution to flood mitigation. It intends to create natural interdependence among land, environment and water resources. In the global scope, an extensive awareness has been perceived to consider environment, resources and development as a whole (Qian and Zhang, 2001; Maksimovic and Tejada-Guibert, 2001). The emphasis has given to cope with floods instead of merely protecting against them. The third group solution, non-structural measures comprise regulations and polices, organizational and social support, such as emergency flood rescue, disaster aid and flood insurance, which have formed an effective system for flood recovery.

In addition, special attention should be paid to flood control in combination with drought mitigation. This is due to the dual problems of flooding and water shortage in the same area but different seasons. It is the situation in many regions in the world. Therefore, storing the floodwater and then releasing it in dry period for irrigation and other reuses is the supplementary aim of flood control. It has succeeded in many projects (Cheng and Liu et al., 2002; Gu and Zhang et al., 2001)

1.2.3 Urban Flood Management Issues

As described in section 1.1, floods not only happen in river basins, the risk of urban flooding is also increasing due to rapid urbanization. Unlike river floods, urban flooding happens more frequently and causes large amount of accumulated damage, though the damage per event is relatively smaller compared with the severe consequences caused by river flooding (TM, 1990-1999; if, 2000; Gjensidige, 2000). In addition, urban flooding has brutal impacts on municipality's activities when it happens. Therefore, more attention should be paid to it. Urban flood management addresses the following aspects:

- ***Urban flood protection and damage mitigation***: protecting life, reducing tangible damage and intangible adverse consequences and lessening the risk to public health and safety are the main objectives of urban flood control. In addition, urban flood control seeks for solutions to minimize the annoyance, or even the interruption on community activities. The interruption does not only exist during flood period but also after flooding during the clean and repair period. Besides, the impact often extends beyond the flooded areas and affects people and activities elsewhere. Therefore, urban flooding has been a concern of flood topic.

- ***Storm water quality control***: protecting channels and sewers from blockage by branches and other large buoyant materials transported by floodwater, and sewer sediment from heavy substances drained in floodwater is among the aims of urban storm water quality control. In addition, attention should be paid to bacteria, heavy metals and other sewage constituents discharged from polluted sources, particularly when storm water is drained by combined sewers. The sewage must be properly treated before it drains into the receiving water, or is reused. The research on this topic started from earlier 70s (Lindholm, 1974; Yen, 1987; Schilling and Bauwens et al., 1996; Thorolfsson, 1997; Schilling and Milina et al. 1999).

- ***Urban environment and aesthetic issues*****:** As urbanization proceeds, consideration should be given to retaining natural water storage capacities, such as swales, ponds and wetlands, and incorporating them as part of urban drainage systems. Meanwhile, the quality of life in urban areas can be enhanced by conservation, or even restoration of these features for recreational, aesthetical, ecological, and cultural function. In the perspective of urban environmental conservation, the urban flood control can be viewed as more an opportunity than a problem.

Overall, the goals of flood management tell us that we have a long way to go to cope with floods. This thesis focuses only on the risk of urban flooding, i.e. the quantity control of the stormwater.

1.3 Study Objectives and Procedures

This study aims to provide approaches and models to understand comprehensively the problems of urban flooding. The study procedures and objectives are demonstrated in Fig. 1.3.

The study proceeds in two main steps: extensive analysis and intensive simulation. The former one is carried out by a risk-based approach. Where, the focal objectives are to identify flood hazards, to estimate frequency and consequences of flooding and to evaluate the flood risk. Then, an intensive study follows to develop urban flooding simulation models and procedures. The developed models are examined through two case studies, and on these bases, the capacities of existing sewer systems in two case studies are examined, and the solutions for flooding mitigation are tested.

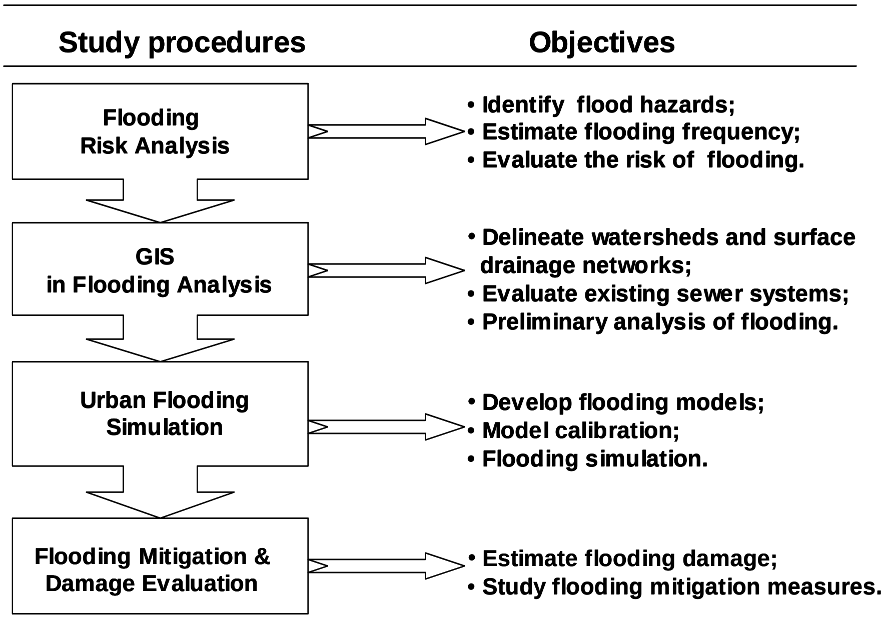

Figure 1.3 Study paradigm

Case studies from Norway and China are carried out through the established methods, models and measures.

1.4 Organization of the Thesis

The introductory chapter of this thesis addresses flooding relevant problems, where the growing risk of flooding is highlighted. Then the objectives of flood management are discussed, and emphasis is given to urban flooding control. On this basis, the study objectives are promoted and procedures are illustrated.

The second chapter is a literature review. It begins with the basic concepts: flood definitions and types. Then, the state-of-the-art of urban drainage systems is introduced and the design standards from several countries and regions are presented. After that, an overview of risk management programs and research development follows. Then, urban flood model development together with the use of GIS is reviewed. The problems of today's models and the needs for further development close the topics of Chapter two.

Chapter three is describing the risk-based study, where the risk of urban flooding and the urban flooding system are defined. The causes of flooding are identified and the probable flooding scenarios are analyzed. The formula to calculate flooding frequency and potential consequences are introduced, and flood mitigation measures are discussed according to risk acceptance criteria. Finally, a case study of Trondheim, Norway, illustrated the process.

GIS technology is able to process, analyze, store data and data management. It is also an ideal intermediate tool of flooding analysis. Chapter four introduces the basic GIS concepts and major models used in flooding analysis. In addition, GIS is used to produce the basic hydrological elements for the flooding model development and flooding simulation in Chapter five.

Three flooding models are introduced in Chapter five: the MOUSE model and its fictive surface flooding tank, and two other models, the “basin” model and the dual drainage model, developed on the basis of the MOUSE program. All these three models are examined through two case studies. On the basis of flooding simulation, flooding mitigation measures are tested in Chapter six where, in addition to flood mitigation, flood damage evaluation is also addressed.

Main results and conclusions are summarized in the last part of this thesis, Chapter seven. In addition, suggestions for future research are also put forward.

Other relevant information and results are bound into the appendices of the thesis.

Chapter 2

Literature Review

"Through wisdom is a house built, and by understanding it is established."

— King James (1995)

2. LITERATURE REVIEW

Chapter two introduces the basic concepts of flooding, explains the mechanism and characteristics of urban flooding and describes the state-of-the-art of urban drainage systems. The research progress of urban flooding model development is overviewed, and the role of GIS in urban flooding analysis is highlighted. As a result, the needs for further development of urban flooding analysis and flooding model improvement are figured out.

2.1 Concepts of Flooding

Flooding is one of the most severe natural disasters. It is extremely important to know when it happens, how it propagates and how large the magnitude will be. They are all factors valuable to know for flood control and protection, for making development plan and for environmental issues.

2.1.1 Definition of Flooding

Flooding has been defined in a number of ways as follows:

- A flood is relatively high flow, which overtaxes the natural channel provided for runoff (Chow, 1956).

- A flood is a body of water, which rises to overflow land that is not normally submerged (Ward, 1978).

- Flooding is defined as temporary inundation of all or part of the floodplain or temporary localized inundation occurring when surface water runoff moves via surface flow, gutters and sewers (Walesh, 1989).

- Extremely high flows or levels of rivers, whereby water inundates floodplains or terrains outside of the water-confined major river channels. Floods also occur when water levels of lakes, ponds, reservoirs, aquifers and estuaries exceed some critical values and inundate the adjacent land, or when the sea surges on coastal lands much above the average sea level (Rossi, Harmancioglu and Yevyevich, 1992).

- Flooding is defined as a condition, where wastewater and (or) surface water escapes from or cannot enter into a drain or sewer system and either remains on the surface or enter into buildings (NS-EN 752-1, 1996).

Chow (1956) defines the floods in relation to rivers. Ward (1978) specifies floods to inland. Later, Walesh (1989) attempts to embrace floods both in floodplains and on urban surfaces. Rossi, Harmancioglu and Yevyevich (1992) provide more comprehensive definition for floods from rivers, detention and retention storage as well as storm surges. Recently, NS-EN 752 (1997) defines the floods scenarios on urban surfaces.

2.1.2 Types of Flooding and Their Characteristics

According to the above definitions, floods are classified in terms of induced causes in combination with geographical locations (Table 2.1).

Table 2.1 Types of flooding (Parker[1], 2000).

Agent	Details and examples
Rainfall	Riverine or inland Slow on-set or flash flood
Snowmelt	Overland flood Riverine flood
Icemelt	Flood caused by glacial melt water
Flooding during freeze-up	Riverine
Flooding by ice breakup	Riverine (also called ice-jam floods)
Mudfloods	Floods with high sediment content
Storm surge	Coastal/sea/tidal floods
Dam	Dam-break flood Dam overtopping
Urban drainage flooding	Storm discharge exceeds capacity of sewers or drains
Water mains	Flood caused by pipe burst
Raising water tables (high Groundwater levels)	Land subsidence, rising sea level, temporal reduction in water abstractions from aquifers
Combined events	Rainfall/tidal flooding/snow melt/ice melt…

Apparently, flooding often occurs in river floodplains, coastal areas or inland surface. Therefore, flood control has to do with locations regarding to the induced causes.

The magnitude of flooding in large river basins is generally larger than flooding in local urban areas and the consequences of river flooding are severe. Historically, emphasis was given to extreme floods in natural watercourses. Hydrological and hydraulic models have been developed and structural and non-structural been evaluated in order to formulate mitigation strategies and take effective protective action. This focus has undoubtedly increased awareness of government and publicans and played a significant role in formulating rational floodplain management schemes.

With the development in urban areas and the expansion of urbanization, the frequency of urban flooding increases and so do the consequences. The considerable adverse impacts of flooding on private dwelling and properties, on municipality facilities and activities have been concerned by governments, city planners, researchers, engineers and the publicans. National standards, engineering measures and research towards urban flood control have been made great progresses in recent years. The literature review focuses on the design standards of urban drainage, storm sewers and the development of urban flood models.

2.2 Definition of Urban Drainage Systems

Urban drainage systems are defined as "physical facilities that collect, store, convey, and treat runoff in urban areas. These facilities normally include detention and retention facilities, streets, storm sewers, inlets, open channels, and special structures such as inlets, manholes, and energy dissipaters" (ASCE and WEF, 1992).

Urban drainage systems are needed in developed urban areas because of the interaction between human activity and the natural water circulation. This interaction has two main forms: the abstraction of wastewater from the systematic cycle after providing for the needs of human life, institutions' activities, and the consumption of industrial and commercial products; and secondly, diverting rainwater from the covering lands of impermeable surface away from local natural areas or systems.

Although cities are in contact with water from various origins such as ground water, streams flowing through or near the city as well as the sea being receiving water, the major concern of urban drainage systems is water originating in the city itself, i.e. water from local rainfall and its interaction with the water originating from other water bodies (Maksimovic and Prodanovic, 2001).

The urban drainage systems can be completely artificial, or combination of man made sewer facilities and natural watercourses.

2.3 The State-of-the-Art of Urban Drainage Systems

Urban drainage systems can be thought of consisting of two main parts (Walesh, 1989): the convenience-oriented, or the minor system, which contains the components that accommodate frequent, small runoff events; and, the emergency, or major system, which comprises the components that control infrequent but large runoff volume. Although many of the components are common to both of convenience and emergency systems, their relative importance in the two systems varies significantly.

2.3.1 Components of Urban Drainage Systems

2.3.1.1 The Convenience-oriented (Minor) Systems

The convenience (minor) system is generally called the sewer system, and can be represented conceptually as a network consisting of catchments and subcatchments, nodes, links, ancillary structures and outlet. The system receives inflow from nodes, i.e. manholes or inlets, and then transports the sewage to wastewater treatment plant (WWTP), or drains directly to receiving water (Fig. 2.1).

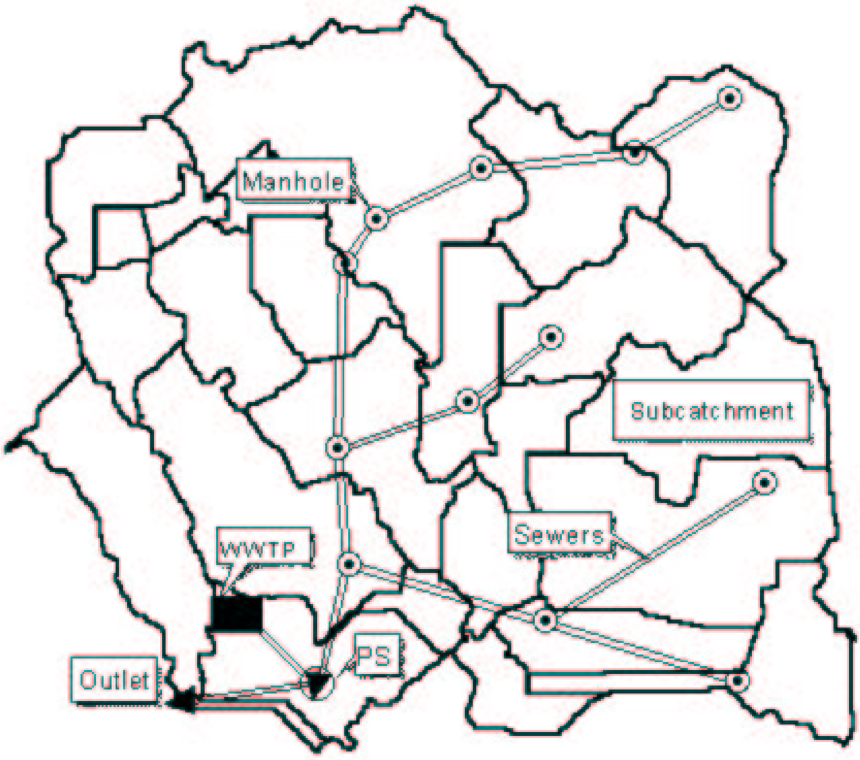

Figure 2.1 Representation of sewer systems

A summary of system components and their functions of urban stormwater drainage are given in Appendix B. The major components of sewer systems are explained as follows.

Catchment and subcatchment A catchment is the area collecting water from nearby higher terrain surface, which is delineated by topographic contour lines. In order to collect surface runoff efficiently and to reduce the waterlogging, i.e. ponding of water, in local areas, a catchment can be further divided into several subcatchments according to the variation of topography. A catchment or subcatchment is usually described by its parameters: catchment area, the percentage of impervious area, average slope, the longest flow length and approximate shape.

Nodes are junctions to link the sewers. They also provide storm water transition between surface and subsurface systems. Typical examples of nodes are manholes or storm water inlets.

Links transport flow in the system, and are often open channels or closed sewers with regular or irregular cross sections.

Ancillary structures Ancillary structures include weirs, gates and pump stations. They are designed to relieve the load of sewer systems. Weirs overflow extra sewage to outside of the system, or to receiving waters, or inside of the system to higher capacity conduits. Gates are used to regulate the flow during transportation. Pumps lift the sewage from lower sewers to higher ones, or pump sewage from sewer systems to wastewater treatment plants.

Outlet The most downstream component of the urban drainage system, which discharges the sewage from the system to receiving waters, or in an opposite way, it may bring back water into the sewers while the water level in receiving water is higher than the level of outlet, so-called backwater effects.

The sewer systems are designed either as separate systems, where the sewage and stormwater are conveyed separately, or combined systems, in which all the sewage is transported within one pipe. Typically, combined sewers are older and can be founded in the city centers.

In addition, combined sewer overflow (CSO) are diversions of a blend of sanitary and storm sewage into receiving waters that often adversely affect the water quality in receiving water, which should be avoided as far as possible.

2.3.1.2 The Emergency (Major) Systems

In addition to the sewer system, other system components composed of road networks, detention or retention facilities will take into action when the minor system components are full of their capacities.

As described in Appendix B, roadways with ditches or gutters and curbs not only transport, but also provide temporary storage for surface stormwater (Fig. 2.2). In addition, natural ponds, parking lots, flat roofs and other impervious open surfaces can also service as temporary storage of the excess water. Moreover, man made detention and retention facilities can put into use whenever they are needed.

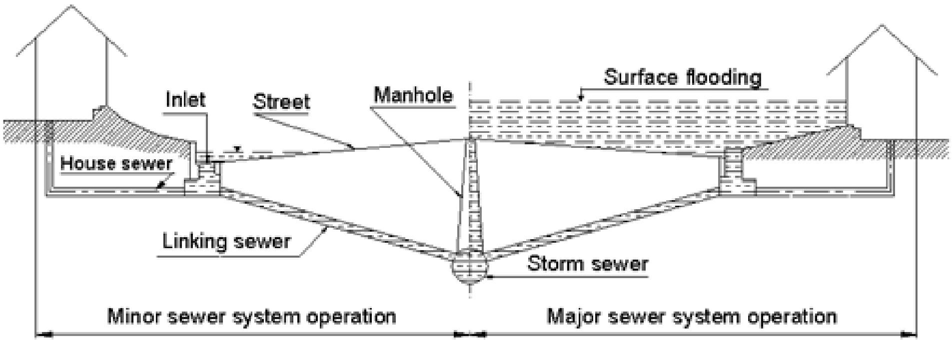

Figure 2.2 Minor and major urban drainage systems (Walesh, 1989)

2.3.2 Design and Practice of Urban Drainage Systems

Due to the difference in climate, topography, land use, the progress of urbanization and financial situations, the status of sewers vary greatly from country to country. An overview of sewer design standards available from several countries and regions is presented in this section and the consequent discussion follows.

The terminology applied in the sewer design will be introduced at first.

2.3.2.1 Terminology in Sewer Design

Design frequency or return period Concerning the stochastic characteristics of rainfall, the frequency (f) of occurrence should be included in the design criteria. Ideally in practice, the frequency or return period (T , $f = 1/T$) is selected for sewer design on the basis of cost-effectiveness analysis. However, in establishing tolerable flooding frequencies and the acceptable risk, people’s safety must be given the first priority (Schmitt, 2001)!

IDF-curve A convenient form to summarize rainfall information in a certain catchment is given by the intensity-duration-frequency (IDF) relationship. A sample of IDF is displayed in Fig. 2.3. It indicates that at given frequency, rainfall intensity and duration are inversely related, i.e. heavy rainfall comes in short period; and so do the relationship between intensity and frequency, a rare rainfall event tends to have a higher intensity, given the same duration.

Design storms Design storms are hypothetical processes of rainfall intensity derived from the statistics of investigated historical heavy rainfall events, and long period of observed rainfall time series. A simple design storm is the constant block rainfall, which is widely applied in many national standards, for

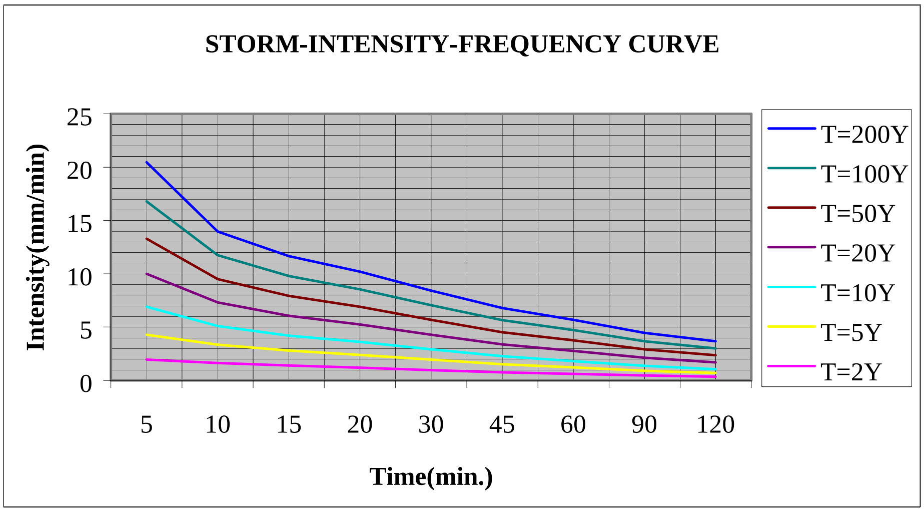

Figure 2.3 The Intensity-Duration-Frequency (IDF) Curve for Beijing, China (HGSB, 1991)

example, the Austrian and the Dutch standard. In addition, the synthetic design storms defined by frequency, duration, time interval and rainfall depth, so called typical storm distribution, can be derived through analysis of historical rainfall.

Sewer surcharge is defined as a "condition", in which wastewater and/or storm water is held under pressure within a gravity drain or sewer system, but does not escape to the surface to cause flooding (NS-EN 752-1, 1996). It is displayed in Fig. 2.4.

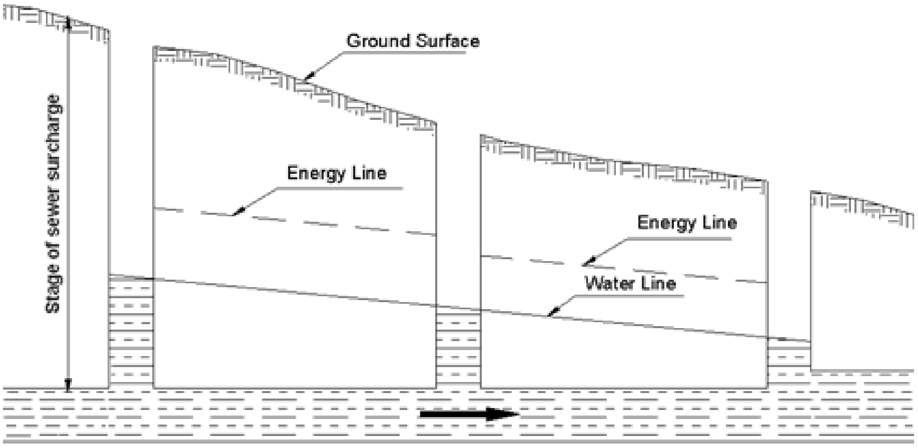

Figure 2.4 Representation of sewer surcharge

Flooding In NS-EN 752-1 (1996), flooding is defined as a condition, where wastewater and/or surface water escapes from or cannot enter into a drain or sewer system and either remains on the surface or enter into buildings (Fig. 2.5).

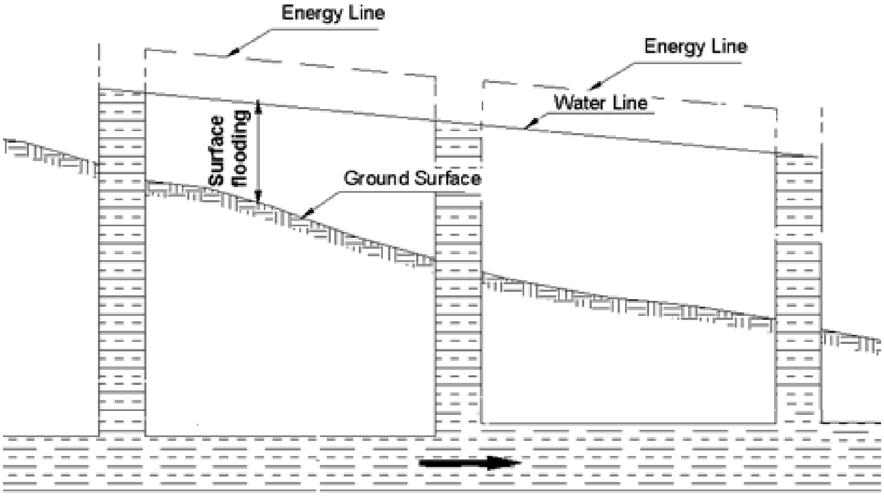

Figure 2.5 Representation of sewer surface flooding

2.3.2.2 Sewer Design Standards

In order to know the state-of-the-art of current sewer systems, the design standards and engineering practice available from different regions and countries are summarized in Appendix C. Their brief descriptions are given below:

- **EN752**

The European Committee for Standardization (CEN) mandated standard for Drain and sewer systems outside buildings, which consists of seven parts listed in table 2.3.

European standards shall be given the status of national standards in bound European countries since it mandated. Both “design storm frequency” and “design flooding frequency” are applied in NS-EN 752-4 (1997) for sewer design and flood checking.

Before mandating EN752, the standards of sewer design varied so greatly from country to country that the status of sewer systems was rather complicated in practice. Efforts have been made in individual countries to follow the new EN standard since its mandating. However, the engineering practice indicates that it is difficult to apply a uniformed standard to different places due to difference in climate, topographical conditions and economic consideration.

Table 2.2 Contents of EN752 (NS-EN 752-1, 1996)

Section	**Title**
Part 1	Generalization and definitions
Part 2	Performance requirements
Part 3	Planning
Part 4	Hydraulic design and environmental considerations
Part 5	Rehabilitation
Part 6	Pumping installations
Part 7	Maintenance and operations

In the following section, standards and engineering practice of several countries both inside and outside Europe are discussed.

- **Germany Standard**

ATV-A118, the national regulation for hydraulic design of urban drainage systems in Germany, was first produced in 1956 and revised in 1977(ATV-A118, 1977).

Unlike EN752, ATV-A118 considers flooding frequencies to be an inappropriate criterion for direct computational assessment due to two main reasons: firstly, in practice, physical data are not available to accurately describe surface characteristics; and secondly today's simulation models are not adequate to simulate all the hydraulic phenomena associated with surface flooding and relevant physical constraints on the surface. As a result, another criterion of hydraulic performance, surcharging frequency, rather than flooding frequency, has been applied in ATV-A118 (Schmitt, 2001). It considers that the rise of the maximum water level at manholes up to ground level (street surface) to be a critical flow situation

- **Austrian Standard**

Telegdy (2002) explained the sewer design situation in Austria, where most of the sewer systems are designed according to the rational method with a frequency of 1 in 1 year, though the guideline 11 of the national standards suggests heavier events with a lower frequency for city centers. One city requests for a series of five-year block rains ($f = 0.2$) remain sewage under the ground level, so this comes nearer to the ATV-A118 approach.

In addition, Telegdy also addressed the status and problems in existing sewer design standards in Austria:

- The existing guidelines do not reflect recent development in cities;
- The EN 752 has become a new national standard in Austria, but it is different to introduce it as the design guideline;
- The German ATV A118 has an influence, but there is no clear statement if or how it should be used in Austria.

As a result, the Austrian Water and Wastewater Board have formed a specialist group to revise the existing guideline for sewer design.

– Dutch Standard

The traditional hydraulic design of sewer systems in the Netherlands is based on simple rules. They are characterized by steady flow simulation, a design runoff intensity of 60 $l.s^{-1}.ha^{-1}$ for flat areas, 90 $l.s^{-1}.ha^{-1}$ for in inclined areas, and a free board of 0.2m between maximum water level and ground level (Van Luijtelaar, 1999). The sewer system is checked on two aspects: firstly, the discharge capacity of the system is checked under extreme rainfall conditions to protect the buildings from flooding, where a maximum intensity of 110 $l.s^{-1}.ha^{-1}$ at a return period of 2 years in 5 minutes is applied; and secondly, the storage capacity of the system in a long-term simulation with continuous rainfall series (1955-1979) to limit the emission of polluted water from the system to surface or receiving water.

In addition, Van Luijtelaar (1999) stated that application of the European standards in the Netherlands is impossible due to the small difference between ground elevation and the surface water.

– Norwegian Standard

Before EN752, there was no national standard of sewer design in Norway. The sewers were designed to discharge storms of 1 in 10 years and 1 in 15 years in most cities or counties so far. The system analysis and flood checking for existing systems are rarely done. Oslo is an exception, though (Schilling, 2002). The engineering practice has often been to fix a problem when floods repeatedly happen (TM, 1990-99).

– United Kingdom Standard

The traditional standard of designing sewers in the UK depended on the surcharge frequency. However, Orman (2002) states that, in the UK, the weakness of sole reliance on surcharge frequency as design criterion has been recognized for many years. The use of more complex hydraulic models to optimize designs to protect against flooding is now well established part of practice. It is used as part of rehabilitation planning.

Since its publication, EN752 has been a national standard in the UK. The progress and situation are described below (Orman, 2003):

For new development, the system should initially be designed with a design surcharge frequency as given in appendix C. In addition, the design must be checked to ensure that all parts of the site exceed a design flooding frequency of 30 years.

For upgrading existing systems, there is no published standard. A general guide and the level of flooding checking are taken from the Sewerage Rehabilitation Manual (SRM), which is also included in appendix C. It should be noticed that the minimum target for upgrading should meet regionally acceptable levels of service; figures quoted in appendix C are generally accepted as maximum values. Surcharge frequencies are sometimes limited to prevent damage to old pipes.

Additionally, the sewer design standards available from several other countries outside European are given below:

– Chinese Standard

China has its own standards for sewer design. Referring to the existing national standards of sewers design (GBJ14-87, 1997), the sewers are designed for storm ranging from 3 in 1 year to 1 in 10 years and the design frequency varies from city to city. Storm frequencies used in some cities are given in Appendix C to illustrate the situation in China.

Neither surcharge nor flooding frequency is recommended in today’s Chinese criterion. Consequently, sewer flooding checking has not been done except for few case studies in research projects (Cheng, 2001).

- Japanese Standard

Concerning the design frequency for sewer systems, the Japanese national guideline indicates that sewers should be designed to protect flooding with recurrence intervals ranging from 1 in 5 to 10 years.

Due to climate change, some cities have been trying to improve their sewers system by means of constructing new storm sewers or runoff control facilities such as infiltration facilities and storage ponds (Zaizen, 2003; Funayama and Shinkawa et al., 2002).

– Thailand Standard

In Thailand, another Asian country, sewers are designed in two levels: design storms of 1 in 2 years are applied for secondary/lateral sewer; and 1 in 5 years for primary/main drain (Wangwongwiroj, 2003).

- **USA and Canadian Standards**

In USA and Canada, unlike European countries, the drainage systems are designed as major and minor system (Appendix C). Higher design criterion of 1 in 100 years is applied for major drainage systems, whereas recurrence intervals ranging from 1 in 1 year to 1 in 5 years are applied for minor sewers (ASCE and WEF, 1992).

- **Conclusions**

Comparing the available standards above, EN752 comes to be the most comprehensive and advanced one, which embraces different operational sewer situations and considers designing sewer system capable of transporting flooding of 1 in 100 years. The UK standards have progressed closest to EN 752. Other countries are attempting to combine EN752 with their own guidelines, or are still performing their rules in engineering practice.

2.4 Risk Management

Uncertainties are unavoidable in the design and planning of engineering systems, particularly for those systems that relates closely to the stochastic events such as meteorological phenomena. Therefore, the methodology of system analysis should include concepts and approaches for evaluating the significance of uncertainty on system performance and design. With this regard, the concepts and methods of risk management consist of an important part of flooding analysis.

2.4.1 Definition of Risk

Risk has been defined slight differently in the literature. Examples are given as follows:

- Risk designates the danger that undesired events represent for human beings, the environment or material values. Risk is expressed in the probability and consequences of the undesired events (NSF, 1991).
- Risk is a measure of the probability and severity of an adverse effect to life or health, property or the environment (CAN/CSA, 1991; Fell, 1997; Salmon, 1997).
- Risk is often estimated by the product of probability and consequences of undesired events (Kjellen, 2000).
- Risk is an expression of probability for and consequence of one or several accidental events, where risk is expressed qualitatively as well as quantitatively (NTS, 1998).

Obviously, risk is evaluated by a product of probability and the adverse effects of unexpected events. It is expressed both quantitatively and qualitatively.

2.4.2 Risk Management Programs

Fell (1997) presented the risk management process (Fig.2.6) adapted from CAN/CSA (1991), where the risk management was defined as an unity of risk analysis, risk assessment and risk mitigation.

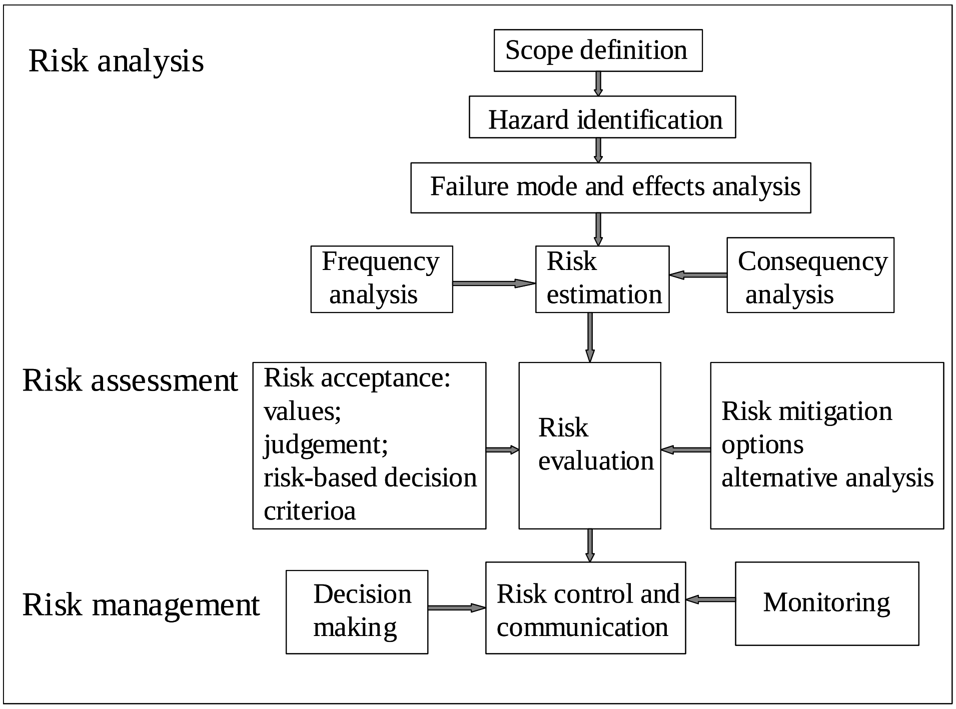

Figure 2.6 Risk management process (CSA, 1991)

In addition to the risk management procedures applied in Australia and Canada, the Norwegian Technology Standard Institution (NTS, 1998) also worked out a risk management diagram illustrated in Fig. 2.7, which is supposed to establish requirements for effective planning, execution and use of risk and emergency preparedness analysis in Norwegian offshore fields.

Comparing the procedures displayed in Fig. 2.6 and Fig.2.7, it is obvious that risk management has been addressed similarly in the two programs. Where, the risk management consists of risk analysis, risk evaluation and mitigation. These procedures have been extensively applied in the analysis of risk management of different disciples given in next section.

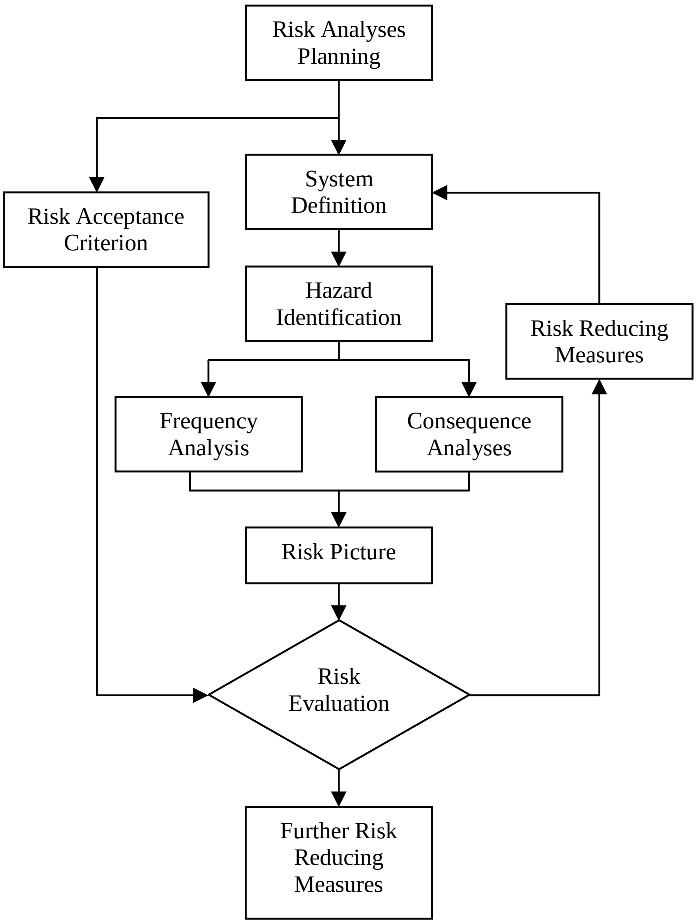

Figure 2.7 Risk estimation, analysis and evaluation (NTS, 1998)

2.4.3 Risk Management Applications

Kjellen (2000) introduced basic concepts, advanced methods and models of risk management for general accident prevention. Jenssen (1997), Alfredo &Wilson (1997) carried out risk analyses of dam safety. Blaikie and Cannon et al. (1994), Ahmed (1999) presented case studies of seeking root causes, dynamic pressures and unsafe conditions regarding to Bangladesh flooding. In addition, many numerical models were presented on the title of risk analysis of flooding. However, from the point of view of risk management, those studies are restricted to risk estimation, i.e. estimating the frequency of flooding by given rainfall intensities, or design storms. Hence, a comprehensive study of risk management of flooding is needed.

2.5 Urban Flooding Modelling Development

2.5.1 Urban Flooding Modelling Introduction

Flooding is not a new natural disaster. Throughout history, flood control has been being one of the key tasks of governments, municipalities and social institutions as well as city planners, designers and engineers. It is also one of the major research subjects. Great efforts have been made to protect vulnerable objects from flooding. Among them, plenty of models have been developed to simulate different flooding situations, which range from single process-based models, such as various loss models, rainfall runoff model, channel or pipe flow model, to integrated modeling package that combines several single-processed models. Those models definitely play significant roles in flooding forecast, protection and mitigation.

In this section, only the integrated models, which have the potential to simulate urban flooding, or which are able to simulate urban flooding are reviewed.

2.5.2 Integrated Stormwater Software

Many integrated stormwater models have been developed to cope with stormwater related phenomena. A few of them have been become popular software and applied in many projects. MOUSE, SWMM and Wallingford program are among such products that are applied globally in stormwater transportation. These programs will be reviewed below.

2.5.2.1 The MOUSE Program

The MOUSE program developed by Danish Institute of Water and Environment (DHI) is an advanced and comprehensive software package, consisting the submodels of ***Rainfall-Runoff, Hydrodynamic (HD), Water Quality process (WQ) and Sedimentation Transportation (ST)*** etc. It provides powerful facilities to solve water quantity and quality problems in urban catchments by running one model, or combing several submodels (DHI, 2000).

MOUSE is one of the most popular programs applied broadly, with applications documented in the proceedings of several DHI software user conferences, other literature and project reports. However, MOUSE was developed originally for sewer design and implement both of stormwater and (or) sanitary quantity and quality control, but not for simulating urban flooding. The fictive urban flooding tank in MOUSE is used to keep overall water balance in flooding manholes. Nevertheless, the possibility to simulate urban flooding exists by improving and combining several existing MOUSE modules.

2.5.2.2 The Storm Water Management Model (SWMM)

SWMM was developed by a consortium of American engineers for the US Environmental Protection Agency (EPA). It is used in the United State for the design of stormwater drainage systems and has been incorporated in regional water quality management planning. In addition, it has been applied globally for stormwater planning, design and rehabilitation purposes (Hsu, Lei and Yen, 1990; ASCE, 1992). SWMM takes the rainfall and catchment characteristics, determines quantity and quality of runoff, routes the runoff through a combined or separate sewer system and identifies the effluent impact on receiving waters. Thus, it is a mathematical model capable of representing urban storm runoff including sewage storage and treatment and combined sewer overflow phenomenon (Huber and Dickinson, 1992; Show, 1988). However, improvements have to be done, or additional modules or structures have to be added on SWMM in order to simulate urban flooding.

2.5.2.3 The Wallingford Procedure

The Wallingford Procedure describes the hydraulic design and analysis of pipe networks for both new schemes and existing systems. It can accommodate both stormwater sewers and combined sewers. The whole package provides a range of methods from which a series of calculation techniques can be selected to suit the conditions of any particular design scheme. It comprises: (a) the ***Modified Rational Method*** which still gives peak flow only; (b) the ***Hydrograph Method*** models surface runoff and pipe flow, which provides a pattern of discharge in time; (c) the ***Simulation Method***, which is developed from Hydrograph Method and is able to analyze the performance of existing systems or proposed designs operating under surcharged conditions.

The application of the Wallingford procedure in storm water drainage design in the UK has greatly assisted local authorities and engineers dealing with the complex renewal problem of old systems. It has also provided a comprehensive tool for the developer and consulting engineer to evaluate the pipe system precisely. Additionally, the suite of the programs has been adapted for application outside the UK (Shaw, 1988).

As the rapid progress of urbanization, the risk of urban flooding is obviously increasing, and flood paths, when flood happens, are getting complicated due to the changes on surface. On the other hand, the existing models are not designed to simulate urban flooding. Thus, new procedures have to be developed to simulate overloaded sewer systems that, if possible, should be made based on the existing models.

In short, the three commercial programs mentioned above were made originally for sewer design. Additional module must be developed, or improvement must be made on the existing models to simulating sewer flooding.

Examples of user made improvements based on MOUSE modules are introduced in the following section.

2.5.2.4 Flood Simulation by Two Dimensional Tank Modelling (Japan)

Kinoshita, Sato and Terayama (1996) presented a model, called Flood Simulation by Two-Dimensional Tank Model, which was composed of runoff, conduit, network, pump station and ponding model. Among them, ***the Runoff Model*** was used to produce inflow hydrograph to the sewer systems; ***the Conduit Model*** was constructed by the same principle as the Mouse pipe model; ***the Network Model*** was used to simulate confluence and divergence of the flow. The flow diversion at a diversion manhole was calculated by using the overflow weir formula and orifice formula; ***the Ponding model*** was a fictitious tank used to store excess water located on the top of the overflow manhole. It was assumed that when the water level at the overflow manhole would exceed the level of the ground surface, the ponding model would start to work. Conversely, this overflow was absorbed into the sewer through the manhole when the flow would decrease and the amount was assumed to be equal to the amount of empty space brought by the reduction of the water level at the manhole. Taking into account the two-dimensional and the irregularity of flow, the inundation analysis was done in the ponding model. Grids covered the drainage area. One grid was regarded as one tank. The flood flow was moving from one tank to another, and the flow between two tanks was performed as an open channel. The basic equations were continuity equation and momentum equation. The weir conditions were applied at four sides of the grids as boundary conditions.

2.5.2.5 Dynamic Waterlogging Modelling (DHI, Dhaka)

Dhaka, the capital of Bangladesh, suffers from a severe waterlogging problem recurring several times each year due to even moderate rainstorms, because of the unplanned or poorly planned urban development along with manmade intervention in the natural drainage systems. A pilot study was carried out in order to understand the flooding problem (Kamal and Rabbi, 1998), where, the MOUSE program was used in combination with GIS. In addition to the rainfall-runoff and pipe flow models, a surface flow model was developed considering the interaction of underground pipes and street drainage networks, so called Dynamic Waterlogging Modeling. GIS technique was applied for producing flood maps and visualizing simulation results.

2.5.2.6 Urban Flood Dynamic Simulation Modelling (UFDSM, China)

China is a country frequently suffering from flood disasters. Particularly in last twenty years, as a consequence of rapid urbanization, urban flooding has become a severe problem. In order to study the risk of urban flooding and implment effective measures for flooding control, a project sponsored by the Chinese National Natural Science Fund was implemented during 1995-1997 (Liu, 1998). A flood model, called An Urban Flood Dynamic Simulation Model (UFDSM) was developed by this project team (Hu et al., 1999), where five submodules: infiltration, rainfall-runoff, pipe flow, surface flow and linkage model were integrated into the modeling package. That modelling can simulate urban flooding in sewers and on the surface.

2.5.3 Special Topic: GIS in Urban Flooding Modelling

On the one hand, urban flooding simulation generally requires a broad range of spatial data, such as catchments or subcatchments, their geometric and hydrologic characteristics, flow routes on surface and the database of sewer elements. On the other hand, GIS is an ideal tool of data management, processing and analysis. Therefore, the integration of numerical flood modeling and GIS is a natural trend of flood modeling development (Djordjevic, Prodanovic and Maksimovic, 1999; Makropoulos, Butler and Maksimovic; 1999; Zech and Escarmelle; 1999). In addition, the commercial programs are proceeding in the incorporation of GIS and numerical models. Examples are given below.

2.5.3.1 MOUSE GIS

MOUSE GIS is a module added to the Mouse program and works in the ArcView GIS environment, which consists of two parts: The Network Editor and The Results Presentation.

The Network editor allows to extract data from a number of different asset management systems, to condense the network automatically according to user specified criteria and still maintain consistency of physical system and, finally to store the data as a model for further analysis in MOUSE. ***The Result Presentation*** allows presenting results from fully dynamic simulations in Mouse (DHI, 1997).

The import and export of sewer networks and results between GIS and MOUSE, the advanced graphic presentation are the advantages of MOUSE GIS.

2.5.3.2 MIKE 11 GIS

MIKE11 GIS integrates the Mike11 river and floodplain modelling technology with the ArcView GIS of Environmental System Research Institute (ESRI). Through a generated DEM, MIKE11 GIS works as an auxiliary tool to extract longitudinal and cross section data to Mike 11, and then import the simulation results back to Mike 11 GIS, create flood maps and present the result of flood simulation of MIKE 11 HD (DHI, 1998). MIKE 11 GIS is not only an ideally suited tool for river and flood plain management, but also possible for urban flooding simulation (Nielsen, 2001; Boillat, Ihly, and Mardini, 2001).

Mike 11 GIS requires spatial analyst extension of ArcView GIS and works on DEM model.

2.5.3.3 HEC_GeoRas

HEC-RAS is designed to perform one dimensional steady or gradually unsteady flow hydraulic calculations for networks of natural and artificial channels (HEC, 1997).

HEC-GeoRAS is an extension to work under ArcView GIS environment. HEC-GeoRAS provided similar functions as Mike11 GIS. It is able to create a set of files of geometrical data, such as river longitudinal profile and cross sections from the Digital Terrain Model (DTM), and then to extract into HEC-RAS for hydraulic simulation. It also enables viewing of exported results from HEC-RAS.

Unlike Mike 11 GIS, HEC-GeoRAS requires 3D extension of ArcView and DTM represented by a Triangular Irregular Network (TIN) (HEC, 2000).

2.5.4 Recent Progresses

The review above is mostly based on the literature published before 2000. Research on urban flooding has been progressing since then. The most significant progress is reviewed in this section.

Maksimovic and Prodanovic (2001) developed GIS-assisted flood model in urban areas based on the dual drainage concept. The Research Project in the European EUREKA framework - Risk Management for Urban Drainage Systems - Simulation and Optimization (Schmit and Schilling et al., 2002) was fulfilled in the beginning of the year 2003. The overall objective of this project is the development of an integrated planning and management tool to allow cost-effective management for urban drainage systems. In addition, the development and applications based on DHI software, i.e. MOUSE, MOUSE GIS, MIKE 11 and MIKE 11 GIS have progressed integrating GIS and numerical models (DHI, 2001). Many models and results have been presented during the Ninth International Conference of Urban Drainage (9ICUD) (Iwata, Fujiwara, et al., 2001; Apirumanekul, and Mark, 2001; Boonya-aroonnet, Weesakul and Mark, 2002; Freni and Schilling et al., 2002).

2.6 Conclusion of Literature Review: The Needs for Flooding Analysis and Flooding Modelling Development

Reviewing the research progress of urban flooding analysis and flooding modeling development in recent years, risk analysis of flooding was carried out focusing on flood frequency analysis and creating flood maps. It is incomplete from the point of risk management. Secondly, many commercially available models, for instance MOUSE and SWMM, are relatively reliable when dealing with free surface and pipe flow separately. However, when the underground drainage system becomes surcharged, the reliability of these models turns out to be strongly dependent on the assumption or restriction of models and the interactions among different sub-systems, particularly surface and underground (Maksimovic and Prodanovic, 2001). The improvements on the present models should focus on these two aspects: the proper interaction of different parts of the flooding systems and the better presentation of the terrain in flooding areas.

Therefore, the following aspects constitute the framework of the present thesis:

- Performing complete risk analysis from the risk sources to risk mitigation;
- Searching for GIS information support with respect to surface characteristics, such as: information on land use, flow paths on the surface and carrying out hydrological analysis based on the available terrain data;
- Establishing advanced model capable of modeling underground sewer flow and flow on the surface, with proper transition between free surface and surcharged flow and proper interaction with flows in sewers and on the surface;
- Seeking for effective flooding mitigation measures in combination with flooding simulation.

The contexts have been depicted in Fig. 1.3 of Chapter one. Progresses are made step by step through Chapter three to Chapter six.

Chapter 3

Risk Management of Urban Flooding

Risk exists due to the stochastic characteristics of natural phenomenon and the vulnerability of physical objects.

Higher protection means lower risk but higher investment and needs for more efficient management and vice versa.

There is no absolute safety. However, man can reduce the risk by various efforts.

3. RISK MANAGEMENT OF URBAN FLOODING

- Why do floods happen?
- How do they happen?
- How often do they happen?
- What are the potential consequences?
- How to alleviate the flooding problems and mitigate the potential consequences?

Chapter three concerns the understanding floods from their occurrence to cease, and aims to:

- Identify the potential hazards or threats of flooding;
- Analyze the likely flooding scenarios;
- Estimate the frequency of individual or joint flooding events;
- Assess the potential consequences; and
- Mitigate the risk of flooding and alleviate the potential consequences.

A Norwegian case study is applied throughout the analysis process.

3.1 Risk Management Concepts and Methodology

3.1.1 Terminology

The following terminologies are used in this chapter:

Hazard means a potential danger, either an event or a condition, which may cause damage or other adverse effects. It might be controlled or reduced by maintenance or protection measures.

Incident indicates a small operational obstacle without or with limited damage.

Event expresses either a large operational accident or a natural disaster that probably has severe consequences.

Accident can be between an incident and an event, with small or medium damage.

Root cause is the most basic and important origin, which leads to either small incident, or large event.

Contributing factors are others hazards except for root cause.

3.1.2 Definition of the Risk of Urban Flooding

Flooding may be triggered when a large volume of stormwater is transported by drainage systems. Consequently, the objects in flooding areas, such as people, estates and assets as well as public infrastructure, may be damaged. Therefore, **the risk of urban flooding is expressed by the products of probability of flooding and the corresponding consequences**. It is illustrated in Fig. 3.1. For a certain urban drainage system, the rare the storm event, the higher the frequency of flooding is; and the more vulnerable the physical objects are, the more severe the consequences will be. In one word, the higher risk of flooding is.

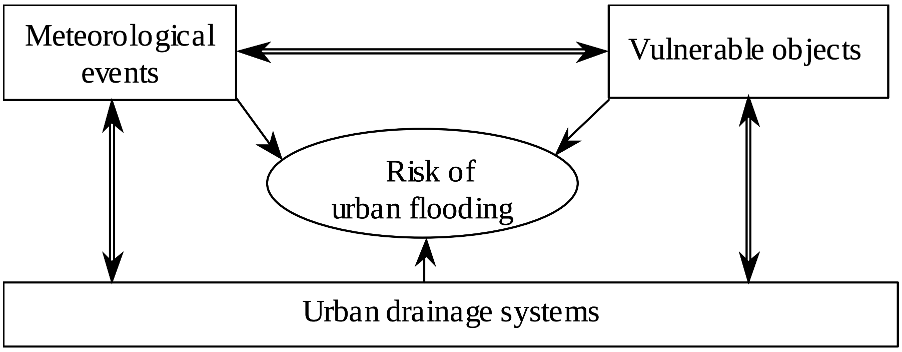

Figure 3.1 Urban flooding system

3.1.3 Risk Management Procedures

Applying the procedures displayed in Fig. 2.7 and the system defined in Fig. 3.1, a risk management study is performed in the following section 3.2.

3.2 Risk Management Progress

3.2.1 Risk Analysis

3.2.1.1 Risk Identification

The threat of flood may exist in any stage and at any time during a system performance. For analysis purpose, the hazards of flooding are identified from three main risk domains: the natural meteorological events, the drainage systems and human errors. Among them, the natural causes are relatively clear and easy to distinguish. The technical and structural hazards are rather complicated. They may exist in any stages ranging from preliminary investigation and field survey, design, construction, operation and maintenance. Human errors also spread in different stages, for instance, strategy mistakes may occur at higher levels;

others human induced defects, such as planning or design may be poorly carried out, insufficient maintenance or mis-operation may happen at operation stage. In the contexts of mentioned above, the potential flood hazards are diagnosed for general situation of in urban drainage systems and summarized in table 3.1.

Table 3.1 Checklist of urban flooding hazards

Risk domain	**Technical/Natural hazards (A)**	**Human errors/Other hazards (B)**
Technical risk in preliminary investigation and field work stage	1) Inaccurate or incorrect locations of streets, buildings, ditches and streams; 2) Inaccurate or incorrect elevation, high and low points and changes in the surface slope; 3) Inaccurate or incorrect location of water and gas mains, power and heating lines; and other underground structures; 4) Unclear ground water condition.	1) High survey cost; 2) Heavy workload; 3) Less work efforts; 4) Human error/deviation
Technical risk in design stage	5) Buildings sills or basement windows lower than ground surface; 6) Building sewers lower than lateral/main sewers; 7) No backwater valve or siphon in basement; 8) Inadequate sewer capacities; 9) Under dimensioned inlet capacity and sewer hydraulic bottleneck; 10) Sewer diameter smaller than 200mm; 11) Inadequate sewer slope and flow velocity less than the value of self-cleaning velocity; 12) Too steep sewer and flow velocity larger than erosion one; 13) Missing grinder pump in pressure sewers, or missing valve in vacuum sewers;	5) Lower design standard; 6) Inadequate investment; 7) Without consideration of snow melting; 8) Lack of data about design storm and connected areas; 9) Human deviation.
Technical risk in construction stage	14) Poor material quality; 15) Improper connection of pipes; 16) Incomplete cleaning construction site and sewer; 17) Cross connection storm sewers with other pipes;	10) Higher material price; 11) Inadequate specification; 12) Heavy workload 13) Less work efforts. 14) Human error/deviation 15) Insufficient supervision

To be continued

Continued from table 3.1

Technical stage in operation and maintenance stage	18) Pipes partially or completely clogged by construction faults; 19) Pipes partially or completely clogged by debris (branches, roots, clothes and other wastes); 20) Pipes partially or completely clogged by deterioration (broken, collapse, displaced joints); 21) Pipes partially or completely clogged by large sedimentation; 22) Inlets clogged by weeds and other wastes (leaves, papers, concrete debris, sands); 23) Inlets frozen or clogged by snow; 24) Screen clogged; 25) Gate can not be lifted properly; 26) Pump out of order; 27) Overland flow directly flows into basement or house. 28) Break of main water pipes 29) Break of in-house pipes.	16) High maintenance cost (material and labor); 17) Lack of maintenance targets; 18) Heavy workload; 19) Less work efforts. 20) Human error/deviation;
Natural risk: overloading	30) Catastrophic short term rainfall; 31) Long term rainfall with high intensity at the end; 32) Unfavorable combination of snowmelt and rainfall; 33) Higher rainfall on frozen surface; 34) Sewer backwater caused by higher receiving water; or high tidal level; 35) Surcharge from open conduit and receiving water; 36) Obstruction due to landslides, uprooted trees; 37) Higher inflow from upstream flooding.	21) Low design criterion; 22) Insufficient protection measures.
Urbanization	38) Increasing degree of imperviousness; 39) Increasing connected areas; 40) Increasing inflow due to upstream urbanization; 41) Development inside the floodplain	23) Non-balanced development of human activities and infrastructures as well as resources; 24) Lack of regulations of land use and floodplain management;
Ground water	42) Basement wetting or flooding caused by high ground water level; 43) Blocked soil drainage pipes.	25) Poor design soil drainage system

3.2.1.2 Causal Analysis

In order to distinguish the root cause(s) and contributing factors of flooding from the hazard checklist and to guide the actions of flood control and mitigation, **causal analysis** is performed in two ways, fault tree and event tree illustrated in Fig. 3.2. The **fault tree analysis** employs an analytical tree to display the results of analysis. It starts with a top accident event, a probable flooding event in the present analysis, and proceeds backwards to find out all the prerequisite conditions until the analysis reaches the root cause(s) (Kjellen, 2000). As a result, the logical relations between causes and consequences are obtained in table 3.2.

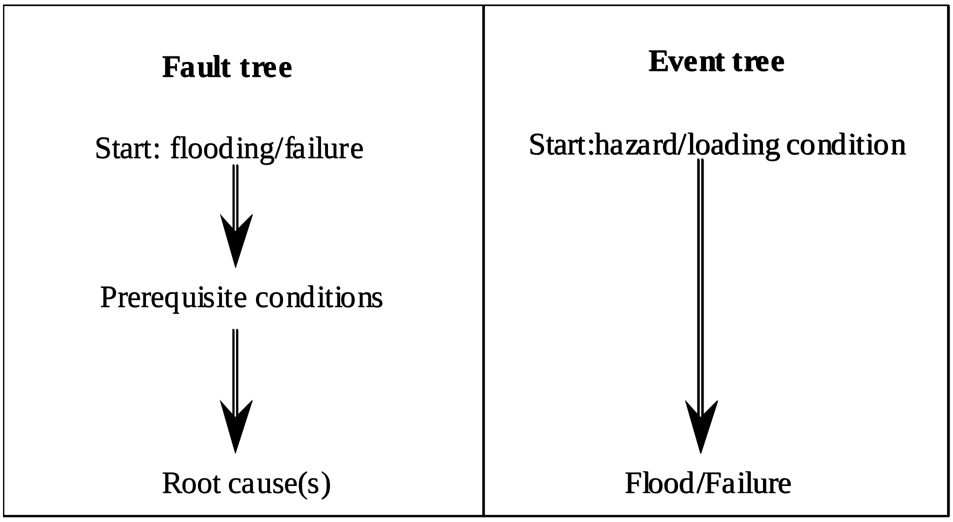

Figure 3.2 Underlying principle of causal analysis

Table 3.2 Tabular fault tree of urban flooding hazards*

Top event		Flooding			
Events/incidents		Sewer blocking	Inlet blocking	Other obstacles	Overloading
Contributing factors	Direct and immediate impacts	A18-21	A8, 9,22,23,27	A24-26, 28,29	A30-37
	Indirect and graduate impacts	A10, 11,16	A5, 6,7	A12-14	A1-4, 15, 17, 38-43
Root causes		Strategy error: B22, 23; Inadequate resources: B1, 2,6,8,10,12,15; Inadequate standards: B5, 7,11,16,20,21; Inadequate compliance: B3, 4,9,13,14,18,19			God's power

*The same codes of flooding hazards have been applied in table 3.2 as in table 3.1.

Unlike the fault tree, **event tree analysis** starts from a hazard, or a loading condition and then propagates to find out the potential failure modes, herein the probable flooding chains displayed in Fig. 3.3. It is carried out according to the following criteria:

- River flooding is regarded as a major flooding scenario, if a river passes through or passes by a city;
- In very wet weather condition, the runoff discharge generated by heavy rainfall dominates the magnitude of flooding, so that the impacts of sewer incidents may be neglected;
- In moderate wet weather condition, the joint probability of precipitation events and sewer incidents controls the risk of flooding;
- In the dry weather condition, the risk of flooding is predominated by sewer operational incidents;
- Flooding may be caused by high tidal level or storm surge at sea;
- Catastrophic flooding might be aggregated by all the hazards above occurring simultaneously.

Where, the values of flood frequencies given in Fig.3.3 will be explained in the following case study in section 3.2.5.

3.2.1.3 Frequency Analysis

From the point of view of probability and statistics, the probability of floods can be calculated by formulae in combination with the flooding situations below (Ang and Tang, 1984).

Probability of Flooding Caused by Single Event

In this simple case, the probability of flooding is equal to the frequency of the flooding event:

Eq. 3-1 $P_{flooding} = P[E]$

Where, $P_{flooding}$ and $P[E]$ represents the probability of flooding and the frequency of induced events E respectively.

Probability of Flooding Caused by Joint Events

The probability of flooding caused by logical sum of several **dependent evens** can be calculated by the following formula:

Eq. 3-2 $P_{flooding} = P\{E_1 \cup E_2 \cup \cdots \cup E_n\}$

$$= \sum_1^n P[E_i] - \sum_{j>i} P[E_i \cap E_j] + (-1)^{n+1} P[E_1 \cap E_2 \cap \cdots \cap E_n]$$

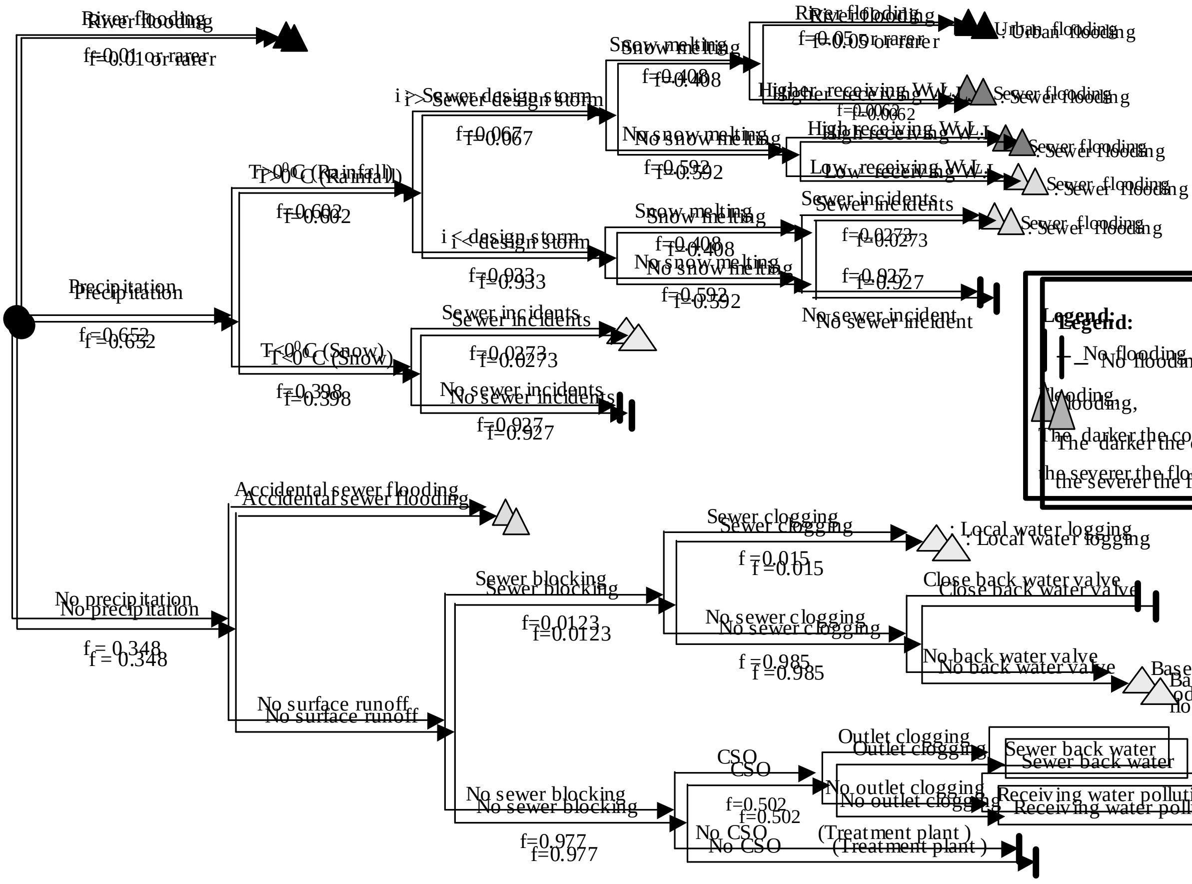

Figure 3.3 Event tree of floods of Trondheim Case study

Where, E_i (i=1, …, n) are dependent events; $P[E_i]$ is the frequency of event E_i , and $P[E_1 \cap E_2 \cap \cdots \cap E_n]$ is the probability of multiplication of dependent events E_i.

When the events are **independent**, then the calculation of the frequency of flooding can be simplified as below:

Eq. 3-3 $P_{flooding} = P\{E_1 \cup E_2 \cup \cdots \cup E_n\}$

$$= \sum_1^n P[E_i]$$

Where, E_i (i=1, …, n) are independent events, and $P[E_i]$ is the frequency of E_i.

The probability of flooding caused by logical multiplication of dependent events can be calculated by following formula:

Eq. 3-4 $P_{flooding} = P[E_1 \cap E_2 \cap ... \cap E_n]$

$$= P[E_1] \cdot P[E_2 / E_1] \cdot P[E_3 / E_1 E_2] ... P[E_n / E_1 E_2 \cdots E_{n-1}]$$

Where, E_i (i=1, …, n) are dependent events; $P[E_i]$ is the frequency of E_i, and $P[E_i / E_j]$ is the conditional probability of event E_i and E_j.

When the induced events are independent, then:

Eq. 3-5 $P_{flooding} = P[E_1 \cap E_2 \cap ... \cap E_n]$

$$= P[E_1] \cdot P[E_2] \cdots P[E_n]$$

Where, $P[E_i]$ is the frequency of independent event E_i (i=1, …, n).

3.2.1.4 Consequence Analysis

Flooding consequences are generally classified into three main categories: (a) people related intangible consequences, including the loss of lives, injuries health problems and lack of their basic life needs; (b) Tangible property damage: damaged goods, lost income, and the cost for flood control; (c) Intangible environmental destruction.

- **The Loss of Life and People at Risk**

The number of lost lives due to flooding is a very important indicator of flooding consequence. The number of people at risk is used to decide upon the level of protection in pre-flooding condition, and the number who might be evacuated from flood prone areas. It is generally estimated according to flood maps. As rule of thumb, an inundation depth of 0.3 m or more at a given dwelling, worksite or temporary use area can be used to indicate a hazard to life (USBR, 1988). In addition, after flooding deluge, many people are still lacking for their daily needs. Therefore, to heal the injured and sick people, to control the spreading of disease, to provide the people in flood-exposed sites with proper shelters, clothes and food, and even to help them to start their new life and production are all challenges of post-flooding.

- **Property Damage and Other Economic Losses**

Property damage is unavoidable when flooding takes place, which may include damage to private and institutional properties, commercial productions, infrastructure and livestock.

Particularly today, the entire society works as a whole, any interruption to the neural systems, such as electricity lines, water pipes, gas lines and road systems, may cause temporal disorder or even disruption of community activities besides the inconvenience to the residents' livelihood.

- **Adverse Environmental Impact**

Consideration of environmental deterioration caused by flooding would address situations inside and outside of buildings, public areas, receiving water bodies, which may harm human beings or aquatic life or stream habitat, or even the quality of groundwater. The destruction of the environment may last a long term in the future.

3.2.2 Risk Acceptance Criterion

Risk mitigation is, on the one hand, a matter of cost-benefit analysis. The higher the risk is accepted, the lower the cost for risk control will be. On the other hand, deciding an acceptable risk of flooding is not only a balance of investment and profits, since the safety of people should always be given the first consideration; In addition, political, social, environmental and long-term impacts are among important issues to be concerned on. Therefore, the risk acceptance criterion can be specified in cost effectiveness, but it should also consider comprehensively the risk and the tolerability of vulnerable objects.

For urban flooding, there is no simple and generally applied risk acceptance criterion. Concerning the practice of sewer engineering, however, the design standard is actually applied as the risk acceptance criterion and the targets of administration and operation as the lower boundary of As Low As Reasonably Practical (ASARP) criteria displayed in Fig. 3.4.

3.2.3 Risk Evaluation

As far as the risk acceptance criterion is specified, the risk of flooding can be evaluated in combination with historical flooding events, design storms, the status of existing sewer systems and the ability of vulnerable objects. For instance, as a rule implemented in Trondheim municipality, if a place had been flooded more than one time by rainfall with recurrence intervals of 1 in 10 years or more, then it means the risk of flooding is high, or in other word, it is unacceptable. Hence effective measures must be taken to increase the withstanding ability of that area.

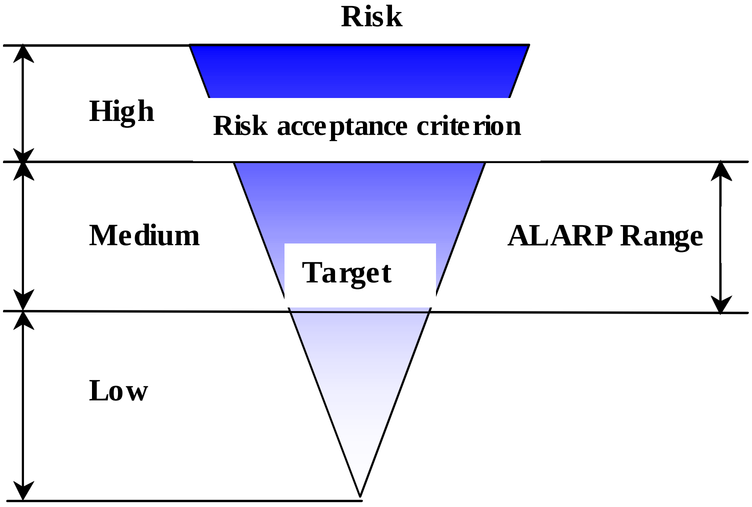

Figure 3.4 Relation between risk and risk acceptance criterion

For purpose of flood forecasting, generally, flood maps are created based on flood simulation. Where, the people and properties in danger at certain frequency of flooding are highlighted. Accordingly, the risk of flooding is defined, and the effective measures of flood mitigation can be taken into consideration.

3.2.4 Risk Mitigation

Risk of flooding may be reduced by structural measures and non-structural measures. According to Hadden's strategies (Kjellen, 2000), Flood mitigation measures are classified into the following three main categories as given in table 3.3.

According to specified risk acceptance criterion, appropriate mitigation measures can to taken.

Table 3.3 Flooding mitigation measures

Measures related to sources	Measures related to barriers	Measures related to vulnerable objects
Prevention measures	**Prediction and defense measures**	**Proofing measures**
Preventing floods from its occurrence: • Modifying the distribution of precipitation along temporal and spatial profile (limited); **Control human-induced floods:** • Floods from operational obstacle; • Effects of urbanization • Flooding due to management oversight and omission.	**Predicting flooding:** • Forecast incoming floods; • Floods warning; • Evacuating floods-prone population and properties; **Defense from floods:** • Reinforcement of dams, levees, dikes and walls; • Using retention and detention facilities; • Restoring channels and sewers; • Using soil infiltration; • Building of temporary defense structures; • Executing regularly monitoring and maintenance.	**Non-structural flood mitigation measures:** • Making flood map and evaluating flooding risk; • Zoning land use and coding activities and construction based on flood risk; • Educating people how to live with floods. • Flood insurance

3.2.5 Case Study

3.2.5.1 The Frequency of Flooding

Deciding the risk of flooding is fairly complicated in reality because the flooding situations vary from case to case. A case study is carried out according to the situation in Trondheim Municipality. The frequency of single event in the displayed event tree of Fig. 3.3 is calculated in the following conditions

- The frequencies of precipitation and temperature are calculated based on the data at Svarttkjønnbekken hydrological station (1980-1989).
- The frequency of snow melting is estimated based on the simulation of HBV model using the same data.
- The frequency of a major river flooding event is set to such a frequency that flooding damage may be caused when it happens (Bævre, 2001; Killingtveit, 1995).
- The frequency of sewer incidents is estimated based on the annual operational records of water and wastewater systems of Trondhein Municipality (TM, 1990-1999; Nie and Schilling, 2001). The frequencies of incidents are calculated by following formulae:

$f_{s.b.} =$ Sewer blocking length per year / total length of sewers

$f_m =$ No. of manhole incidents per year / No. of total manhole

Where, $f_{s.b.}$ and f_m represent the frequency of sewer blocking and manhole incidents respectively. In addition, the frequency of high water level at sea may affect the sewer discharge in form of backwater effects. It is estimated according to the frequency analysis of sea level versus the crest height of the lowest overflow weir. Another index, the damage cases per year, is also used as a valuable indicator.

Assuming all events in the event tree are independent, the frequency of flooding of each chain of the event tree is the product of joint events (“and” events), and the total frequency of flooding is equal to the sum of all probable frequency of flooding chains (“or” events). Therefore, frequencies of probable flooding for the Trondheim case are simply estimated in two main categories given in table 3.4.

Table 3.4 Flooding frequency for the Trondheim case study (in events per year)

Flooding situation		**Flooding scenarios**	**Frequency of flooding**
I	1	River flooding	0.01
	2	Sewer flooding caused by heavy rainfall	0.067
	Sum	Large flooding	0.077
II	3	Moderate rainfall plus melt snow and sewer incidents	21.3
	4	High tidal level at Trondheim fjord*	0.0062*
	Sum	Flooding caused due to sewer operation	21.87

* The average annual damage cases include the impact of high sea level.

In table 3.4, the individual flooding frequency is set according to the following rules:

- River flooding is one of the major flooding conditions in Trondheim. In this case study, a flooding of 1 in 100 years is considered regarding to flooding damage;
- In Trondheim, sewers are designed to protect flooding from 1 in 10 years to 1 in 20 years. Hence, rainfall of 1 in 15 years is used as the frequency of sewer flooding.
- In moderate rainfall condition, flooding may be caused by joint events of rainfall, snowmelt and sewer operational incidents. Therefore, the average annual damage cases are used as an indicator.
- Flooding may also be brought about due to high tidal or storm surge at sea. It is estimated at frequency of 0.0062 according to frequency analysis of water level in Trondheim fjord versus the crest level of sewer outflow weirs (Bævre, 2001; TM, 2003).

The total frequency of flooding in Trondheim is the sum of all the frequencies of events above. However, the frequency and the consequence of large flooding and those caused by sewer deficiencies in moderate and dry weather condition are very different. Therefore, two different types of flooding situations are calculated in table 3.4. The large flooding frequency is 0.077. Whereas, the frequency of flooding caused by operational defects of sewer systems is 21.3.

According to the operational reports of sewer systems in Trondheim (TM, 1990-1999), the sewer damage cases per year and corresponding annual damage compensation are displayed in Fig. 3.5 and 3.6, where one case is defined by one event and in which one house or several houses were flooded.

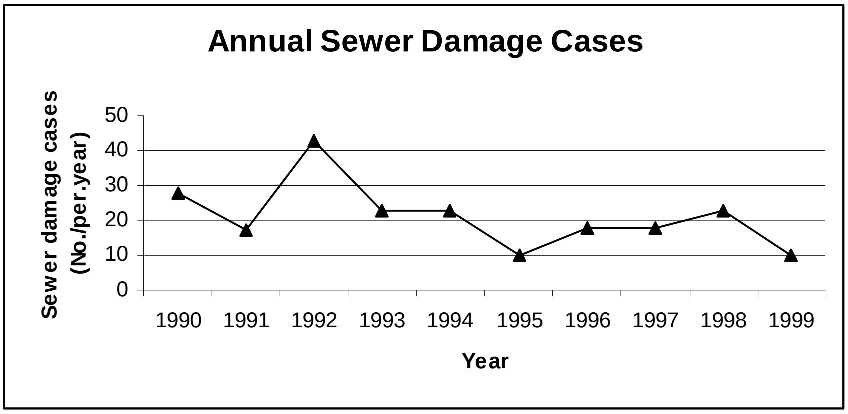

Figure 3.5 Annual sewer small flooding cases recorded by Trondheim municipality

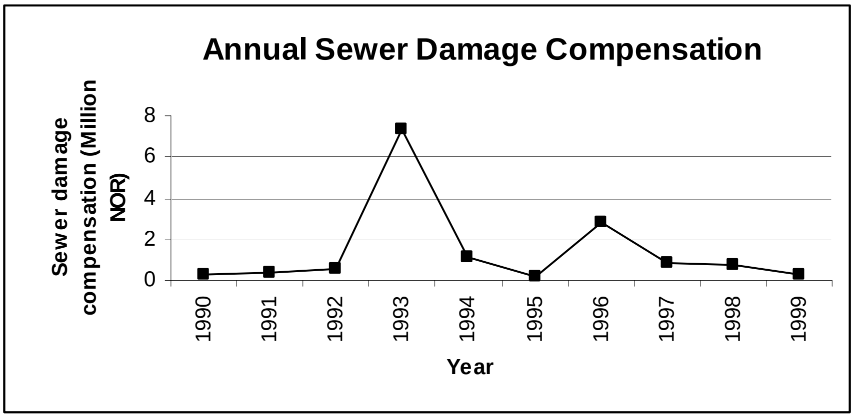

Figure 3.6 Annual sewer flood damage compensation paid by Trondheim municipality

In contrast to the sewer flooding damage, there were very rare flooding damage records caused by river flooding (Milina, 1999; Roald, 2003). Obviously, sewer flooding occurs more frequently than river flooding in Trondheim. Therefore, attention of flood control and mitigation should be paid to sewer flooding in addition to large river flooding.

3.2.5.2 Flooding Mitigation

In order to reduce the risk of sewer flooding and sewer related problems, the administrative targets have been worked out by the Water and Wastewater Department of Trondheim Municipality. The targets together with the achievements achieved in 1999 are given in the following table 3.5.

Table 3.5 Goals of sewer operation and achievements in the year 1999

Items	Goal Descriptions	Goal achievements
Sewer interruptions	No more than 90 unforeseen operational interruptions in transport of sewage per year.	108 unforeseen interruptions were registered, which slightly more than the targets.
Interruptions in pump station & treatment plants.	No more than 10 unforeseen interruptions in operational pump stations and treatment plant per year.	5 unforeseen interruptions were registered. The target was achieved.
Basement flooding	No more than once every 10 years per residence. The result indicator will be compensation payment	2-3 cases in Ila district, had flooding previously, improvement were made to the sewers there in 1999. Total NOK. 1,200,092 had been paid in 1999 to the 18 claims for damages.
Pollution incidents	Monitoring program must be established to find acute pollution incidents	The main 15 of total 89 CSO had been monitored properly. The work is on its way, but not completed yet.

Fig. 3.5 and Fig.3.6 as well as the achievements of sewer operation in 1999 indicate that both of the number of sewer damage cases and the amount of compensation paid by Trondheim Municipality is improving over time. Considerable operational effectiveness has been attained to reduce the risk of sewer problems in Trondheim practice.

3.3 Summary

Main results Sixty-eight (68) potential hazards of urban flooding have been identified for general urban flooding situations. Among them, root causes and contributing factors have been distinguished by the fault tree method and probable flooding scenarios have been discovered by event tree analysis. In addition, the theorem of probability and statistics to estimate flooding frequency are introduced. Flooding consequences, risk evaluation and mitigation are discussed as well. On these bases, a case study of risk of flooding has been carried out based on the situations in Trondheim, Norway.

With regarding to the Trondheim case study, the results reveal that the risk of sewer flooding is remarkable. It happens more frequently and causes large accumulated damage. Among the flooding scenarios that may induce sewer flooding, heavy rainfall in summer and autumn, rainfall plus snow melt on iced soil in late winter or early spring are the two most critical conditions. In addition, another root cause of triggering flooding is regarded to resources restriction, which leads to insufficient capacity of sewers, and limited rehabilitation of vulnerable sewers. Besides, insufficient supervision during construction and insufficient maintenance in operation, as well as human errors are among important contributing factors for flooding. Moreover, in the Trondheim case, sewer flooding may be caused by high tide level or storm surge in the fjord, which may result in backwater in basement, and further on cause basement flooding. Therefore, using sewer backwater valves is an option to avoid such problems in the affected basements.

In addition, risk acceptance criterion has been introduced for flood mitigation. In current practice, the design standard of drain and sewer systems is used as an alternative. Moreover, the ALARP criterion is commonly applied as the operational or administrative targets in many cases. Trondheim municipality has made very good practice.

Discussions As a natural phenomenon, flooding can happen at any time. It is often the joint consequences of natural event, technical, structural and operational defects as well as human negligence. It is a cognitive process to be aware of the flooding risk comprehensively and perceptively. This process consists of the main contents of Chapter three. Such a study may give reference to the operation and management of urban drainage systems towards an active and defensive direction in order to control the hazard before it releases.

Suggestions for future study To evaluate risk of flooding is rather complicated, where the frequency of induced events must be calculated and their dependences must be decided carefully. In this sense, the quantitative study of Chapter three, for instance flood frequency analysis, is rather gross. Therefore, the values should be improved simulations and when long series data are available.

The influence of organizational elements and strategy on the risk of flooding is not included in this study, which is also an important hazard domain. In addition, further study should be aware of the dynamic features in flooding.

Chapter 4

GIS Technology in Flooding Analysis

Information is the source of advanced science and technology.

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4. GIS TECHNOLOGY IN FLOODING ANALYSIS

GIS and its basic concepts start the subject matter of Chapter four. It is followed by the description of one major spatial analysis model: Digital Elevation Model (DEM) and GIS hydrological spatial analysis modeling. These models are then applied to delineate stream networks and watersheds. On these bases, GIS-based preliminary flood risk analyses are performed.

Both Norwegian and Chinese cases are applied under the supposed objectives.

4.1 Introduction of GIS

4.1.1 Definition and Interpretation of GIS

Geographical information system (GIS) is a computer based information system that enables capturing, modeling, manipulating, retrieval, analysis and presentation of geographically referenced data (Worboys, 1995). The study of GIS has emerged in the last decade as an exciting multi-disciplinary endeavor, spanning over such subjects as geography, cartography, remote sensing, image processing and computer science. It has played an extremely important role in land use, resources management, environmental monitoring sciences and other planning activities. An overview of GIS applications is given in Chapter two.

4.1.2 Geographical Objects

Spatial objects are delimited geographic areas, with a number of different kinds of associated attributes or characteristics. **A point** is a spatial object with zero area. **A line** is made up of a connected sequence of points. Lines have no width. **Nodes** are special kinds of points, usually indicating the junction between lines or the ends of line segments. **A polygon** is a closed area. **Chains** are special kinds of line segments, which correspond to a portion of the bounding edge of a polygon.

4.1.3 Data and Variables in GIS

Nominal variables are those, which are described by name, with no specific order. **Ordinal variables** are lists of discrete classes, but with inherent order, for instance, the classes of the streams. **Interval variables** have a natural sequence, but in addition, the distance between the values has meaning, for example, the temperature measured in degrees Celsius. Finally, **Ratio variables** have the same characteristics as the interval variables, but the ratio variables have the natural zero or starting point, whereas, an arbitrary zero point is used in interval variables.

In addition to these four kinds of data, two other different types of data found in most geographical information systems are spatial data and non-spatial data (attribute data). **Spatial data** record the geodetic location of a spatial object, whereas **attribute data** provide other information, which is logically connected to the spatial locations.

4.1.4 Data Structure

4.1.4.1 Raster and Vector Data

Raster and **vector data** are the two main data structures in GIS. In the **raster data** structure, values for the attributes of interested are relate for every cell, frequently regular, in an array over space. In contrast to the raster data, **vector data** structures are based on elemental points whose locations are known with arbitrary precision. For the spatial data in geographical information systems, the coordinate data is encoded, and stored in some combination of points, lines, and polygon (Star and Estes, 1990).

4.1.4.2 Attribute Data

Attribute data describes the features represented by spatial data, which is stored in a vector or raster data structure; and corresponding attribute data is stored in a set of tables related geographically to the features they describe. This is also known as a geo-relational data structure.

4.1.5 Data Presentation in GIS

Spatial data can be thought of as a template composed of cells and or points and lines, to which specific information is linked. As more than one kind of information is usually handled at the same time, e.g. catchments and their boundaries, drainage networks, soil characteristics, land use etc., several themes, each containing the spatial structure associated with a single category in the map, can be defined. In general, categories are implemented separately so that the attributes that describe specific objects in the map are scatted among several, disconnected themes of information (Fig. 4.1). As a result, one must work on several data themes to fulfill one analysis.

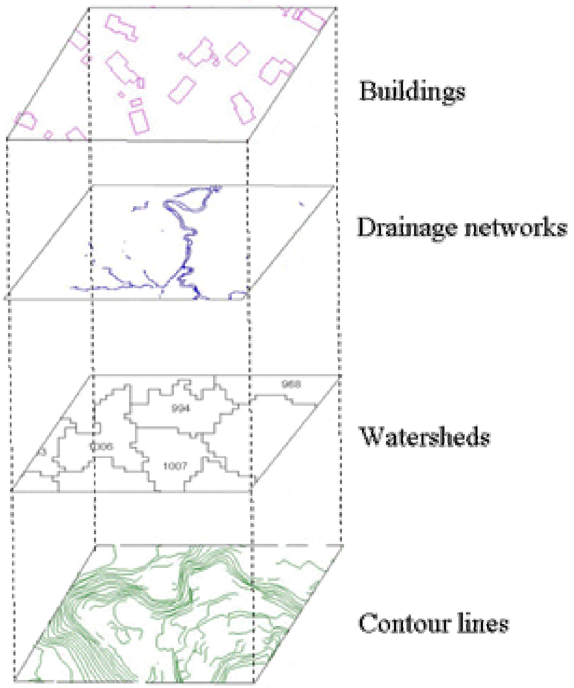


Figure 4.1 Presentation of GIS data

4.1.6 Fundamental Functions of GIS

GIS has five essential functions: data acquisition, pre-processing, data management, data manipulation and analysis and product generation. Details can be found in Star and Estes (1990). These functions make GIS suitable for applications in various disciplines.

4.1.7 Overview of GIS Applications

The early users of GIS in hydrology were municipalities and water distribution authorities and companies (Wallis, 1988); Star and Estes (1990) reviewed the applications of GIS in master planning, evaluation of proposed dam site, irrigation and water resources potential and agriculture production. Zhang et al. (1990) presented overview of hydrological modelling with GIS. DeVantier and Feldman (1993) overviewed GIS application in hydrological modelling, with particular references to rainfall-runoff models, floodplain management and forecasting, and drainage utility implementations. Meyer et al. (1993) applied a physically based, spatially distributed urban watershed model for storm water management in Fort Collins, Colorado. GIS applications in hydrology and water resources management were presented by Singh and Fiorentino (1996), and in urban planning and decision support systems by Birkin and Clarke et al. (1996), Prins (2001) and Sample and Heaney et al. (2001). Moreover, GIS applications in flooding analysis have been reviewed in section 2.5.3. These examples reveal that GIS has been playing important role in a broad range of subjects and disciplines.

4.2 Terrain Analysis Models

Terrain analysis is a special category of GIS spatial analysis. Terrain based GIS hydrological model and its major products are very useful in flooding analysis.

4.2.1 Digital Elevation Model (DEM)

Digital Elevation Model (DEM) is an ordered array of numbers that represents the spatial distribution of **elevations** above an arbitrary datum in a landscape. It generally consists of elevations sampled at discrete points, or lines, i.e. contour lines. DEM is an indispensable tool for presenting and analysing the features of topography.

4.2.2 Models for Creating DEM

The ideal structure for a DEM may be different if it is used as a structure for a dynamic, hydrological model rather than for determining the topographic attributes of the landscape (Moore, Grayson and Ladson, 1992). Two primary models are commonly used for DEM analysis are regular grid model and triangular irregular networks (TIN).

4.2.2.1 Regular GRID Model

In regular grid model, the data structure consists of a matrix of elevation values. These values refer to equally spaced points (mesh points) (Fig. 4.2 (a)). Three different cases need to be considered in order to calculate mesh point values from sample points: (1) if sample points are regularly spaced and the distance between them coincides with the desired grid size, then no interpolation is needed; (2) if sample points are regularly spaced but with a distance between them not coincident with the desired grid size, then usually either a bilinear interpolation method or a cubic convolution method can be used to resample the grid; (3) if sample points are irregularly spaced, then several methods of interpolation can be used for estimating elevation values at positions different from sample point locations. The most commonly used are Inverse Weighted Distance and the Kriging method (Singh and Fiorentino, 1996).

Regular grids have been used for a long time because of the simplicity of handling their data structure and the ease of computer implementation. The choice of grid size is crucial. A small grid size gives a more accurate representation of uneven terrain but generates a large amount of redundant data for representing uniform terrain in the same study area. In contrast, a large grid size, which would be able to represent efficiently uniform terrain without redundancy, but would not be capable of representing complex topographic feature accurately in the mean time.

4.2.2.2 Triangular Irregular Networks (TIN)

In TIN model, the data structure is based on two basic elements: sample points with their x, y, z values, and a series of edges jointing these points to form triangles (Fig. 4.2 (b)). Different from regular grid model, the TIN can give a better representation of areas with complex topography using less data.

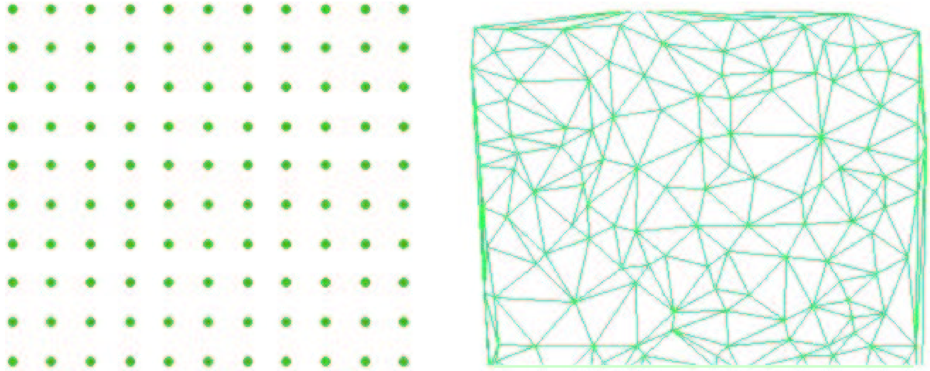

(a) GRID (b) TIN

Figure 4.2 Representation of two DEM models

4.2.3 Data Needs for Creating DEM

4.2.3.1 The Basic Data

The basic data for creating DEM consists of the observation of elevation and features of terrain surface with particular attention to surface discontinuities, such as edges of roads, ridges of mountains, so called breaklines; and special locations, e.g. pits, peaks, points of change in slope and ridges. These are attributes that represent the variation on uncovered terrain and the water storage of the terrain.

Terrain varies over time, particularly with the development of land use. Therefore, terrain database should be kept up-to-date. Consequently, the DEM should be modified in time according to the changed database.

4.2.3.2 Additional Data

In addition to the basic data, other surface features on that may impact the variation of terrain, such as buildings, artificial channels or water tanks, should be included in the terrain data as well.

4.2.4 Major Hydrological Products Derived from DEM

A great deal of information products can be derived from DEM (ESRI[1], 1996; ESRI[2], 1996; ESRI, 1997). The products that play an important role in flooding analysis are particularly slope, watersheds and drainage networks. They will be introduced in the following sections.

4.2.4.1 Slope

Slope is one of the important features to define the surface flow directions. It is defined by a plane tangent to the surface modeled by DEM at any point and comprises two components: gradient, the maximum rate of change of altitude. Slope can be expressed in decimal degrees or percentage in GIS.

4.2.4.2 Watersheds

Using flow direction and accumulation as essential intermediate products, watersheds can be created according to the needs of applications. In addition, the hydrological characteristics of watersheds can be calculated automatically based on either grid DEM or created watersheds.

4.2.4.3 Surface Stream Networks

By identifying concave-upward portions of a DEM, where surface runoff tends to be concentrated, the algorithm marks the highest pixel in a window of 2*2 grid cell going throughout the terrain of the study area, and at the end of the process, all the unmarked cells represent the estimated drainage networks. A threshold value of contributing cells has to be specified to define the density of the stream networks.

In addition to surface flooding, the stream networks are valuable reference for sewer design and rehabilitation.

4.2.4.4 GIS Hydrological Modeling

The delineation and quantification of the hydrological elements mentioned above is tedious and time-consuming when they are implemented manually. Thus, there is a need for computer modeling and program to fulfill the tasks. GIS software provides for the solution. Using a GRID DEM as input, the hydrological modeling running on the template of ArcView GIS (ERSI, 1996) can carry out slope, flow direction and accumulation analyses. On these bases, the program delineates watersheds and stream networks automatically, and calculates the hydrological characteristics specified by the user. The procedures of GIS hydrological modeling operation are explained in Fig. 4.3 below.

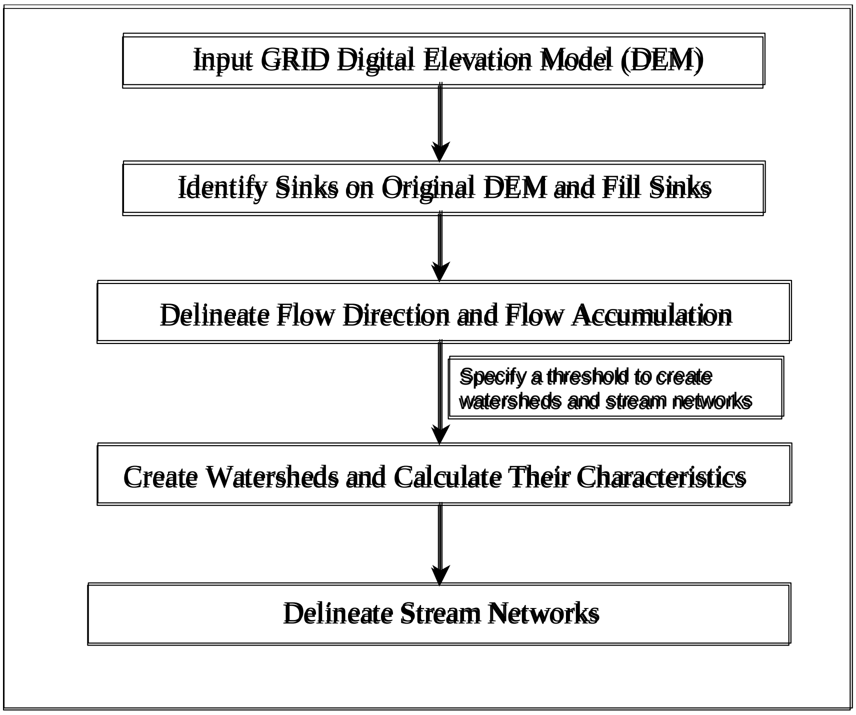


Figure 4.3 The structure and procedures of Hydrological Modeling

Step 1. The hydrological modeling works on a ***grid DEM***. Therefore, importing or creating a GRID DEM is essential to run hydrological modeling.

Step 2. Working on the ***Sink request***, any sinks or depressions, usually the lower cells than its surrounding cells in the original DEM, can be identified and then filled by a proper correction, which ensures proper flow on surface.

Step 3. Running the ***Flow direction request***, the directions to which water will flow out of each cells is determined.

Step 4. Performing the ***Flow accumulation*** request, the number of upslope cells flowing to a location is specified.

Step 5. On theses bases, watersheds and stream networks can be delineated by user specified threshold values.

4.3 GIS in Flooding Analysis

4.3.1 Data Needs of GIS Based Flooding Analysis

GIS is information based analytical tools. Data collection is its the first and the most important step. For flooding analysis, the data that are relevant to runoff generation and stormwater transportation are all needed. Examples are given below.

4.3.1.1 Drainage Systems

Drainage system data are the basic information to describe the geometric features of sewer system elements and surface channels. They include:

- Complete data of sewer systems, e.g. nodes, conduits, weirs, pumps and gates, retention and detention facilities, their spatial attributes and operational functions; longitudinal profiles and cross sections of artificial channels;
- Topographical data that are necessary to present or extract surface channels, including the channel routes, flow directions and cross sections

4.3.1.2 The Hydrological Data

The hydrological attributes of the studied area can be described by a series of pertinent parameters, for instance catchment and subcatchments, catchment area, slope, length, width and shape, the percentage of imperviousness, flow direction and flow path, land use, or soil type etc. Accordingly, the following data are required:

- Precipitation data and design storms;
- Digital topographic data, including contour lines and elevation points, their up-to-date data version and any storage of the previous version of the data required;
- Land use types, which reflect the percentage of imperviousness and the rate of infiltration of the study catchment;
- Other distinctive information, which reflects any depression, or storage capacity of the catchment.

4.3.1.3 The Hydraulic Data

When flow proceeds in pipes or on surface, the information, which represents or reflects the flow hydraulic performance in the systems, should be collected:

- Sewer hydraulic parameters, such as sewer material and Manning coefficient; sewer expansion and abstraction coefficient; change in direction and elevation of sewers and relevant loss factors; outlet shape of manhole and loss coefficients, overflow and energy loss coefficient etc.
- The Manning coefficient of surface channels.

4.3.1.4 Other Data

In addition, the following data are also needed for flooding analysis. They are:

- Dry weather flow (DWF);
- Domestic water consumption for combined sewers;
- Boundary conditions at upstream and downstream of the sewer systems and surface channels.

4.3.2 GIS in flooding Analysis

As introduced in an earlier section of this chapter, GIS technology has been applied in broad fields and disciples. Flooding analysis is among such applications. Samples of GIS related flooding analyses are displayed in Fig.4.4.

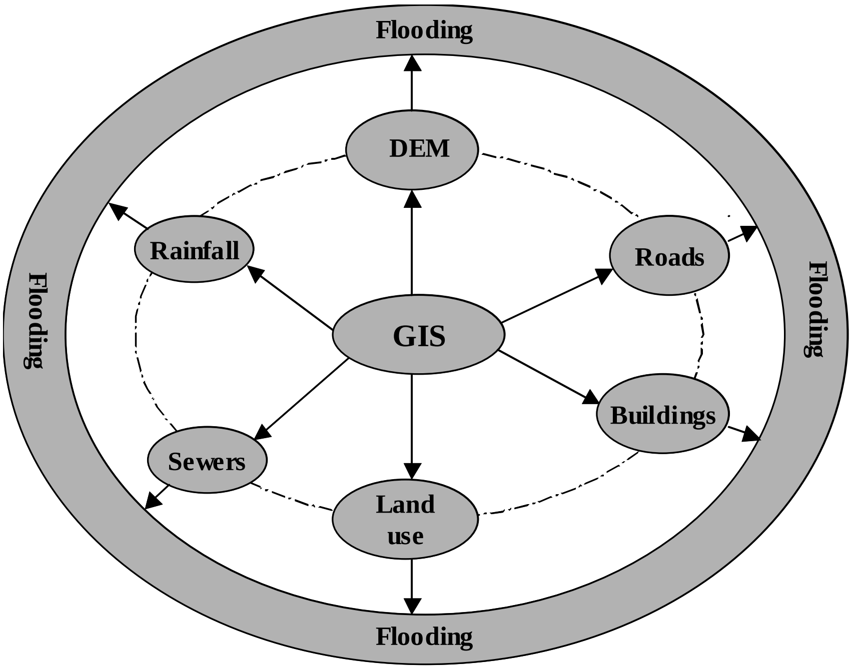


Figure 4.4 GIS based applications in flooding analysis

4.4 Case Studies

With respect to different flooding situations, two case studies, Trondheim, Norway and Jingdezhen, China, are applied in this section to carry out the following analyses: (1) Present DEM models; (2) Delineate major hydrological products; (3) Check the status of existing sewers; (4) Analyze the risk of flooding.

4.4.1 Trondheim Case Study

4.4.1.1 General Situation of Study Area

Trondheim, or Nidaros, as it used to be called, was the first capital of Norway. Now it is the third largest city. It is situated along the Trondheim fjord as displayed in Fig. 4.5. The study area is about 137km^2.

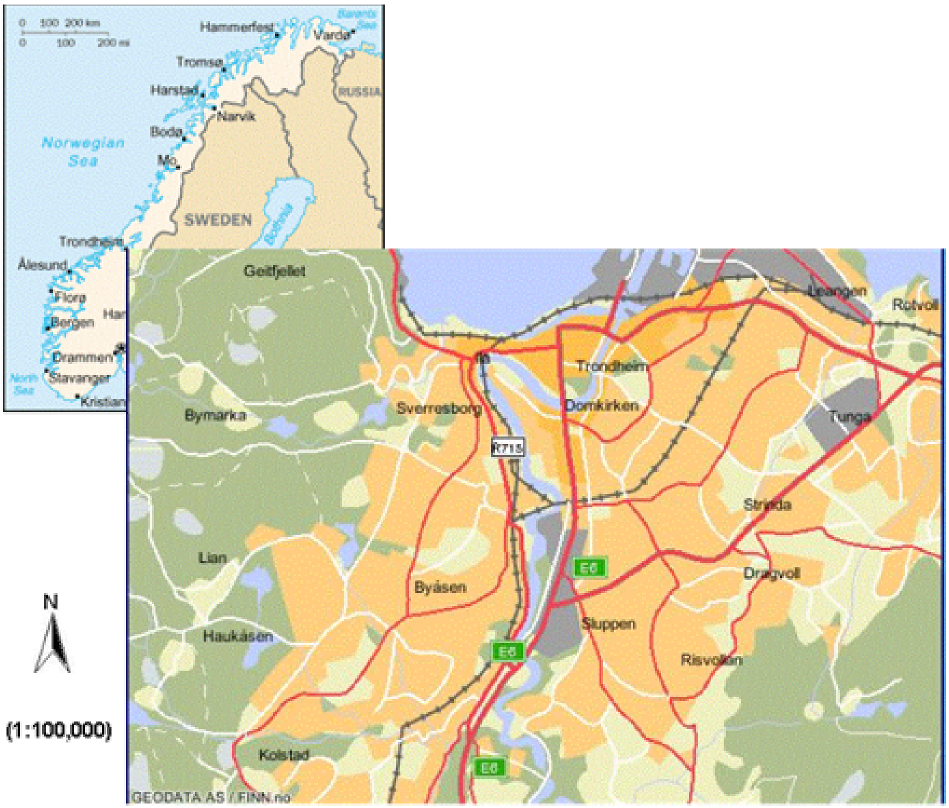


Figure 4.5 Map of Trondheim

The available digital data of sewer systems, topography and other spatial objects on terrain make this case study possible. All the digital data used in this thesis are produced in SOSI data format, which is described in Appendix D. The three different elevation systems are illustrated in Appendix E.

4.4.1.2 Precipitation Distribution

Precipitation, the major cause of flooding, varies with spatial locations both horizontally and vertically. The average annual precipitation in Trondheim varies with altitude is displayed in Fig. 4.6 (Killingtveit, 1998).

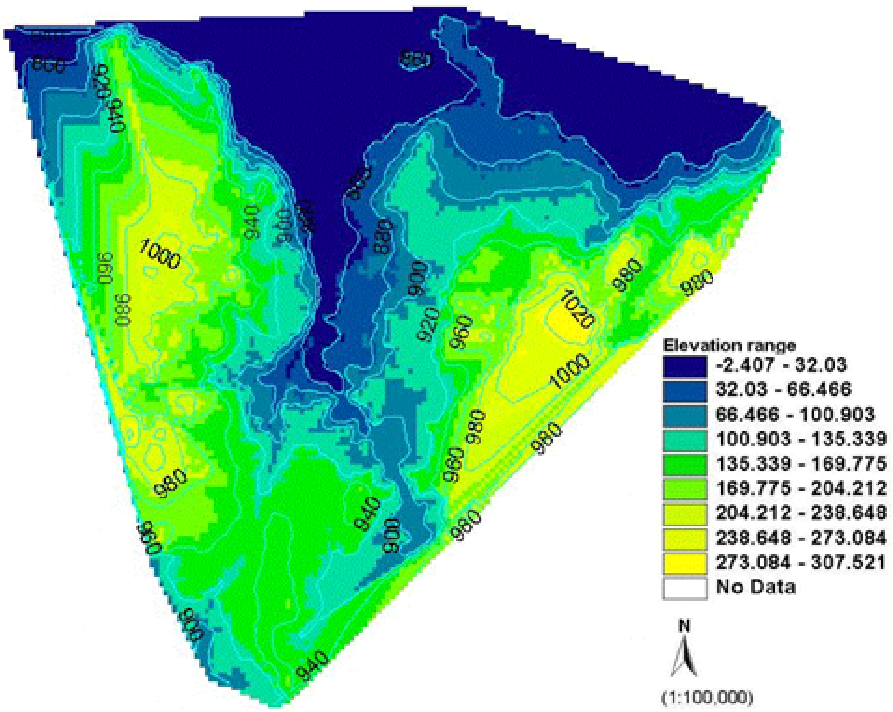
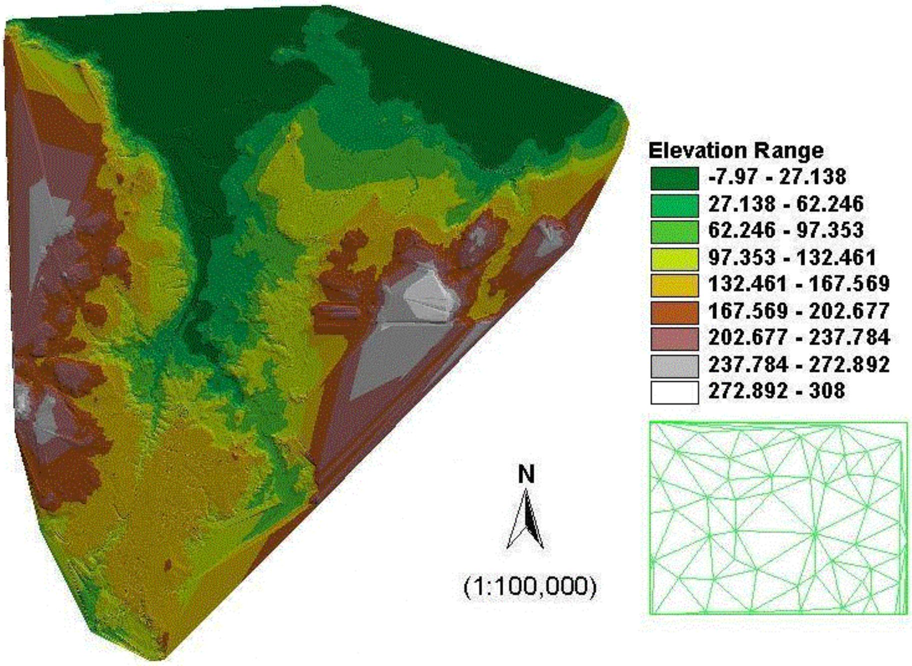


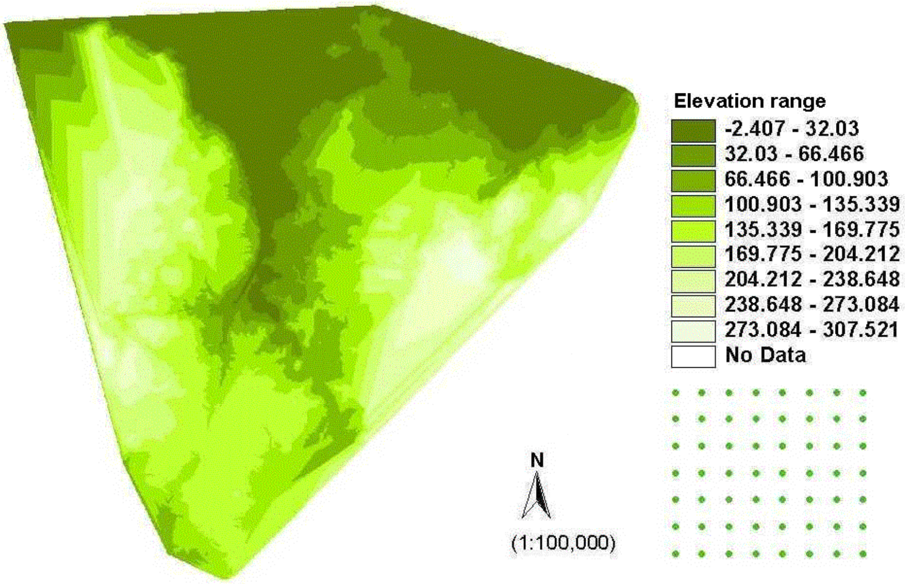
Figure 4.6 Distribution of average annual precipitation along altitude in Trondheim

4.4.1.3 The TIN and GRID DEM Model of Trondheim

The TIN model of DEM displayed in Fig. 4.7 (a) is created using the 3D Analyst of ArcView GIS; then it is converted to a regular GRID DEM model with resolution of 20m*20m (Fig. 4.7 (b)). These two representations show a "U" shaped terrain with higher lands at eastern and western sides, the Nidelva river meanders through the lower land areas of the city from southeast down to the fjord in the north.



(a) TIN Model



(b) GRID Model

Figure 4.7 Digital Elevation Model (DEM) of Trondheim

4.4.1.4 Watersheds Derived From GRID DEM

Different sizes of watersheds can be derived from GRID DEM, and the primary watershed characteristics can be calculated as well. Samples of watersheds derived from the grid of 20*20m with threshold value of 10,000 cells in each watershed are displayed in Fig. 4.8.

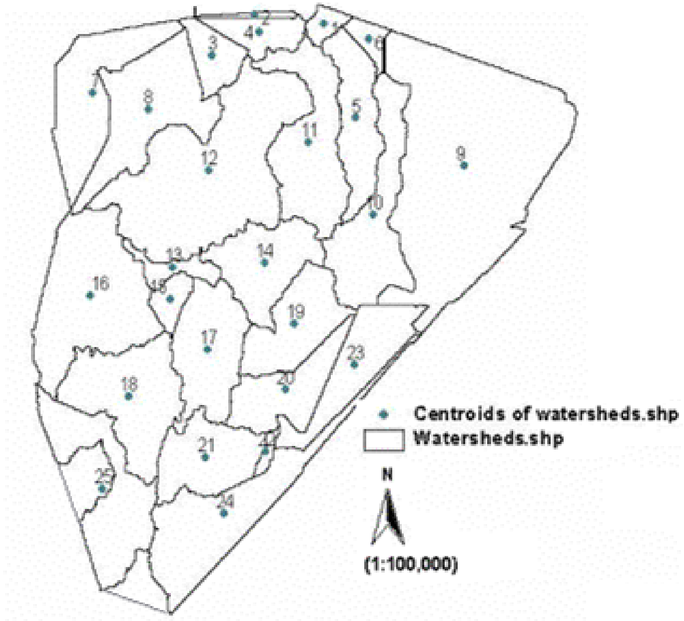


Figure 4.8 Sample of watersheds derived from grid DEM (cell size: 20m*20m)

As displayed in Fig.4.8, the study area is divided into 25 watersheds. The primary characteristics of each watershed are automatically calculated by the program and given in table 4.1.

Other watersheds created by different grid cell resolutions and watershed sizes are displayed in Appendix F, where cell sizes of 20m*20m and 1m*1m are applied respectively. Obviously, the smaller the grid cell size is, the better representation of surface features is, but the larger the PC storage space and memory are needed and the longer the data processing time takes. In addition, the influence of buildings has been studied and displayed in Appendix F as well. The comparison of generated watersheds with and without including buildings is given in table 4.2. The results indicate that the smaller the watershed is, the larger the influence of buildings is. Therefore, the resolution of the grid model, the size of watersheds and the influence of buildings should be carefully specified according to the needs of applications.

Table 4.1 Characteristics of watersheds

BASINID	CENTROIDX	CENTROIDY	BASINAREA	PERIMETER	MFDIST	MEANELEV	BASINSLOP
2	871.5	3120.0	266800	6400	23465	2.79	1.394
1	3091.5	2810.0	708400	4840	17856	21.50	4.555
4	1031.5	2510.0	1918800	9040	23209	10.45	2.869
10	4681.5	-1330.0	6472800	21120	10526	160.23	6.006
6	4381.5	1510.0	400	80	17029	1.61	0.396
3	-8.5	1980.0	1964000	8320	7621	2.35	0.536
7	-3498.5	590.0	6047200	17600	7234	127.40	4.110
8	-1768.5	390.0	7216800	20800	6910	56.88	4.907
5	3741.5	350.0	4312400	16200	6193	58.55	3.564
11	2361.5	70.0	6947600	22360	7806	81.70	3.268
12	-378.5	-530.0	14923200	29520	20627	66.06	5.737
13	-1118.5	-3180.0	1193600	10960	13172	97.75	7.132
14	1341.5	-3430.0	4854000	15440	4817	94.47	6.532
9	7061.5	-1110.0	22559600	32080	15776	97.03	6.365
15	-1128.5	-4190.0	1059200	6160	8573	74.03	10.289
19	2261.5	-4530.0	4593600	13760	5219	142.21	6.660
16	-3078.5	-4110.0	9782400	20640	6782	179.24	8.161
17	-58.5	-5460.0	5546400	16000	12281	77.72	8.695
20	2061.5	-5960.0	4031600	14800	8345	149.66	7.180
23	3701.5	-6020.0	4582400	17800	6057	222.24	5.791
22	1441.5	-7860.0	330400	4160	6568	90.83	7.078
18	-2488.5	-6780.0	6923200	18480	4886	148.31	6.677
21	-38.5	-7980.0	4492000	13120	5624	141.28	4.465
25	-2128.5	-8760.0	6346800	23160	8644	156.01	4.955
24	1881.5	-8430.0	7640400	30680	6065	145.60	6.273

Table 4.2 Watershed resolutions and the influence of buildings

Watershed division (No. of cells)	**Number of watersheds**	
	With buildings	**Without buildings**
1	96265	98410
100	1807	1811
500	350	333
1,000	184	179
5,000	43	43
10,000	23	23

*Grid cell size of 20m*20m is used in the watershed delineation.

4.4.1.5 Stream Networks

The stream networks displayed in Fig. 4.9 are delineated from GRID DEM of 20m*20m in terms of a series of threshold value of streams: 10,000-, 1000-, 100 cells and 1 cell respectively in each level of streams. Other resolutions of stream networks including the influence of buildings are given in Appendix F.

Stream networks are very valuable for deciding flow paths in case of surface flooding and for designing or modifying the layout of existing sewers. Fig. 4.10 displays the natural streams and the delineated streams. Apparently, the major streams fit well with the natural ricers.

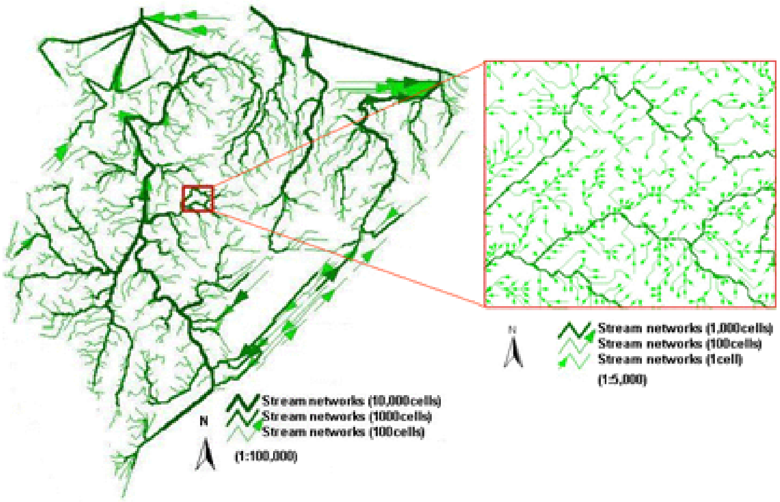


Figure 4.9 Stream networks delineated from GRID DEM of 20m*20m

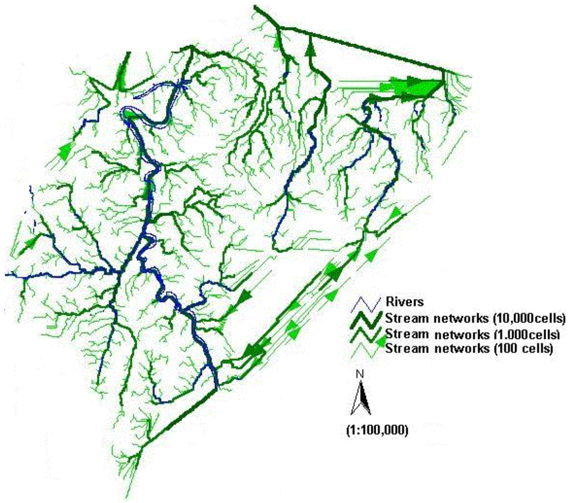


Figure 4.10 Comparison natural rivers and delineated streams

4.4.1.6 GIS Based Preliminary Analysis of Flooding

The risk of flooding generally depends on the distribution of rainfall, the topography and the drainage systems. Regarding to its meteorological and topographical characteristics as well as geographical location of Trondheim, there exist three major potential threats of flooding: flooding from the river Nidelva (Fig.4.5), flooding in urban drainage systems and the influence from the sea.

During heavy rainfall period, or snow melting time, the surface streams might be full of their capacities. Generally, the closer to the major streams, the lower lying and the flatter area are, the higher risk of flooding will be. Based on this point of view, the flood risk zones in Trondheim are identified and displayed in Fig. 4.11. Where, the risk zones 1 and 2 present the subcathments that connect to the stream level I and II respectively. In addition, the three highlighted areas were among the areas flooded in 1997 and 1999.

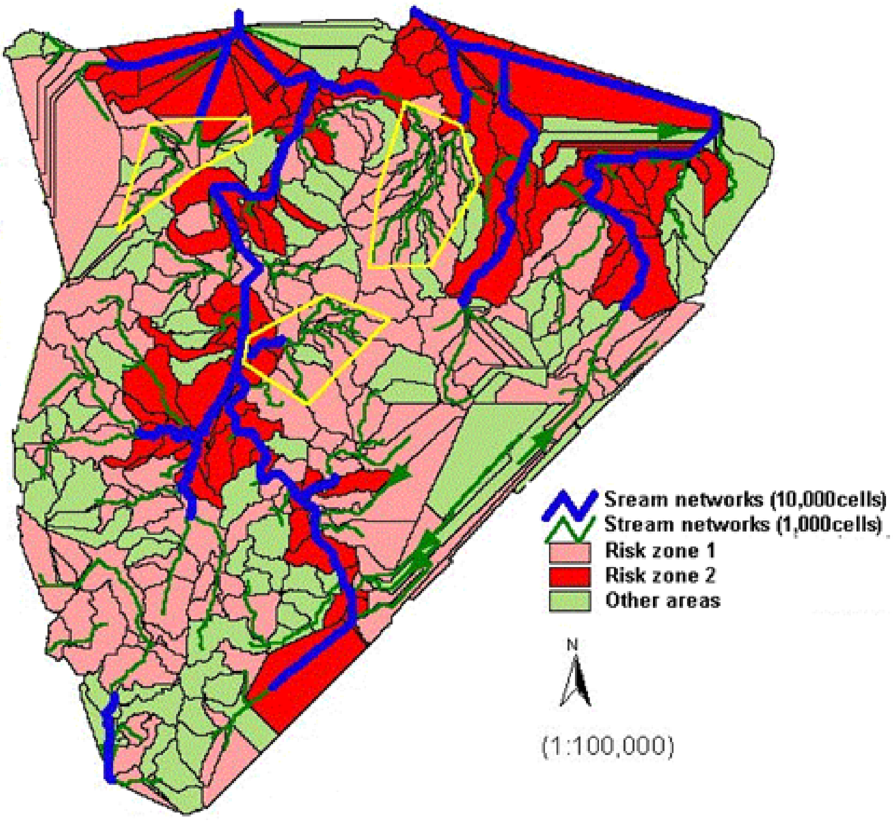


Figure 4.11 The potential flood risk zones of Trondheim

As displayed in the following Fig. 4.12, Nidelva originates from the Selbu Lake, which receives discharge from the Nea river upstream. Nidelva runs through forest and farmland areas in the Klæbu municipality down to meet Leirelva, one tributary comes from Trondheim Bymark and merges to Nidelva at Sluppen Bridge. Further on, Nidelva flows through the city center of Trondhiem and merges to Trondheim Fjord.

Figure 4.12 River systems and river catchment description of Nidelva (Kartulf, 2003)

The flow rate in Nidelva gradually increases when it passes through the city. The flow variation between flooding period and low flow period is decreased due to the regulation of Selbu Lake. For that reason, it is the Selbu Lake that protects Trondheim from the risk of river flooding. Moreover, the normal discharge of Nidelva in winter is relatively stable and is about 110m^3/s, which is far less than 1 in 10 years' flow discharge of 567m^3/s (Hagen, 2000).

Therefore, the risk of flooding of Nidelva is reasonably low. Several studies have got the similar results (Geir, 2000; Bævre, 2001; Nie and Schilling, 2001).

In contrast, some areas in the city of Trondheim highlighted in Fig. 4.11 had been flooded due to large runoff generated by heavy rainfall, or rainfall plus melt snow, or encountering sewer problems such as hydraulic bottleneck, backwater caused by high tides in Trondheim fjord (TM, 1988-1999; Milina, 1999; IF, 1997-2000). Some observed damage cases in 1997 and 1999 are displayed in the following Fig.4.13 ~ 4.15.

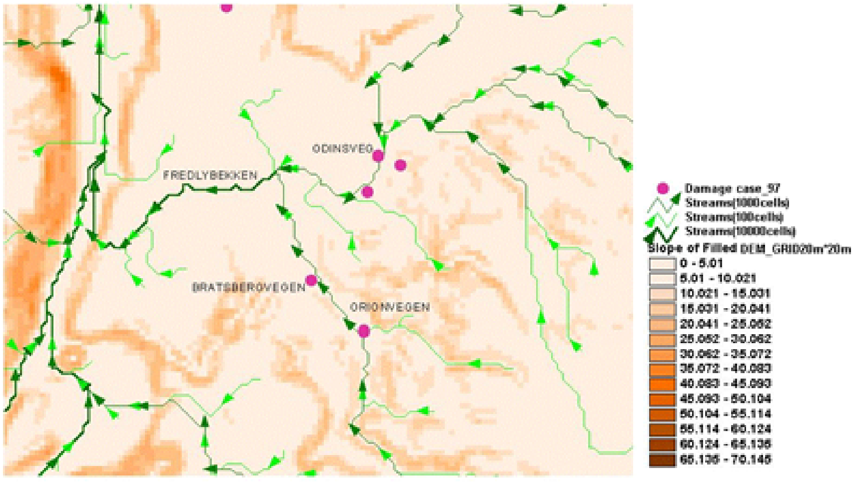


Figure 4.13 Observed flooding events in Trondheim, 1997

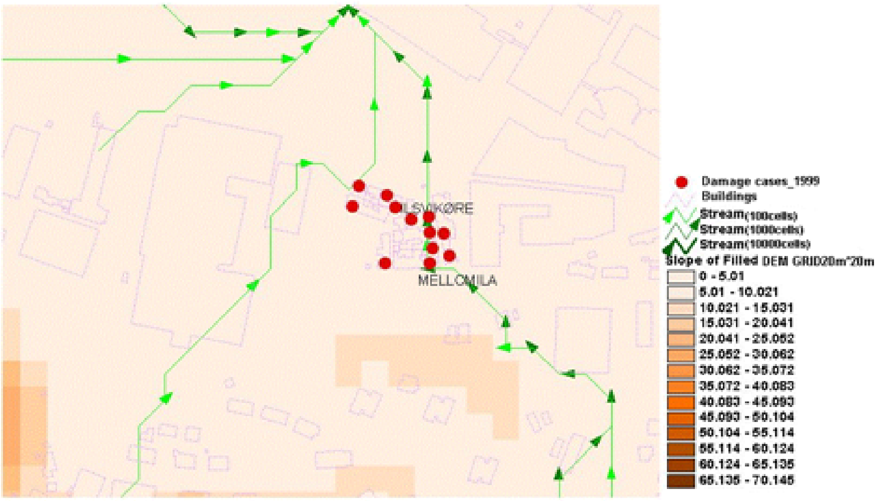


Figure 4.14 Observed flooding events in Trondheim, 1999

Fig. 4.13 and 4.14 clearly display that the flooding events occurred in the areas with densely surface streams. Figure 4.15 shows flooding events in 1999, where some basements were flooded by higher sea level. Meanwhile, it also displays some inland flooding events without the influence of the sea level.

Overall, from the preliminary analysis of flooding for Trondhiem case study, it is concluded that attention of flood control should be paid to flooding of urban drainage systems in addition to probable large river flooding.

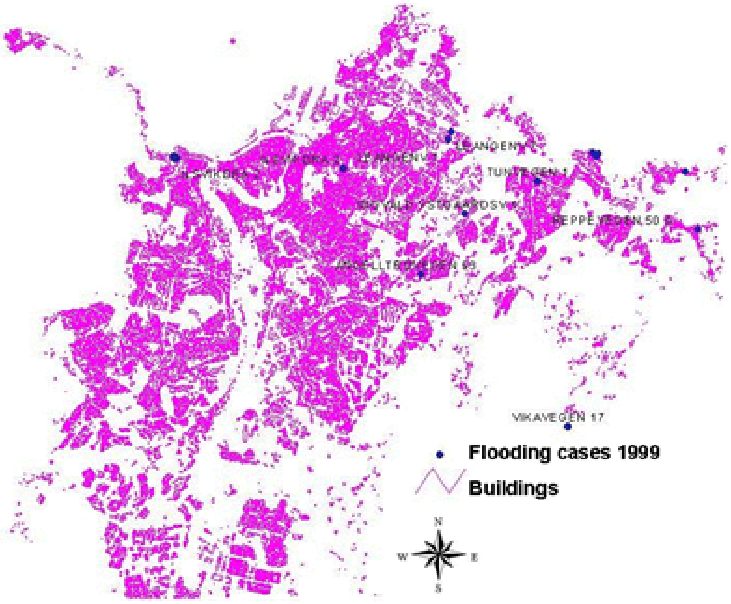


Figure 4.15 Example of basement flooding events in Trondheim, 1999

4.4.1.7 The Status of Sewer Systems

In addition to understanding the characteristics of precipitation and the features of topography, knowing the status of existing sewers is important for flooding analysis and for sewer system performance. Taking the Fredlybakken catchment in the city of Trondheim as an example, the system components and the present status are carefully checked by using GIS tools. The errors in sewer database and the potential deficiencies of existing sewer systems are identified and displayed in Appendix G.

Examples are given in Fig. 4.16 and 4.17 to demonstrate the potential vulnerable sewers. In Fig. 4.16, sewers from node 447659 to node 25980 may have higher risk of flooding because two large subcatchments connect to this part at manhole 447659 and 447632, i.e. large amount of surface runoff may flow into the system at these two manholes, where there is no equivalent increase in sewer size. Thus, flooding may be caused due to insufficient capacity in this area. The observed flooding cases (Fig.4.16) proved the analysis. Fig. 4.17 displays another damage case, the highlighted house was flooded 2000 (TM, 2000) due to insufficient sewer capacities. The sewers were changed after flooding.

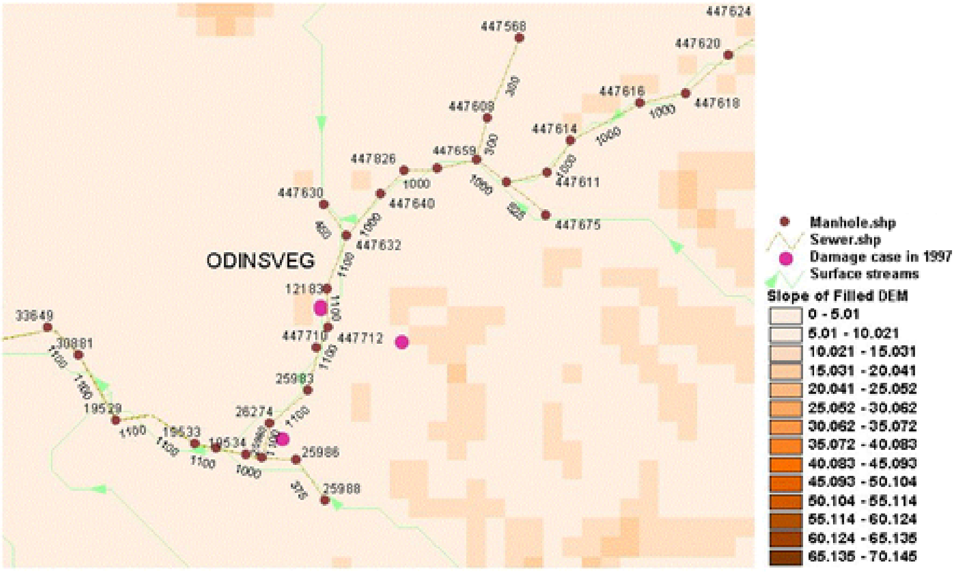


Figure 4.16 Potential vulnerable sewers and observed flooding cases in 1997

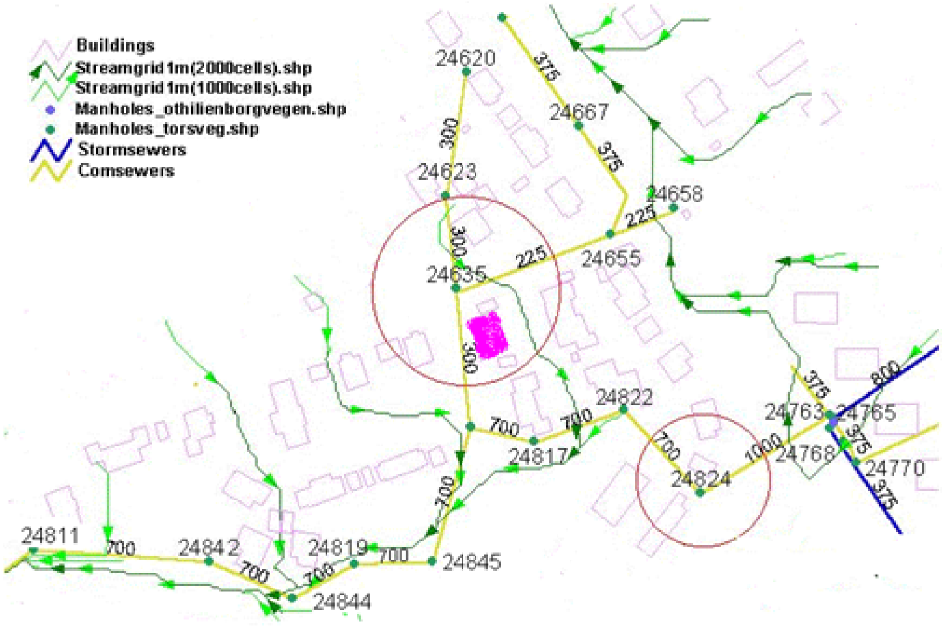


Figure 4.17 Sewer deficiency and observed flooding case in 2000

4.4.2 Chinese Case Study: The City of Jingdezhen

Another case study is carried out using GIS to analyze the risk of flooding of Jingdezhen city, Jiangxi Province of China. Due to lack of detailed digital data, this case had to be simplidied.

4.4.2.1 General Information

Jingdezhen is situated in Jiangxi province, the southeast part of China (Fig. 4.18). The city area is around 408 km^2 with population of 403,000. As displayed in Fig. 4.19, the Changjiang River flows through the city areas from north to south; one tributary, West River, flows from west to east and converges into Changjiang River at Sanlvmiao. Another tributary, Nanhe River flows from east to west and joins the Changjiang River at the southern part of Xiguazhou.

The Yutian reservoir situates at upstream of the Nanhe River, 19km from Jingdezhen city. The large discharge of Yutian reservoir at flood period threats the downstream areas being along the Nanhe River banks.

Higher mountains surround the lower city center of Jingdezhen. The elevation varies from 13m to 218m above the Yellow sea level in that region. However, the city center locates lower at elevation of 20m to 50m. A GRID DEM is displayed in Fig. 4.20.

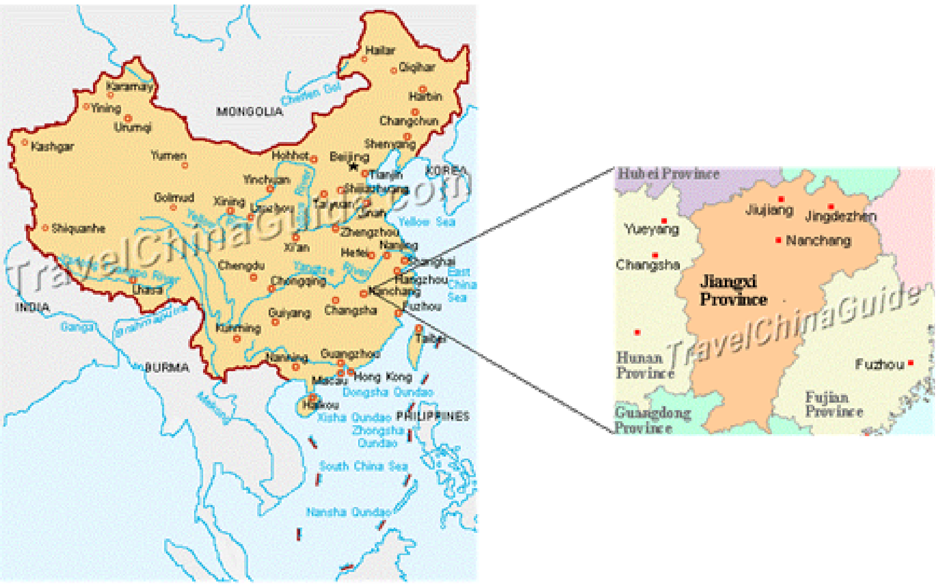


Figure 4.18 Geological location of Jingdezhen city

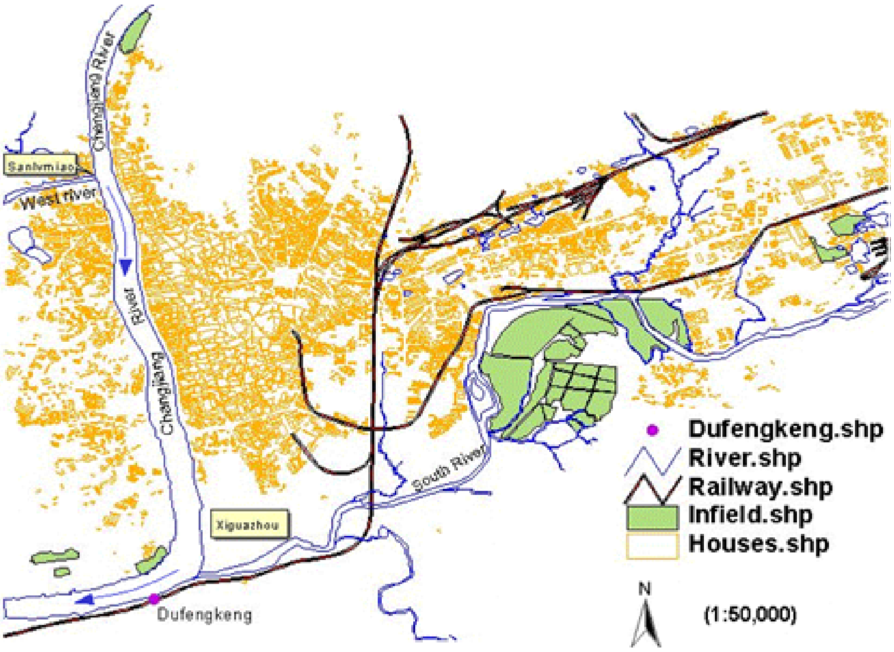


Figure 4.19 Digital map of Jingdezhen city

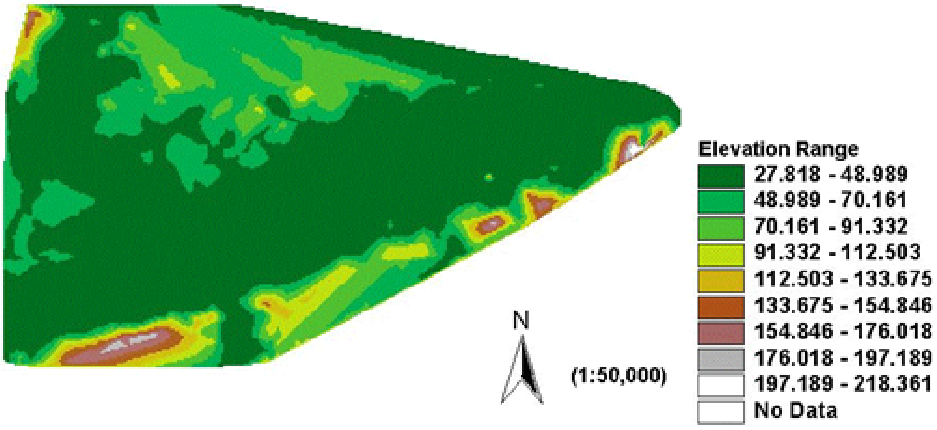


Figure 4.20 GRID DEM of Jingdezhen city (cell size: 5m*5m)

4.4.2.2 The Characteristics of Storms and Historical Floods

The weather of Jingdezhen city belongs to the subtropical climate with mild winter and hot summer with ample rainfall. According to the statistics, 46 % of the annual rainfall occurs in April to June. After July, due to the effect of the typhoon, there are frequently storms of short duration. The average annual rainfall is 1763.5mm, the maximum annual, daily and hour rainfall is 2673.6mm (1994), 228.5mm (June 18th, 1955) and 82.7mm (June 3rd, 1992) respectively. The floods are mostly triggered by storms from April to June. After July, floods are generally caused by Typhoons. In addition, continuous flood peaks might occur because of series of subsequent storms. A single flood peak usually lasts 2-5 days, whiles double or multiple floods peaks will take more than 6 days.

According to flood records, the investigation of historical flood events and statistical analysis, the most severe floods happened in 1884, 1916 and 1942, and the corresponding flood peak discharges were 13000m^3/s, 11000m^3/s and 10000m^3/s respectively.

In addition, large floods attacked the city in 1955, 1996, 1998 and 1999 as well. The main characteristics of floods and the gross damage are given in table 4.3.

Table 4.3 Characteristics of floods and gross damage of the large flooding events in Jingdezhen since 1949

Time	**Water level at Dufengkeng station*(m)**	**Flow rate at Dufengkeng station* (m^3/s)**	**Causes**	**Inundation areas (km^2)**	**Economic damage (Million Yuan)**
1955	33.85	8500	Heavy storm		
July 1, 1996	33.18	7580	River flooding plus storm	15.0	1305
June 26, 1998	34.27	8640	River flooding plus storm	21.4	1593
July 23, 1999	31.94	5960	River flooding plus storm	9.2	713

* Dufengkeng is the only hydrological gauge station at downstream of the Changjiang River in Jingdezhen, see Fig. 4.19.

4.4.2.3 Flood Risk Zones

Unlike the Trondheim case, major risk of flooding in Jingdezhen comes from the rivers, i.e. the Changjiang and the Nanhe River, flowing through the city. During large storm periods, flash floods from upstream hilly areas hit the city. Meanwhile, large discharges also come from the Nanhe River. Moreover, the flooding in urban areas was deteriorated because of the insufficiency of the storm drainage systems (JDZ, 1999).

The potential flood risk zones are delineated from DEM and displayed in Fig. 4.21. Flood map of 1 in 50 years is highlighted in Fig. 4.22.

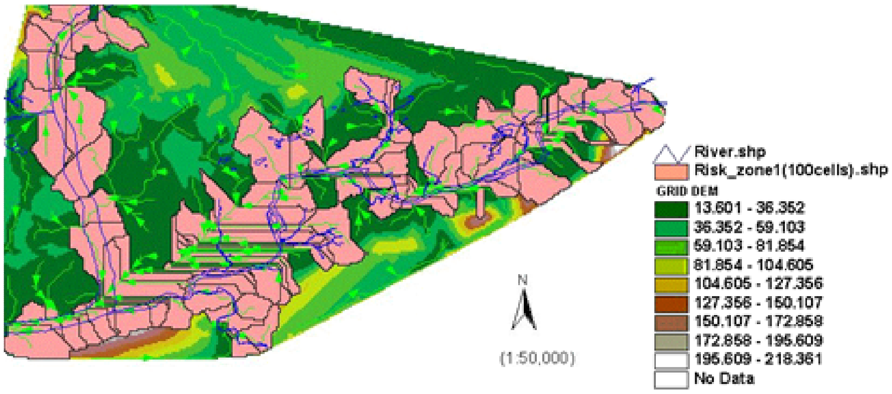


Figure 4.21 Flood risk zones of Jingdezhen

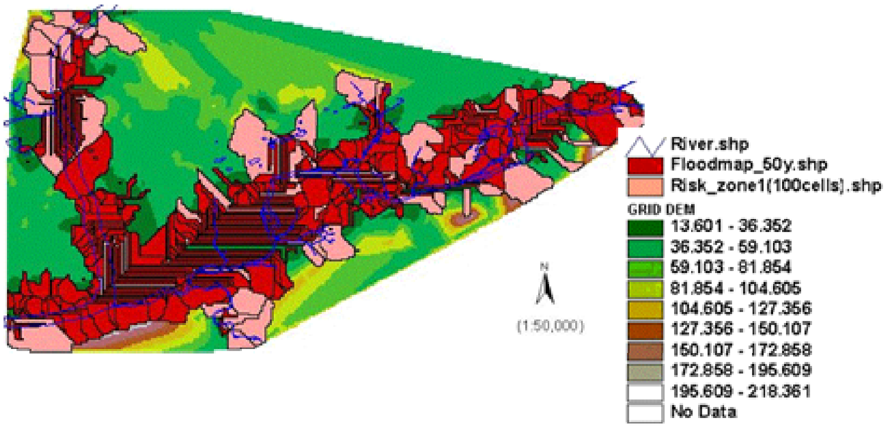


Figure 4.22 Flood risk map of Jingdezhen for flooding of 1 in 50 years

As displayed in Fig. 4.22, the flood areas of 1 in 50 years (dark red) are among the delineated potential flood risk zones (light red). It is concluded that as soon as the rivers are full, the low areas besides rivers have higher risk than other areas. In such cases, advanced flooding simulation should be performed to make accurate flood maps.

4.5 Summary

Main results and conclusions Chapter four introduces basic GIS concepts and two important spatial analysis models: TIN and GRID DEM model. They are applied for hydrological analysis to delineate watersheds and stream networks on the surface. Two case studies are introduced to examine these models and methods.

The following analyses have been carried out in the Trondheim case study:

Digital Elevation Models (DEM) in TIN and GRID format are created. Two different grid resolutions with cell sizes of 20m*20m and 1m*1m are studied. It indicates that the smaller the cell size is, the more accurate of the DEM, but the large PC storage space and memory is needed and the longer the data processing time takes. Therefore, appropriate grid cell size must be defined according to the needs of applications in order to get the desired results under reasonable time and cost control.

Two major hydrological products, watersheds and stream networks, are delineated from DEM. Meanwhile, the sizes of watersheds and the levels of stream networks are analyzed. The analysis reveals that size of watersheds and levels of streams can be produced flexibly to meet the requirements of applications and under reasonable time and cost control. In addition, the influence of buildings on the delineation of watersheds and streams are studied. The smaller the watersheds and the finer of streams, the more sensitive the influence of buildings is. Similarly, it depends on the needs of applications whether the influence of buildings is considered or not.

As an example, the status of the existing sewer systems of Fredlybekken catchment in the city of Trondheim is carefully checked using GIS.

Watersheds, stream networks and sewer systems are important intermediate products for flooding analysis. On this point of view, Chapter four produces basic data for Chapter five.

In addition, the preliminary flood risk is studied in the two case studies: Trondheim in Norway and Jingdezhen in China. The Trondheim case study indicates that more attention should be put on sewer flooding and flooding from small streams in the city. There exists the risk of flooding from the river, Nidelva, but it is relatively lower due to the regulation of the Selbu Lakes upstream.

Unlike the situation in Trondheim, the major risk of flooding in Jingdezhen originates from the rivers passing through the city. Large discharge may come from upstream hilly areas during storm period. As the rivers are at their capacities, the topography, particularly the elevation and the slope, dominates the magnitude and consequences of flooding.

The above case studies illustrate that GIS builds a bridge between digital data and applications. It is a useful analytical tool in flooding analysis.

Restrictions and suggestions for further research It should be noticed that the delineation of watersheds and stream networks simply neglects the soil condition, or in other words, it assumes that the soil is saturated. Therefore, the soil infiltration is actually not taken into consideration in the analysis. Besides, the depressions, so called "pits" or "sinks" on DEM, are filled by the hydrological modeling to ensure continuous flow paths on surface. Moreover, as the terrain based GIS flooding analysis does not take hydrodynamic effects into the account, numerical simulation using hydrological and hydraulic should be applied.

Finally but very important, the quality of digital data dominates the accuracy of analysis to a large extent. Digital data are generally produced by special map departments for administrative purposes, although they have been increasingly used for research, planning and operation. The two case studies in this chapter indicate there is still a gap between available data and the need for special applications. Therefore, the cooperation between data producers and users is encouraged.

Chapter 5

Development of Urban Flooding Models and Flooding Simulation

A mathematical model is a simplified representation of a physical system in reality. Through a group of structures, equations and assumptions, it describes how this system works in reality.

5. DEVELOPMENT OF URBAN FLOODING MODELS AND FLOODING SIMULATION

The aim of Chapter five is to develop models and procedures to simulate flooding of urban drainage systems, i.e. flooding in underground sewers and on the surface. Two models are developed on the basis of the MOUSE model (DHI, 2000b). All together, three flooding models are introduced in this chapter:

- Model I: MOUSE model. Emphasis is given to the fictitious surface flooding tank;
- Model II: "basin" model. It is developed based on the "basin" structure in the MOUSE model;
- Model III: dual drainage model where both sewer flow and surface flow can be simulated simultaneously by combining several structures in the MOUSE model.

The techniques of GIS are incorporated into the modeling development.

The above three models are examined using two case studies.

5.1 Mechanism of Urban Flooding

Urban flooding is greatly different from the flooding in rivers and river flood plains. It is characterized by underground sewer systems, surface open channels, such as roads, walking paths, other open spaces, and underground structures, for instance basements, subways and other underground plots etc. Moreover, urban flooding may be affected by receiving waters, particularly in coastal or estuary areas. Therefore, the mechanism of flooding in urban areas is rather complicated. The following physical progresses should be taken into account:

- Rainfall-runoff;
- Flow in separate, or combined sewer systems;
- Flow along surface streams;
- Flow or ponding in other open surface spaces;
- Flooding in basement or other underground structures, and
- Flow exchange between different parts of the drainage systems.

The above descriptions of flows in urban drainage systems are illustrated in Fig. 5.1.

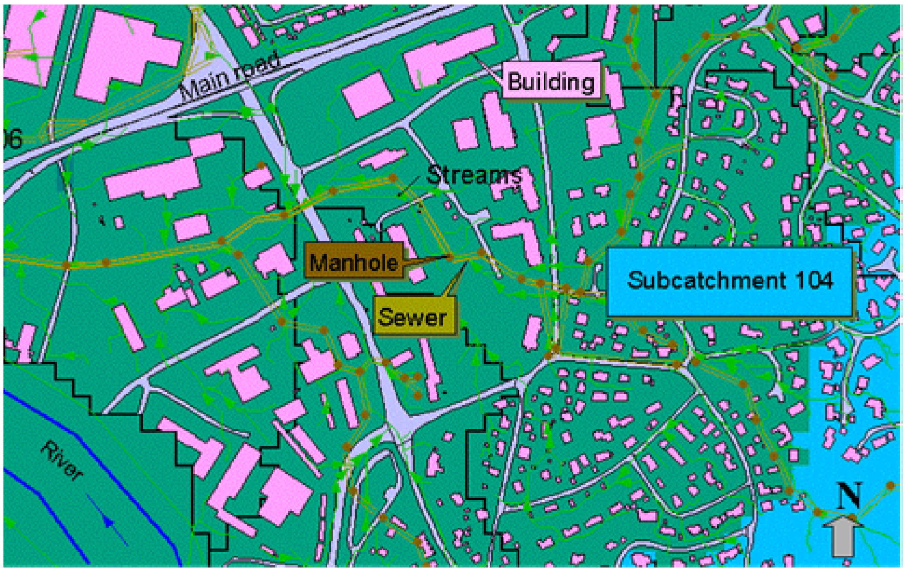


Figure 5.1 Sketch of urban drainage system

5.2 Needs for Urban Flooding Model Development

A detailed overview has been given in Chapter two. The prerequisites for flooding model development are summarized into following aspects:

a) The need for topographic data with good quality, i.e. sufficient accuracy to perform the flooding analysis, good resolution in horizontal and vertical profile, and different temporal resolutions;

b) The need for sewer data with complete information to carry out sewer simulation;

c) The need for observed meteorological and discharge time series to calibrate the developed models;

d) The need for informatics tools to process, analyze the available data and to present the analytical results;

e) The need for advanced hydrological and hydraulic model to deal with rainfall runoff, pipe flow and surface flow, as well as their interaction.

The GIS-based analyses performed in Chapter four produce watersheds and stream networks that are very useful for flooding simulation. In addition, they also provide very detailed sewer information. On these bases, Chapter five will focus on the development of urban flooding models in combination with GIS.

5.3 Components of Urban Flooding Model

As described in previous sections, a comprehensive urban flooding model should be able to cope with rainfall runoff, flow conveyance both in underground sewers and on the surface, and to consider the storage in basements or other underground structures. In addition, proper structures and functions should also be designed to model the water exchange between different parts of the system, and the water exchange between the system and its surroundings. Overall, an ideal urban flooding modeling package should embrace the sub-models included in the following Fig.5.2.

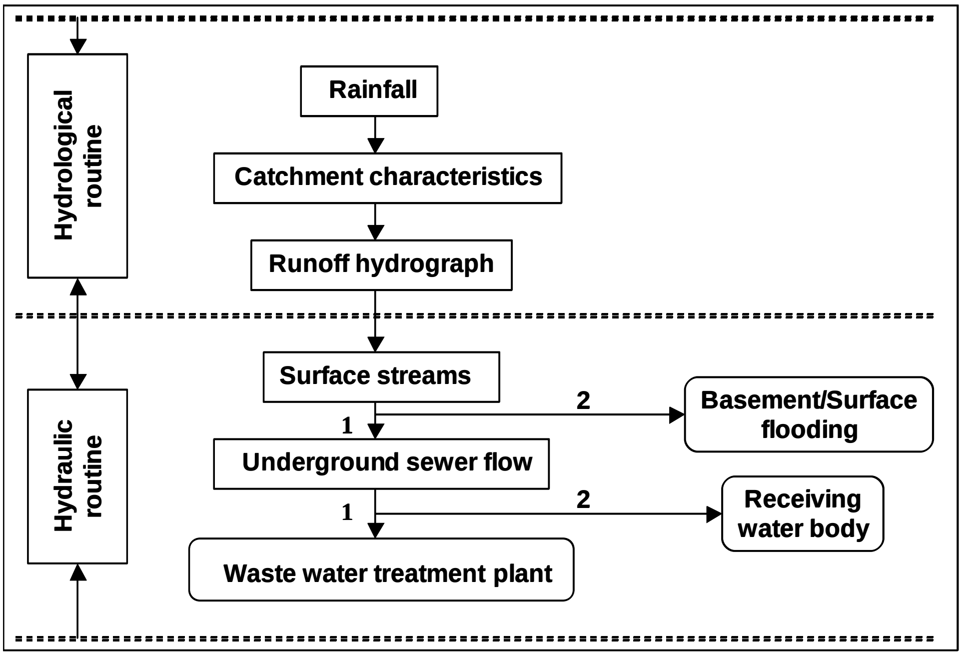


Figure 5.2 Components of urban flooding model

5.4 Introduction of Basic MOUSE Models

The flooding models are developed on the basis of the MOUSE software. Therefore, the basic MOUSE modules: rainfall-runoff model, pipe flow model and relevant structures as well as resistance calculation will be introduced in this section.

5.4.1 MOUSE Rainfall-Runoff Model A

The MOUSE runoff model A is constructed according to the ***Time-Area method***. It is assumed runoff is generated only from impervious areas, which is described by the percentage of total catchment areas in the model. The input rainfall is reduced by initial loss i_0, and the lumped, constant hydrological reduction F due to imperfect imperviousness and evaptranspiration, affected by the catchment shape (Fig.5.3) and the concentration time t_c (DHI, 2000). Therefore, the proportion of impervious areas, the initial loss, the hydrological reduction factor of imperviousness and the type of time/area curve as well as the concentration time of each catchment (subcatchment) have to be specified.

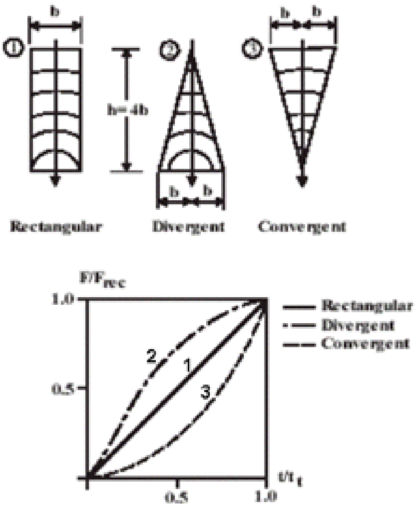


Figure 5.3 Standard MOUSE Time/area curve (DHI, 2000)

5.4.2 Governing Equations of MOUSE Pipe Flow Model

The MOUSE Pipe Flow Model is a computational tool for the simulations of one-dimensional unsteady flows in sewer networks with alternating free surface and pressurized flow conditions. The computation is based on the free surface, one-dimensional Saint Venant equation (Appendix K). Both subcritical and supercritical flows can be treated by means of the same numerical scheme, which adapts according to the local flow conditions.

In addition to the assumptions described in Appendix K, the following hypotheses are also applied:

- Lateral inflow $q_L = 0$;
- The water is incompressible and homogeneous, i.e. the variation in density is neglected;
- The wavelengths are large compared to the water depth. This ensures that the flow everywhere can be regarded as having a direction parallel to the bottom, i.e. the vertical acceleration can be neglected and a hydrostatic pressure variation along the vertical can be assumed.

Thus, the conservation of mass, i.e. the continuity equation, can be expressed below:

Eq. 5-1

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

The conservation of momentum, i.e. momentum equation, is expressed as:

Eq. 5-2

$$\frac{\partial Q}{\partial t} + \frac{\partial(\alpha \frac{Q^2}{A})}{\partial x} + gA\frac{\partial y}{\partial x} + gAS_f = gAS_0$$

Where:

Q = pipe discharge, [m^3/s];

A = flow area, [m^2];

y = flow depth, [m];

g = acceleration of gravity, [m/s];

x = distance in the flow direction, [m];

t = time, [s];

α = velocity distribution coefficient;

S_0 = bottom slope;

S_f = friction slope.

The mechanism described by the above equations is presented in Fig.5.4.

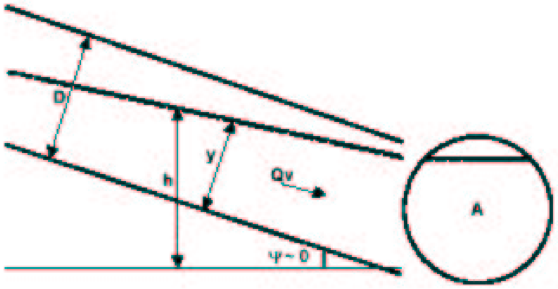


Figure 5.4 Sketch of pipe flow (DHI, 2000)

The solution themes to solve the above equations are described in Appendix K.

In addition, fictitious slot is introduced when the flow in sewers becomes surcharged, see Appendix L.

5.4.3 Energy Losses Described through Links, Manholes and Other Node Structures in MOUSE

In MOUSE, the energy loss caused by friction resistance in free surface conduits is introduced as friction slope into the momentum equation. The head loss in pressurized pipes is calculated on the basis of the continuity equation and pressure distribution. The losses at the node inlet and outlet, losses due to the change in flow direction and in elevation as well as loss due to contraction are expressed by the head losses through a node. More details are described in Appendix L and MOUSE reference manual (DHI, 2000).

5.5 Development of Urban Drainage Flooding Models

On the basis of the MOUSE model, two flooding models are developed. Including MOUSE virtual surface flooding tank, the three models will be introduced in this section.

5.5.1 Flooding Model I: MOUSE Fictitious Surface Flooding Tank

In MOUSE, a simple facility for simulating surface flooding is introduced in order to keep the water volume balance at each node. Where, if the water level in a node reaches the ground level, an artificial tank (Fig.5.5) will be automatically initiated above the node. The surface area of the tank is gradually increased from the manhole area at the node to an area of 1000 times larger. When the outflow from the node surmounts the inflow, the water stored in the artificial tank re-enters into the underground system again.

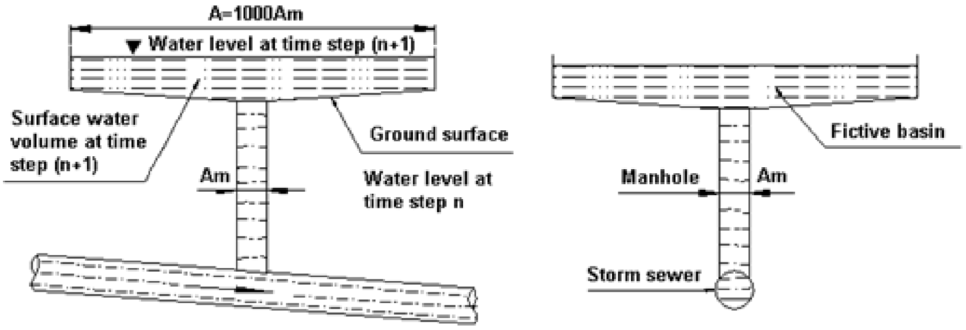


Figure 5.5 Surface flooding facility of the MOUSE program (DHI, 2000)

The MOUSE fictitious surface flooding modeling acts to keep the water balance at each node during flooding, but it does not take the proper flow exchange between sewer and surface into consideration. The water stored in a fictitious tank will go back to the system at the same node, which may not be true in reality. In addition, the fictitious tank of $1000A_m$ surrounding the flooding manhole represents hardly the real flood area and the flood routes in reality. Consequently, the simulation results of surface flooding based on this model might deviate from reality. This model needs to be improved.

5.5.2 Flooding Model II: “Basin” Model

Unlike flooding Model I, Model II treats manhole and surface storage above the manhole as a whole and runs it as one “basin” in MOUSE. A “basin” is defined at the location of each manhole and its storage is a sum of the volume of the manhole and the flooded areas on the surface between the two manholes as they specified from the topography.

Computationally, a “basin” is a type of node in MOUSE. Unlike manhole, a “basin” might have much larger volume. In addition, the structure of a “basin” (Fig.5.6) is expressed differently from the structure of a manhole in the MOUSE program (Appendix L).

5.5.2.1 Description of Surface Flooding “Basin” Model

As displayed in Fig. 5.6 (a), each basin is specified by a group of characteristic points: (1) the bottom of a manhole (pipe); (2) the top of a manhole, which is also the connecting section of a manhole and corresponding surface above the manhole; (3) the position of street curbs; and (4) a hypothetical position that the highest floodwater may reach. The structural features of a basin are defined by a group of parameters consisting of (H, A_c, A_m, K), where:

H = elevation at a specified point of a basin, [m];

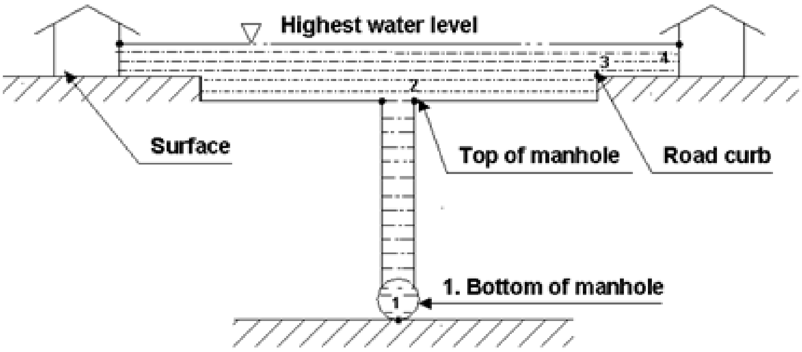
A_c = cross section area of flow at a specified position of a basin, [m^2];

A_s = water surface area at a specified position of a basin, [m^2];

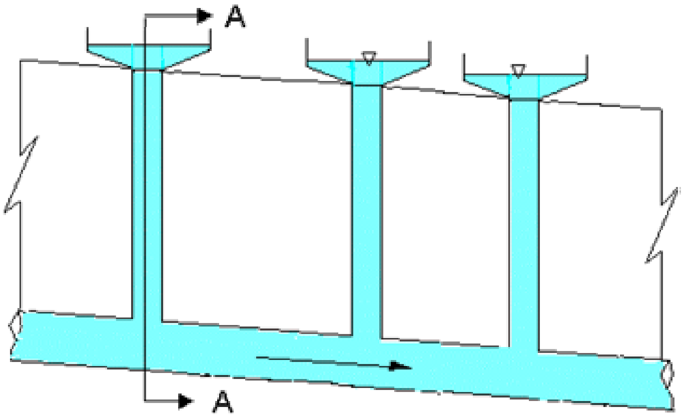
K = outlet shape of a basin.

Among them, the cross section area A_c is used to calculate the flow velocity at the basin, the surface area A_s to compute the water volume and water height of the basin, and the outlet shape of the basin, K, to estimate the energy loss through it.

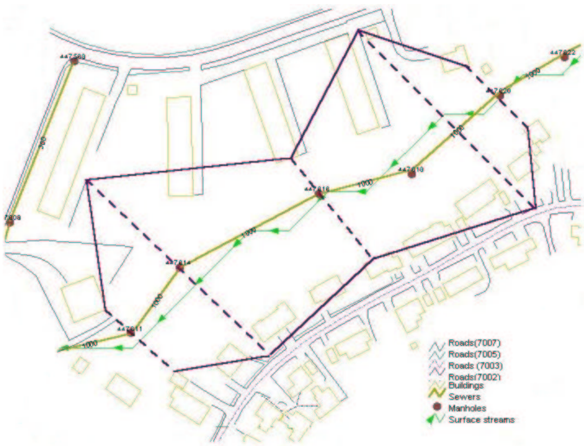
The parameter sets of point 1 and 2 can be taken directly from the sewer network data of MOUSE, whereas the parameters of point 3 and 4 have to be extracted from DEM in combination with the layout of roads and the position of buildings. The surface storage volume of the basin between two manholes is calculated by the volume of the manhole, i.e. the width of a basin at the location of the manhole, the distance between two manholes and the corresponding water level of the basin (Fig. 5.6 (a) and (c)).



(a). Cross section A-A of a “basin”



(b). Vertical profile of “basins” model



(c). Longitudinal profile of “basin” model

Figure 5.6 Structure of the “basin” model

5.5.2.2 Principles of “Basin” Model

The “basin model” is comprised of submodels of rainfall runoff, pipe flow and the routine of basin. The underlying theory of rainfall-runoff model and pipe flow model are the same as the MOUSE modules described in the earlier section 5.4. A “basin” is run as a node in MOUSE. Therefore, the options of nodes in MOUSE are applied for basins.

5.5.2.3 Discussions of “Basin” Model

The “Basin model” has been developed to consider sewer flow and the storage of manhole and surface flooded areas. In addition, the manhole and the surface flooded areas are treated as a whole, which guarantees a continuous water accumulation in each basin. Moreover, the basin is extracted from terrain DEM and the basin height is assumed very high to keep all the water within the basin. In flooding situations, the floodwater is the part of water from ground level of a manhole to the calculated water level in the basin.

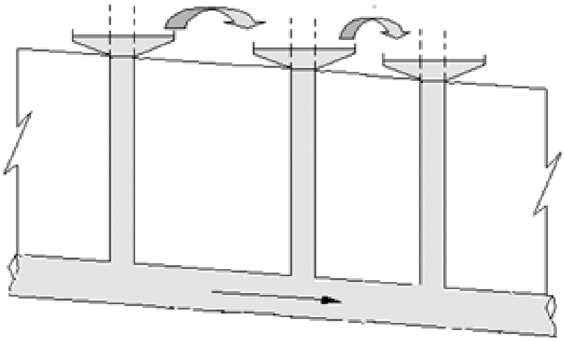
Comparing with the MOUSE fictitious surface flooding facility, the “basin” model fits the flooding surface better because the shapes and sizes of the basins are close to the real flooded areas. However, it still acts as a storage tank. The function to simulate the water transportation between two “basins”, i.e. the surface flooding, is not available yet. Thus, further improvement of the flooding model is still required.

5.5.3 Flooding Model III: Dual Drainage Model

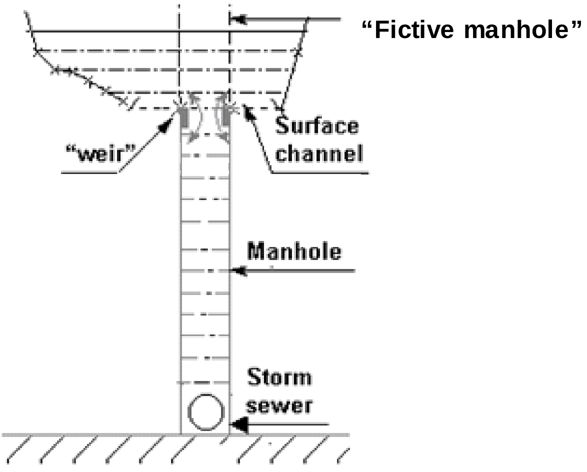
On the basis of Model I and II, the third flooding model, dual drainage model, is developed. It consists of underground sewers and surface channels. Fig. 5.7 illustrates this model, where, (a) displays the longitudinal overview of the flooding model, (b) and (c) show the cross section and the connection of different parts of the model.

5.5.3.1 Structure of Dual Drainage Flood Model

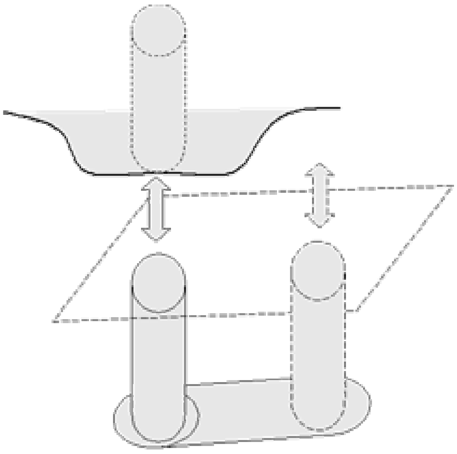
As illustrated in Fig. 5.7 (b) and (c), pipes and surface channels are connected by corresponding manholes at their bottom level and ground level respectively. At the top of each manhole, a fictitious weir is applied to transfer the water between the two layers, and where the water can flow in both directions between underground sewers and surface channels (Appendix L; DHI, 2000b). In addition, the original manholes are extended from their ground levels up to the levels where the expected maximum water levels on the surface may reach. These “fictive” manholes are used to connect flow in surface channels.



(a). Longitudinal profile of dual drainage model



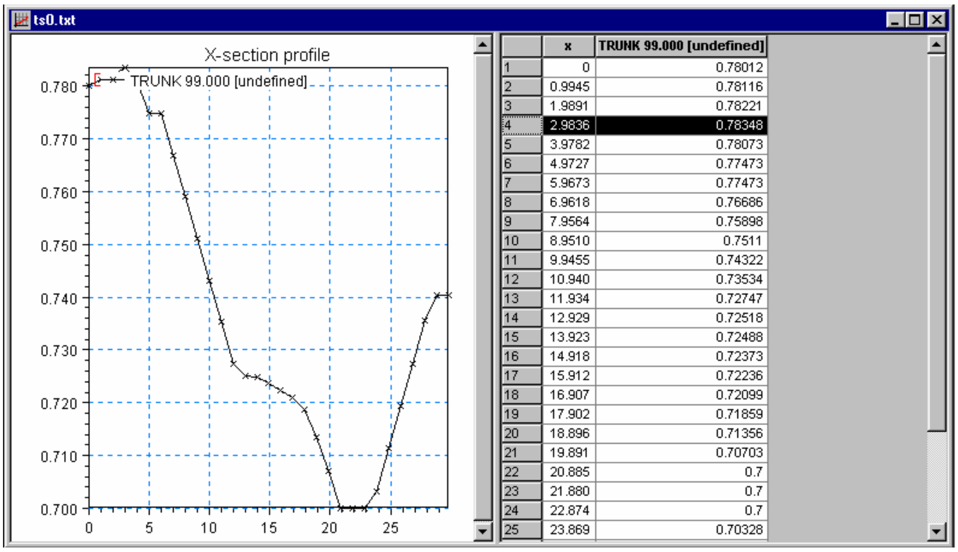
(b). Cross section of dual drainage systems



(c). Connection of underground sewer and surface channel

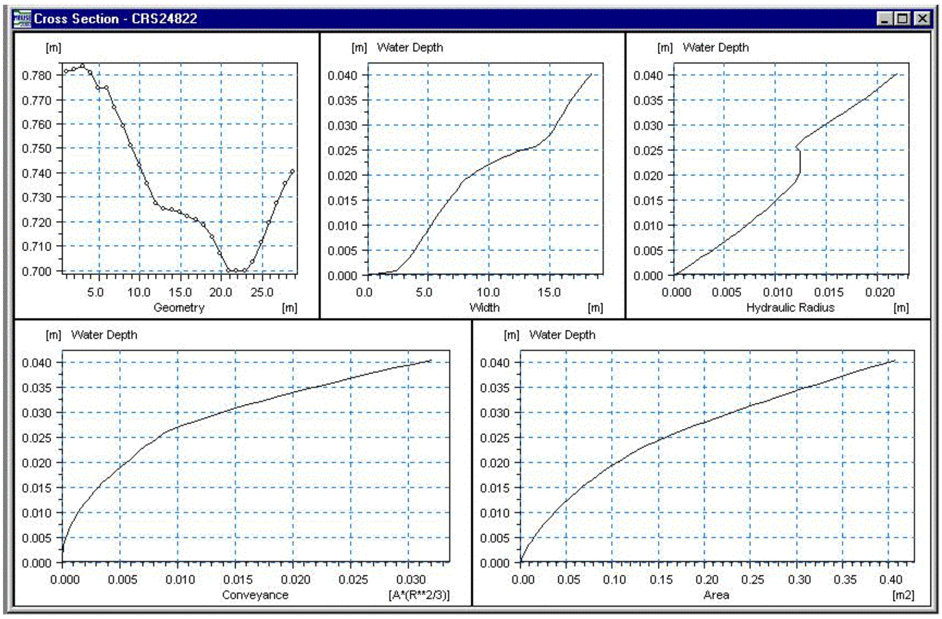
Figure 5.7 Structure of dual drainage flood model

The sewer data, such as pipes and manholes are taken from the sewer database. The surface channels are extracted from the generated DEM as demonstrated in Fig 5.8 (a) and (b).



	x	TRUNK 99.000 [undefined]
1	0	0.78012
2	0.9945	0.78116
3	1.9891	0.78221
4	2.9836	0.78348
5	3.9782	0.78073
6	4.9727	0.77473
7	5.9673	0.77473
8	6.9618	0.76686
9	7.9564	0.75898
10	8.9510	0.7511
11	9.9455	0.74322
12	10.940	0.73534
13	11.934	0.72747
14	12.929	0.72518
15	13.923	0.72488
16	14.918	0.72373
17	15.912	0.72236
18	16.907	0.72099
19	17.902	0.71859
20	18.896	0.71356
21	19.891	0.70703
22	20.885	0.7
23	21.880	0.7
24	22.874	0.7
25	23.869	0.70328

(a) Extracted channel cross-section from DEM (grid size: 1m*1m)



(b) Geometrical and hydraulic characteristics of cross section

Figure 5.8 A sample of extracted cross section of surface channel and its major hydraulic characteristics

5.5.3.2 Underlying Principle of Dual Drainage Flood Model

This model consists of submodels of rainfall runoff, pipe flow and surface channel flow. The rainfall runoff model is the same model as described in Model scheme I. The flow in pipes and surface channels is calculated according to the one-dimensional Saint Venant equations, which have been described in Model I. In addition, pipe flow can be calculated both as free surfaces flow and as pressurized flow, whereas surface channel flow simulation runs as free surface flow only.

5.5.3.3 Discussions of the Dual Drainage Flood Model

Comparing with Model I and II, Model III has two main advantages. Firstly, it can simulate both sewer flow and surface flow including the water exchange between them; secondly, the surface channels are extracted from DEM, which represent better the real flooding areas. Therefore, from the point of view of the representation of reality, Model III is regarded as being the best one among these three models. However, due to the complexity of the model structure and the influence of initial condition, as well as the impact of the default MOUSE fictive surface flooding tank, the simulation results from this model should also be checked carefully.

5.6 Case Studies

Two case studies, Fredlybekken catchment in Trondheim, Norway, and Baiwanzhuang (BWZ) catchment in Beijing, China, are applied to examine the models developed in the section above. Model calibration and flooding simulation constitute the main contents of these case studies.

5.6.1 Case Study I: Fredlybekken Catchment of Trondheim, Norway

5.6.1.1 Catchment Description

Fredlybekken, one of the catchments in the city of Trondheim (Fig. 5.9), was flooded several times in early spring 1997, in winter 1999 and in the summer of 2000 (Adresseavisen, 1997; Adresseavisen, 1999; TM, 2000). It is used as a case study to examine the flood models developed in section 5.5 and then to check the sewer capacity to withstand flooding.

The catchment area is 485 ha (level I). It is divided into 9 subcatchments (level II) displayed in Fig.5.10. The corresponding subcatchment characteristics are calculated from DEM and given in table 5.1, where the percentage of imperviousness of each subcatchment is calculated by the proportion of paved roads and areas occupied by buildings, paved roads and other areas identified as impervious in the digital map. Then, each subcatchment is further on divided into sub_subcatchments at level III, which are displayed in Fig.5.10 as well.

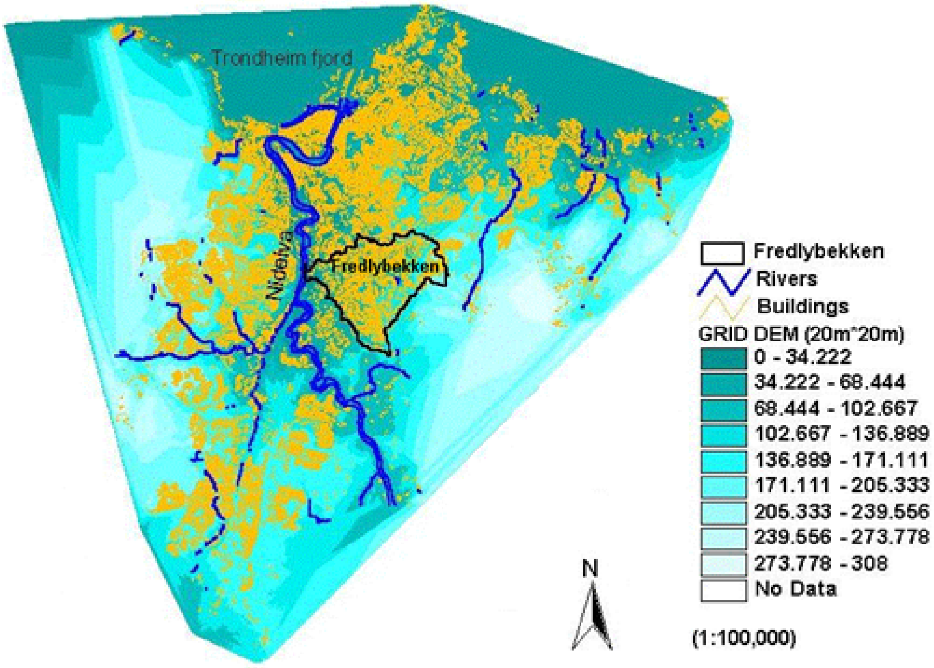


Figure 5.9 Map of Trondheim and the study catchment, Fredlybekken

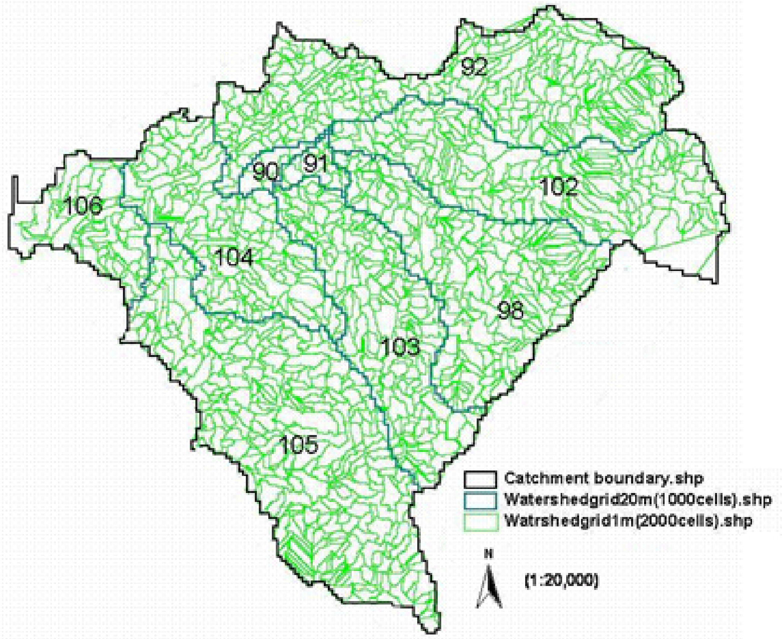


Figure 5.10 Subcatchments at three levels

(level I: black boundary; level II: dark blue boundary; level III: green boundary)

Table 5.1 Subcatchment characteristics at level II

Subatchment	Area (ha.)	$P_{imp.}$ (%)	Mean slope (%)	Mean F.L.* (m)	Mean Elev*. (m)
90	3.88	33.79	6.200	462	58
91	4.64	21.26	6.100	359	60
92	87.8	28.34	6.262	3142	96.17
98	66.56	18.84	6.955	1867	110.44
102	74.84	23.37	6.046	2487	130.26
103	55.76	24.80	5.737	2078	104.21
104	51.28	42.22	6.257	3760	57.82
105	114.36	24.52	8.223	2804	88.46
106	26.08	37.69	2.939	4817	34.57

* F.L.: Flow length; Elev.: elevation.

5.6.1.2 Sewer System of the Fredlybekken Catchment

Fredlybekken catchment is serviced by mixed sewer systems with separate systems upstream (part I) and combined sewer systems downstream (part II) (Fig.5.11).

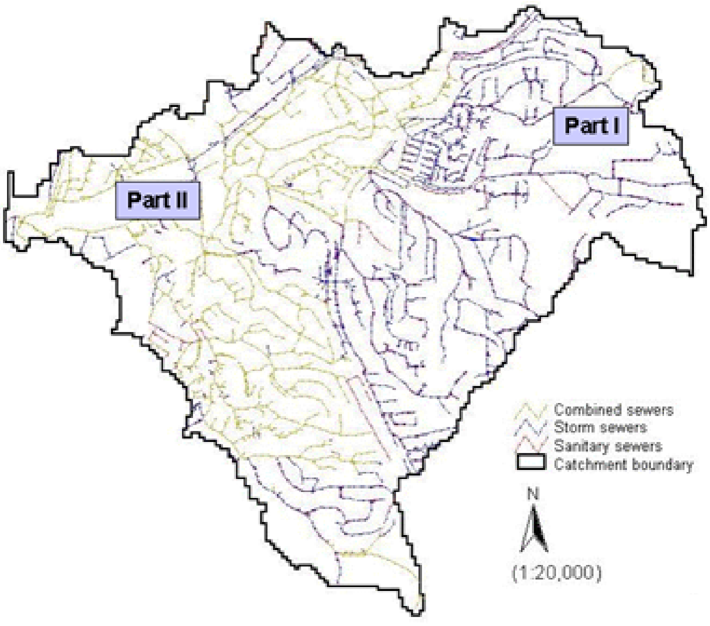
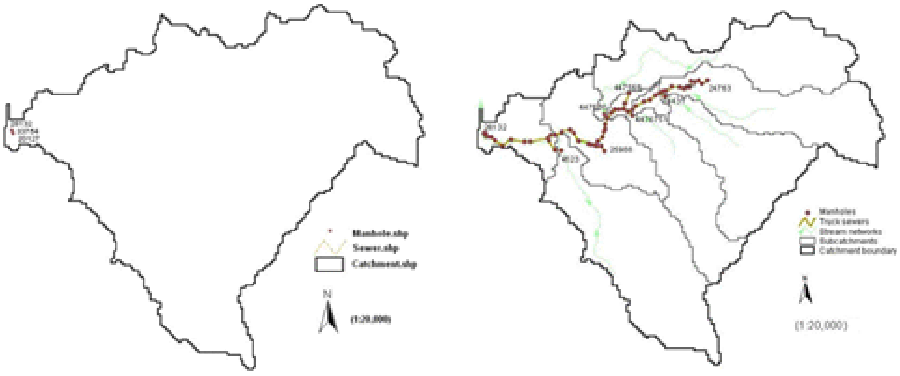


Figure 5.11 Sewer system of the Fredlybekken catchment

Because there is no proper receiving water, the discharge, both stormwater and sanitary sewage, from the separated system upstream is drained into the combined sewers downstream. At the outlet of the system, the sewage is either be pumped to a wastewater treatment plant, or discharged as overflow to the river, Nidelva. In practice, the separate sewers upstream in the catchment unfortunately do not play the role of pollution control they are supposed to.

In correspondence to catchment level I and level II, the sewer system of Fredlybekken is simplified at the two levels displayed in Fig.5.12.



(Level I) (Level II)

Figure 5.12 Simplified sewer systems of Fredlybekken Catchment

Where, the simplified sewers at level I only include the sewers that transport the runoff from the whole catchment. The simplified sewer systems at level II consist of main sewers that connect to the subcatchments at level II.

In addition, the dual drainage systems of model III, the original sewers at level II and corresponding surface channels extracted from DEM, are displayed in Fig. 5.13.

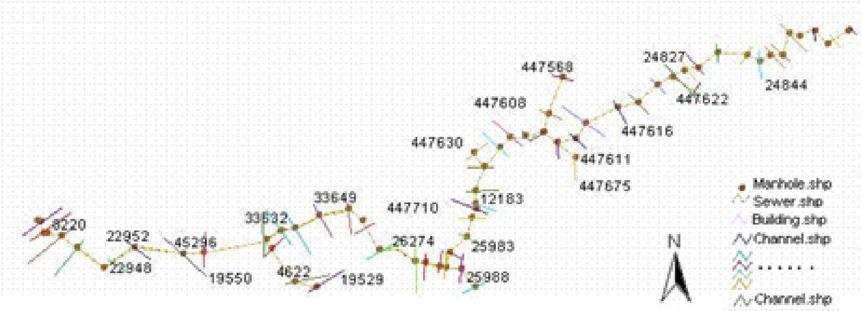


Figure 5.13 Longitudinal profile and cross sections of dual drainage at Level II

In the Trondheim case study, the inverted levels of manholes are not available in the existing sewer database. Measurements have been made at some places but are not complete yet. For those manholes that their inverted levels are still unknown, three meters beneath the ground level of the manholes is assumed.

The sewer system elements for two levels of the above three flooding models in the Trondheim case study are summarized in the table 5.2 below.

Table 5.2 Sewer elements

Model Sewer elements		Model I	Model II	Model III
Level I	Subcatchments	1	1	1
	Manholes	2	–	4
	Sewers	2	2	2
	Basins	–	2	-
	Weirs	–	–	2
	Channels	–	–	2
	Outlets	1	1	2
Level II	Subcatchments	9	9	9
	Manholes	59	–	118
	Sewers	73	73	73
	Basins	–	59	-
	Weirs	–	–	59
	Channels	–	–	73
	Outlets	1	2	2

5.6.1.3 Modeling Calibration

The flooding models of Trondheim are calibrated in this section using one summer rainfall event of 15 August 1998 displayed in Fig. 5.14 and the corresponding discharge at the outlet sewer of the study catchment (Fig. 5.15).

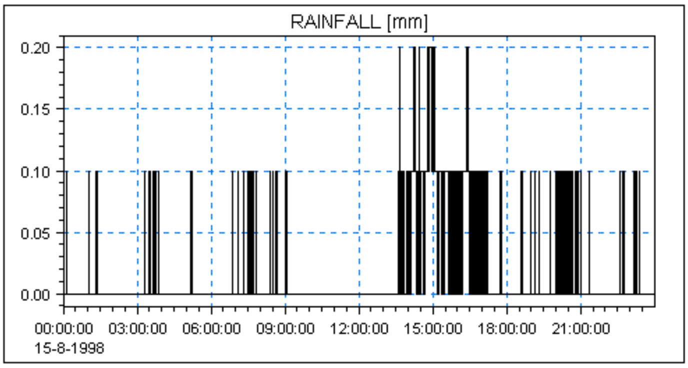


Figure 5.14 Rainfall on 15 August 1998

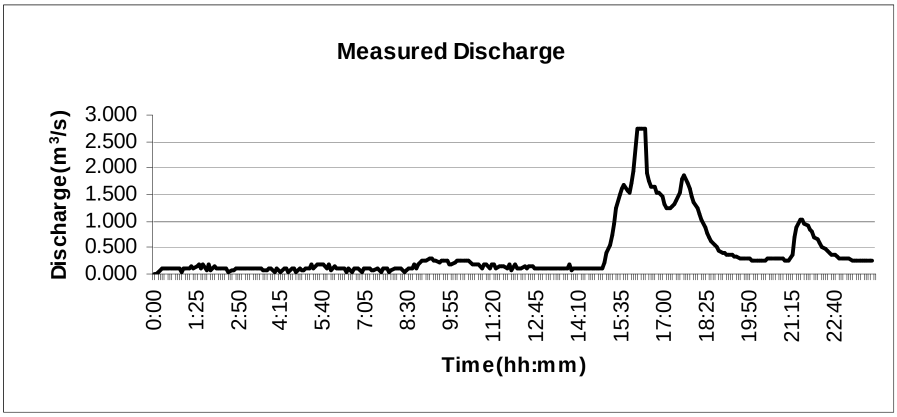
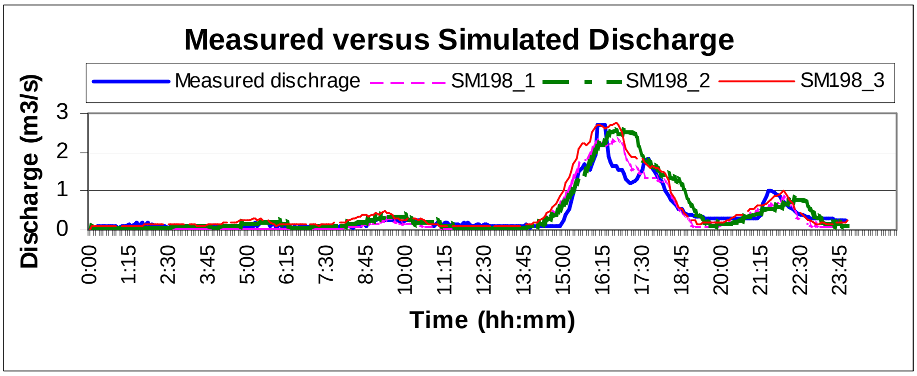


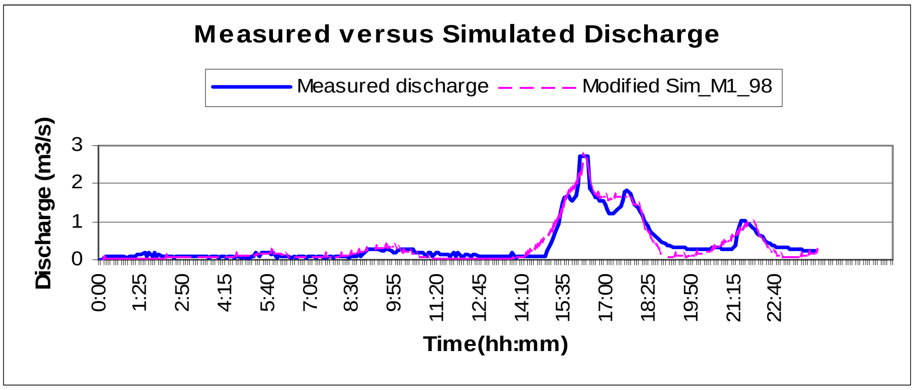
Figure 5.15 Discharge of the outlet sewer of 15 Aug. 1998

First of all, the three models are run applying the simplest drainage system of level I. The concentration time of 120 minutes of the whole catchment gives the best fit of the measured and simulated discharge. On this basis, the calibration focuses on the drainage systems at level II, and results are displayed in Fig. 5.15 (Model I) and Fig. 5.16 (Model II and III). Fig. 5.16 (a) displays the measured discharge and simulated results of the drainage systems at level II for the rainfall event on 15 August 1998. Three different hydrological parameter sets are applied in the simulation scheme of SM198_1, 2 and 3. The results indicate that a set of hydrological parameters can fit well with the measured values for one period rather than the whole simulation process, particularly when rainfall lasts longer. This is because constant hydrological parameters, for example the percentage of imperviousness and hydrological reduction factor, are applied during simulation period. In reality, these parameters vary with time during rainfall. Hence, variable hydrological parameters are applied for modification. The modified result of model I is displayed in Fig. 5.16 (b) and results of model II and III in Fig.5.16 (c). Apparently, the modified results fit better with the measured process than the results from constant hydrological parameters.

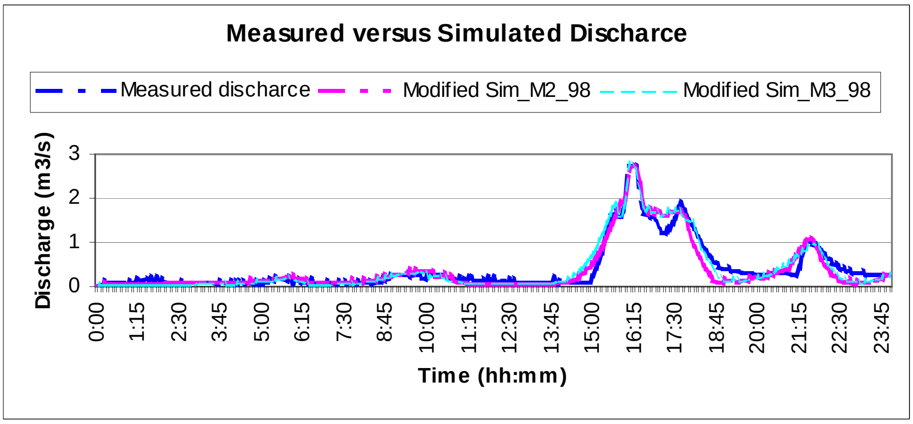
Using the adjusted parameters by the rainfall events on 15 Aug. 1998, another simulation is carried out on an autumn rainfall event of 19 Oct. 1995 (Fig. 5.17). The results are displayed in fig.5.18.



(a). Measured and simulated discharge from model I



(b). Measured discharge and modified simulated results of model I



(c). Measured and simulated discharge from model II and III

Figure 5.16 Measured and simulated discharge at level II on 15 Aug. 1998

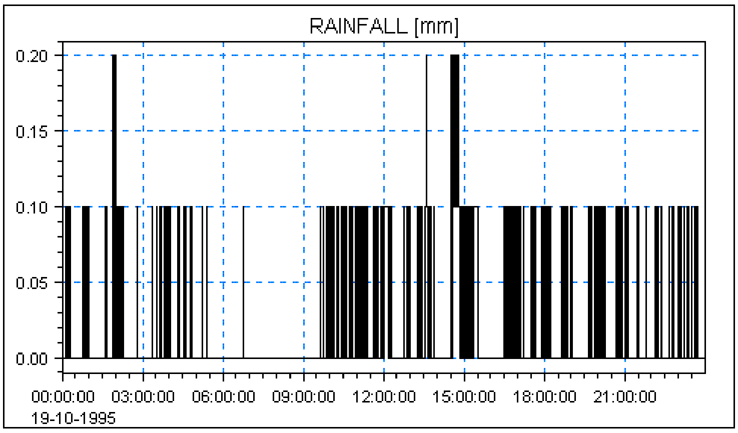


Figure 5.17 Rainfall on 19 Oct. 1995

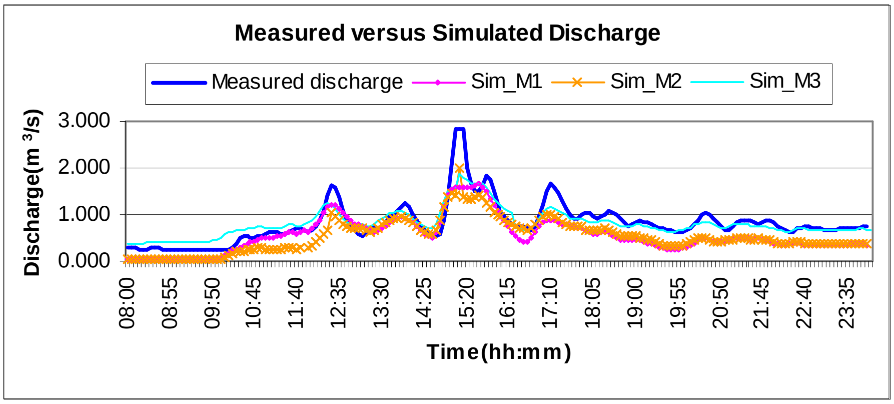


Figure 5.18 Measured and simulated discharge at level II on 19 Oct. 1995

In addition, the hydraulic parameters given in table 5.3 are applied in the model calibration.

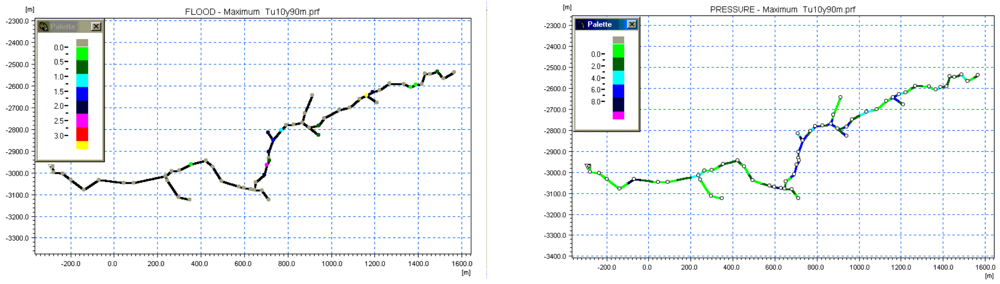
Table 5.3 Hydraulic parameters used in model calibration

Parameters		**Value**	**Objects in models**
Round edged outlet		0.25/km	Manhole
Contraction head loss C (HLC)		0.5	Sewer connection
Friction loss (n)	Normal concrete	0.0133	Normal pipes
	Rough concrete	0.0147	Old pipes
	Others	0.02	Surface channel

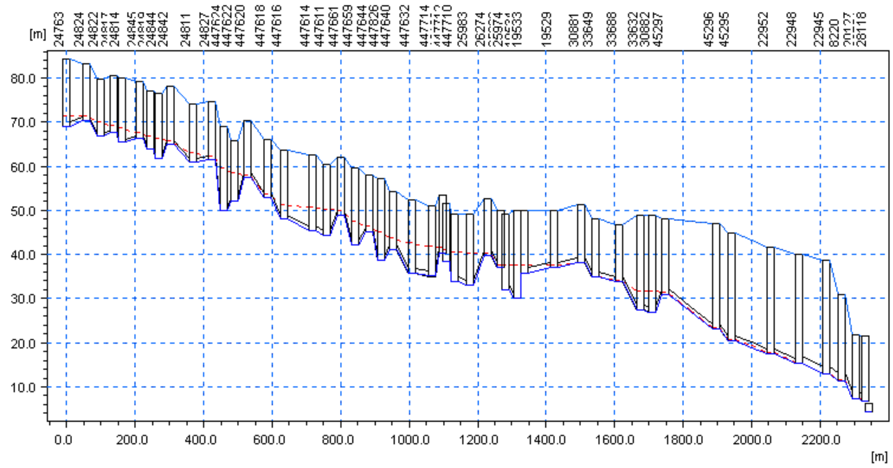
5.6.1.4 Flooding Simulation

Applying the calibrated flooding models in 5.6.1.3, the risk of flooding of sewers at level II is checked applying block rainfall intensities of 10, 30, 45, 60, 90 and 120 minutes duration with frequency of 1 in 10, 20 and 50 years. The IDF curve is displayed in Appendix H. Meanwhile, another IDF curve made from older but longer data series is used as a reference (Bøyum and Thorolfsson, 1999).

The simulation indicates that rainfall intensities of 90 and 120 minutes duration give the most critical situation of flooding. Taking 90 minutes rainfall as an example, flood maps and other relevant simulation information are displayed below from Fig.5.19~Fig.5.21. Others are presented in Appendix H. Some important numerical simulation results are summarized in table 5.4.

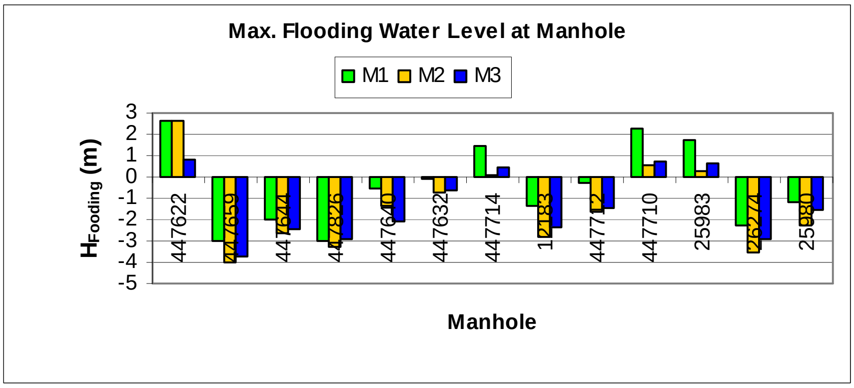


(a) Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 10 years



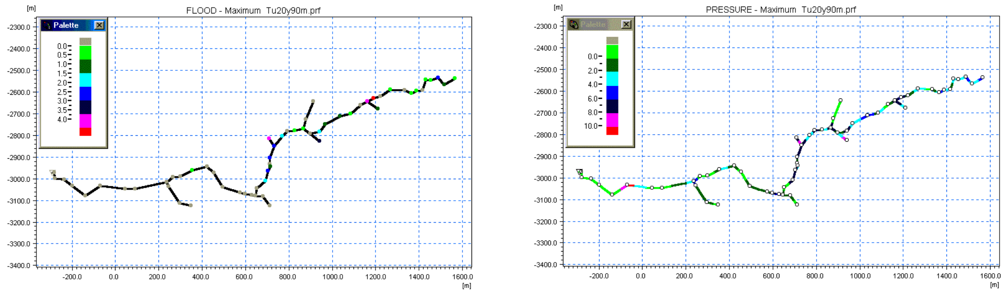
(b). Longitudinal water level profile of rainfall of 1 in 10 years

(c). Flood map of rainfall of 1 in 10 years

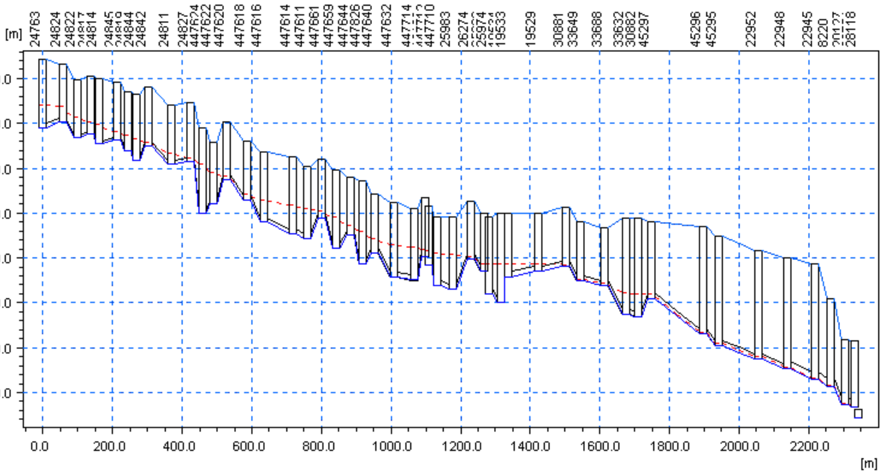


(d) Simulated maximum floodwater levels from Model I, II, III

Figure 5.19 Results of flooding simulation of rainfall of 1 in 20 years

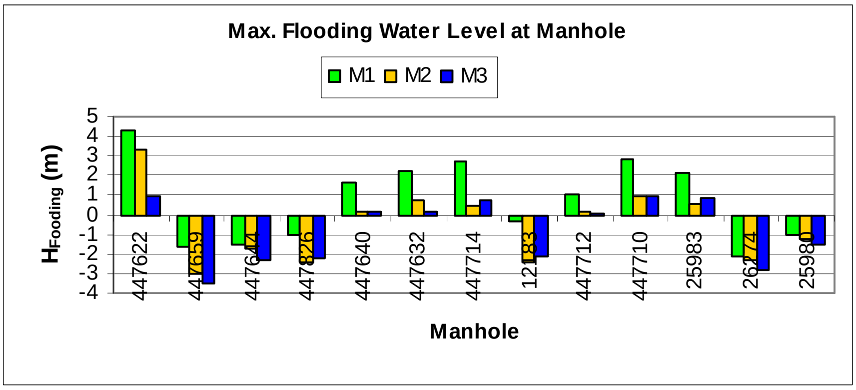


(a) Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 20 years



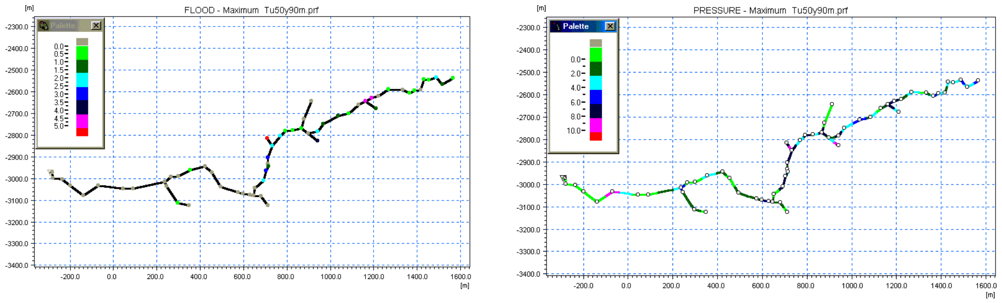
(b) Longitudinal water level profile of rainfall of 1 in 20 years

(c) Flood map of rainfall of 1 in 20 years

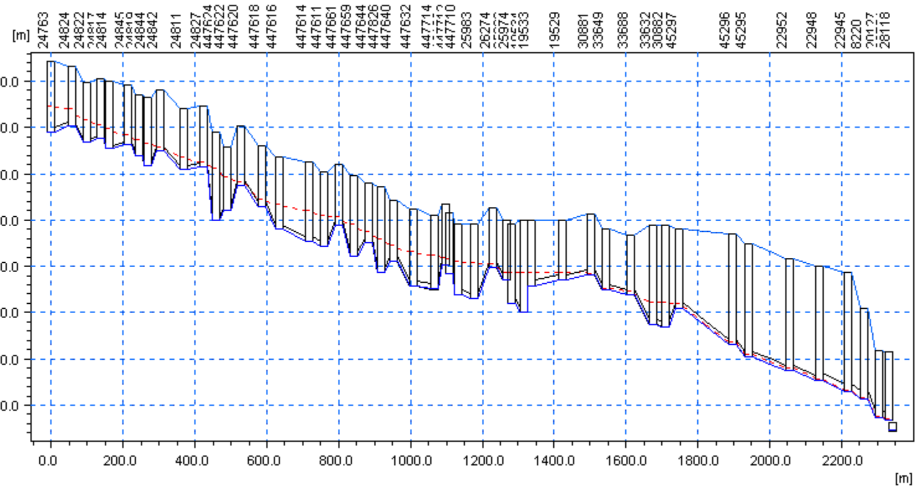


(d) Simulated maximum flood water levels from Model I, II, III

Figure 5.20 Results of flooding simulation of rainfall of 1 in 20 years

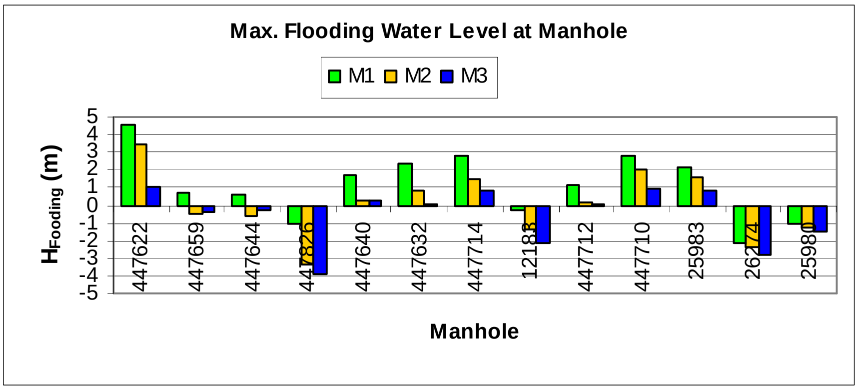


(a) Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 50 years



(b) Longitudinal water level profile of rainfall of 1 in 50 years

(C) Flood map of rainfall of 1 in 50 years



(d) Simulated maximum flood water levels of Model I, II, III

Figure 5.21 Results of flooding simulation of rainfall of 1 in 50 years

5.6.1.5 Results Discussion

The sewers of Fredlybekken are designed to drain storm water with frequency of 1 in 10 years ~1 in 20 years. The flooding simulation shows if the rainfall of 1 in 10 years lasts less than half hour, no flooding occurs from the sewer system. However, when it lasts longer, then some manholes will become full and then are flooded. For 1 in 20 years' events, a few manholes may flood even if the rainfall is shorter than half an hour. When the rainfall lasts 90 minutes or longer, almost half the number of manholes is flooded.

As a result, it is concluded that most of the main sewers have a capacity for rainfall events of 1 in 10 years. Flow of 1 in 20 years can be carried out if the rainfall duration is shorter than approximately half an hour. Otherwise, measures should be taken to protect the few vulnerable sewers from flooding.

For verification, sewer flooding is also checked for rainfall of 1 in 50 years. It indicates that the flooding situation is severer than flooding of 1 in 10 years and 1 in 20 years. However, the flood simulation for rainfall of 1 in 50 years is less reliable because the observed rainfall data series are shorter than 50 years.

Table 5.4 Summary of flooding simulation results

Frequency (1 in n years)	Duration (min.)	Rainfall intensity (mm/min)	Flooding information		
			No. of flooding manholes	No. of pressurized sewers	Max. flood Water level (m)
10	10	0.7843	0	0	0
	30	0.3219	0	1	0
	45	0.3203	5	54	0.48
	60	0.2047	7	60	0.56
	90	0.1578	15	60	0.79
	120	0.1278	16	61	0.98*
20	10	0.9597	0	0	0
	30	0.3726	5	43	0.46
	45	0.2596	6	54	0.52
	60	0.2308	7	60	0.60
	90	0.1754	26	63	0.98
	120	0.1401	17	62	1.02*
50	10	1.1964	5	34	0.41
	30	0.4379	6	51	0.51
	45	0.2971	7	54	0.56
	60	0.2641	11	60	0.65
	90	0.1979	28	63	1.03
	120	0.1558	31	63	1.06*

* During the simulation, highest flood water levels occur mostly at location of manhole 447622 (except for rainfall of 120minutes, which the highest flood water levels shift to manhole 447710).

Geographically, some flooded manholes, for example 447622, 447630, are among the inflow points, where the discharges from large subcatchments drain into the main sewers. Due to the restriction of inlet capacities, flooding may occur in these locations in shorter periods. In addition, the simulation indicates that the capacities of the sewers between manholes 447632 and 25983 may not be sufficient. As displayed in the Fig.5.22, some sewers in these areas were among the inundation areas of the flooding event in early spring in 1997. Therefore, operational attention should be paid to those sewers, and restoration may be considered for them.

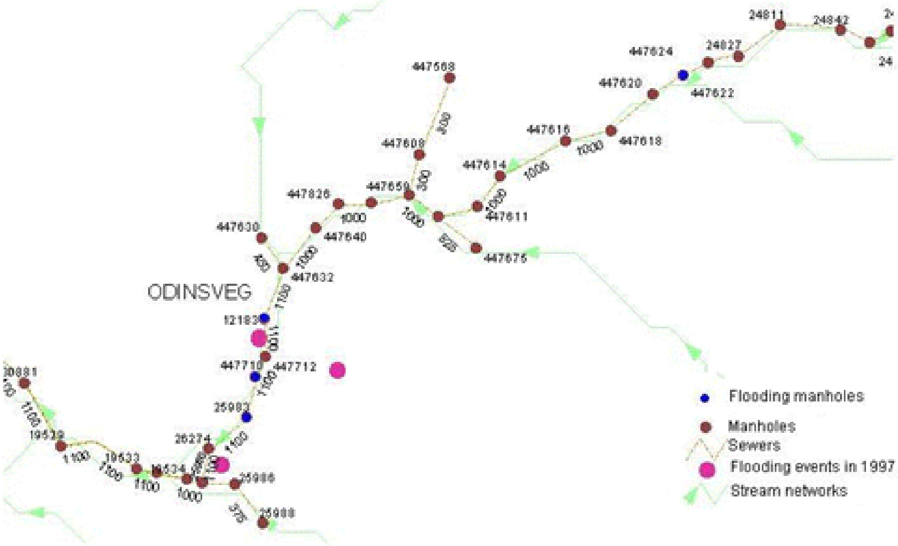


Figure 5.22 Simulated flooding manholes for rainfall of 1 in 20 years in 60 minutes versus flooding cases in 1997 in the Fredlybekken

Moreover, the simulated flood water levels are rather different applying the three models. According to Fig. 5.19 (d), Fig. 5.20 (d) and Fig. 5.21 (d), Model I gives the highest values and Model III the lowest ones. The results from Model II and Model III are relatively similar, though. From the point of model structure, Model III is the most advanced. However, the necessarily complicated modeling components, such as fictive weirs and manholes on surface channels may lead to errors or instability of the simulations. Therefore, these three models will be examined further by another case study.

5.6.2 Case Study II: Baiwanzhuang Catchment of Beijing, China

5.6.2.1 General Information of Beijing

Beijing, the capital of China, is situated around 39°56’ north latitude and 116°30’ east longitude (Fig. 5.23). It has a mild continental climate with cold and dry winter, hot and wet summer and generally the rain season. The annual average precipitation is 595 mm. Due to the impacts of atmospheric, geographic and topographic characteristics, the precipitation is not homogeneously distributed in time and space. According to the historical records, the lowest annual precipitation is merely 242mm, whereas the highest is 1406 mm. Eighty percent of the annual precipitation falls during summer from June to September. Therefore, floods may be brought about during these periods. Meanwhile, water shortage has been incredibly severe in recent years due to limited rainfall versus large amount of water consumption (Nie and Schilling, 2001).

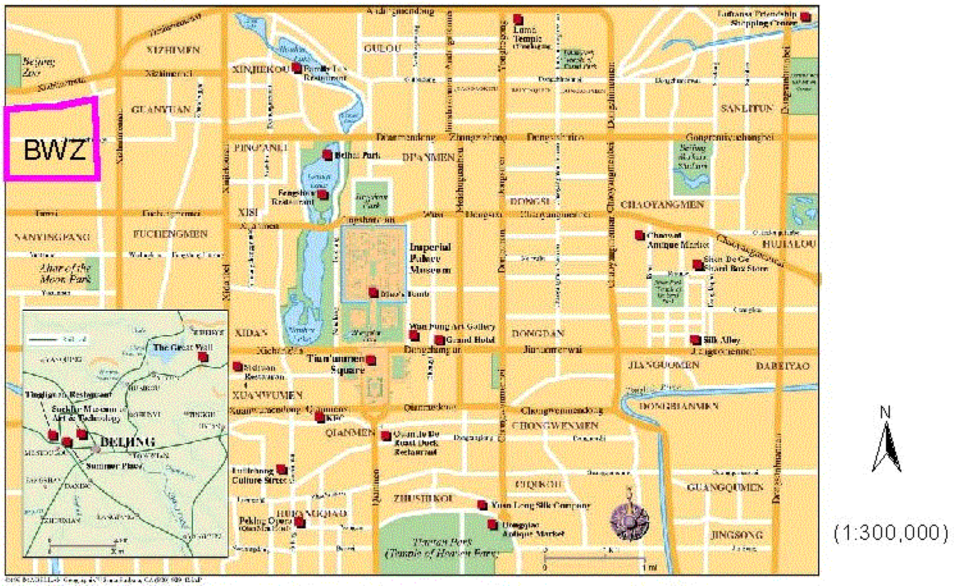


Figure 5.23 Map of Beijing

Regarding the risk of flooding, there are two major types of threats: flooding from the rivers passing by the city and flooding in local urban areas due to heavy rainfall overloading sewers with limited capacity. This case study will focus on the latter situation, i.e. flooding of urban drainage systems.

In Beijing, the storm sewers are designed to transport flow of 1 in 0.5~3 years for general areas and roads, and 2~5 years for important regions and main traffic ways (GBJ 14-87, 1998). In some areas, however, the storm sewers were designed even smaller, yet about ten percent of areas do not have sewers.

5.6.2.2 Description of Baiwanzhuang Catchment

Baiwanzhuang (BWZ) is a densely populated residential area. The catchment size is about 42.6 ha (Fig. 5.24). The average percentage of imperiousness increases from 30% in the 1970s’ to about 90% today. It is a gentle sloping area with slight slope of 1.65‰. A main road, Chegongzhuang (CGZ) Road, goes through this catchment.

Figure 5.24 Map of Baiwanzhuang case study catchment

BWZ catchment is provided by a separate sewer system. It consists of three branched sewers on Wen Xing Jie (WXJ) Street, in Bai Wang Zhuang North (BWZN) residential area and one main sewer line alone CGZ main road. Total length of the storm sewer is 1582m. The storm water in the sewer system is transported by gravity. Node 40, the outlet of BWZN subcatchment connects to the downstream main sewer line with free outflow. The outlet of CGZ main sewers discharges freely to downstream channel at node 18, which means that no water flows back to the system.

The digital data of Beijing are described in Appendix I. Subcatchments and stream delineated from grid DEM together with sewers of BWZ catchment are displayed in Fig. 5.25.

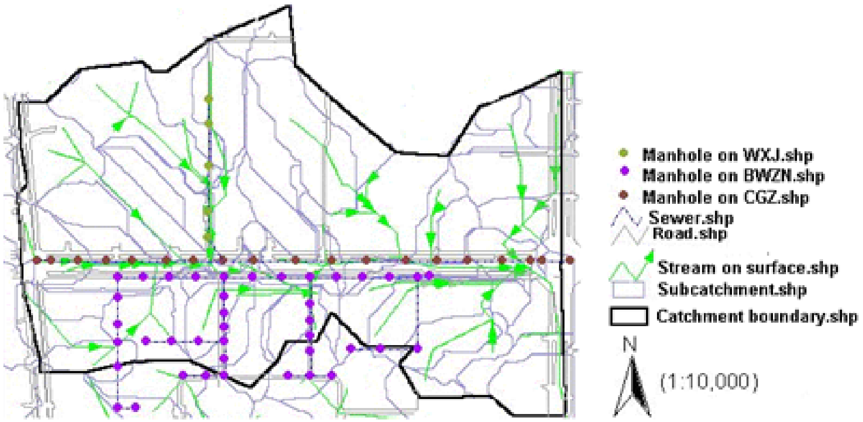


Figure 5.25 Subcatchments of BWZ case study catchment

5.6.2.3 Modeling Calibration

The three developed models are calibrated by BWZN subcatchment according to the rainfall events on 22 July 1974 (Fig. 5.26) and measured discharge at node18, 22. Results of node 18 are displayed in Fig. 5.27. Results of node 22 are given in Appendix J.

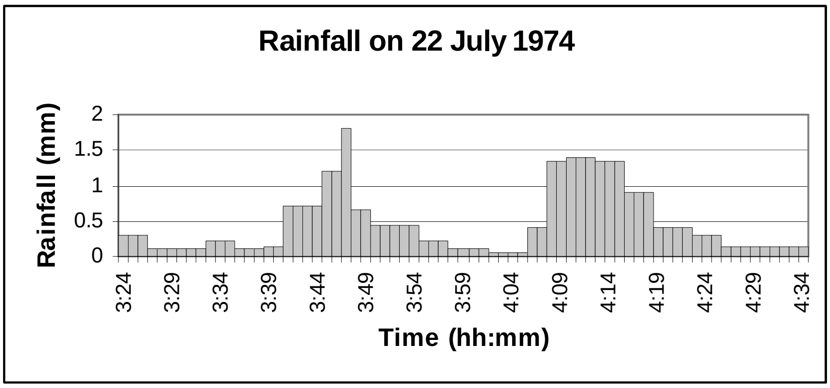
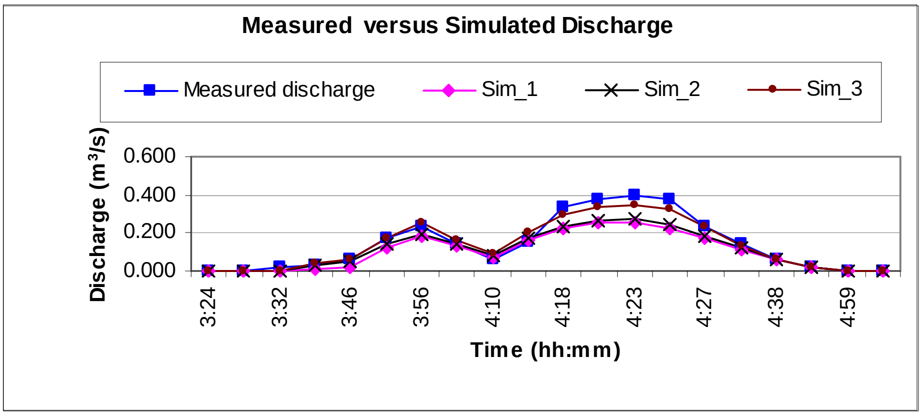
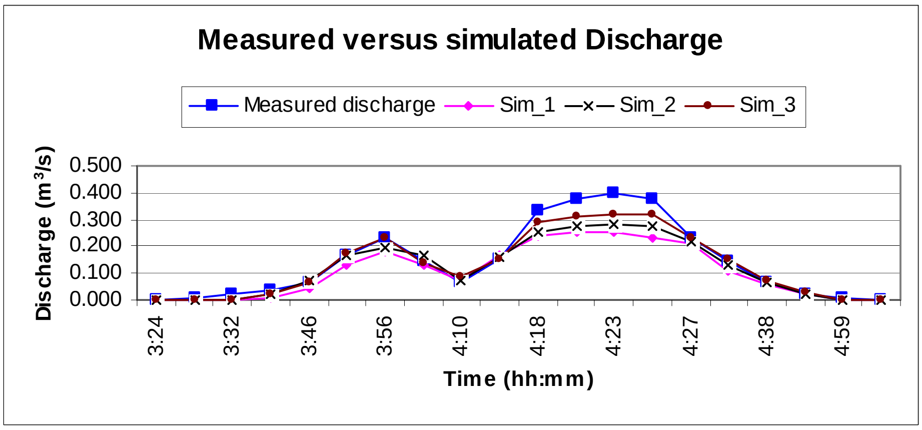


Figure 5.26 Observed rainfall event on 22 July 1974 at BWZN catchment

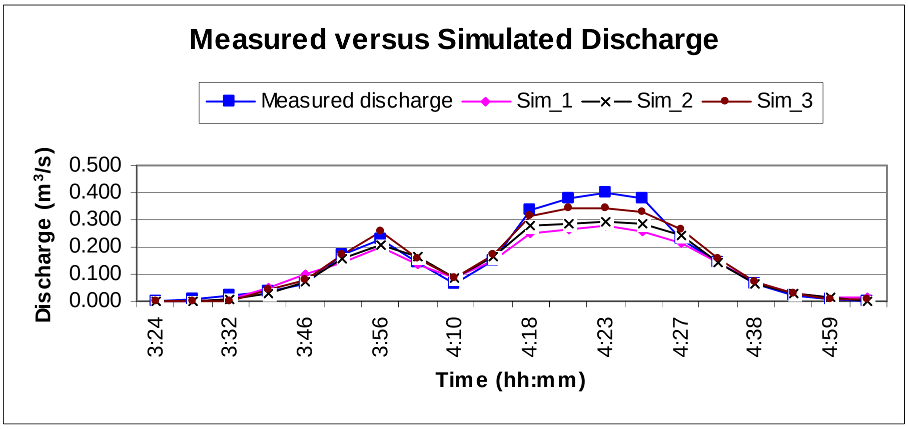
In Fig.5.27, Sim_i (i=1~3) represent the simulation results from three different sets of hydrological parameters. Comparing with the measured discharge, the same simulation trends have been achieved as in the Trondheim case study, i.e. the difference between observed and simulated discharge increases over time. This is because constant impervious catchment area and hydrological reduction factor were applied for the whole simulation period. In reality, however, the runoff contributing areas increase over time because the soil depression is filled up and soil infiltration is at capacity, although the physically paved impervious area is the same. Therefore, a set of constant hydrological parameters cannot calculate an accurate runoff hydrograph.



(a). Measured and simulated discharge at node 18 of Model I



(b). Measured and simulated discharge at node 18 of Model II



(c). Measured and simulated discharge at node 18 of Model III

Figure 5.27 Modeling calibration of BWZN catchment

There is no flooding occurring during the simulation. Therefore, the calibration achieved very similar results from the three models. In addition, three different sets of hydrological parameters applied in the calibration are given in Table 5.5.

Table 5.5 Hydrological parameters of BWZ catchment

Parameters Sets	$P_{imp.}$ (%)	i_0 (mm)	F	T_c (Min.)	T/A
I	70	2	0.95	Varied with subcatchment	
II	75	2	0.95	Varied with subcatchment	
III	90	2	0.95	Varied with subcatchment	

5.6.2.4 Flooding Simulation

Applying the three calibrated models, the risk of flooding of BWZ catchment has been checked applying the synthetic design storms of 1 in 2 years and 1 in 10 years with 10 minutes time resolution and 120 minutes duration. Additionally, a synthetic storm process of 1 in 20 years with 1hour time resolution and 24 hours duration was applied (HGSB, 1991; Appendix J).

The flooding manholes of flooding of 1 in 2 years and 1 in 10 years are displayed in Figures of 5.28~5.30. The simulated maximum flood water levels of 1 in 10 years from the three models are displayed in Fig. 5.31 and Fig.5.32. There is no flooding for rainfall of 1 in 20 years in 24 hours. In addition, the numerical results of flood simulation are summarized in table 5.6.

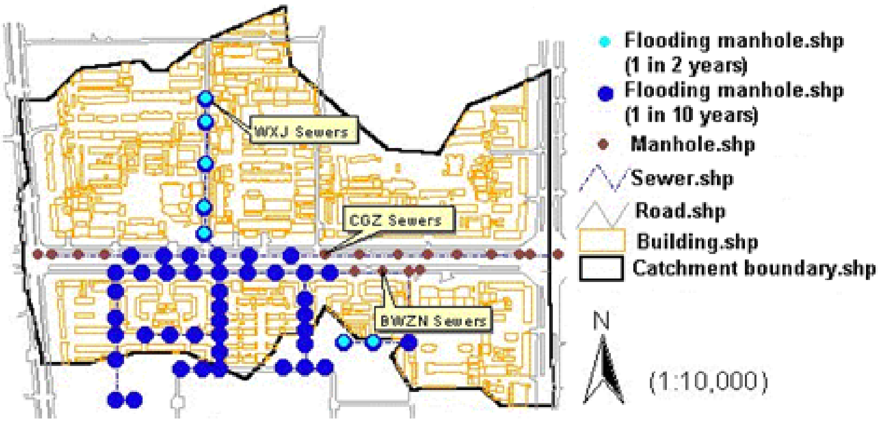


Figure 5.28 Flooding manholes of BWZ sewers (Model I)

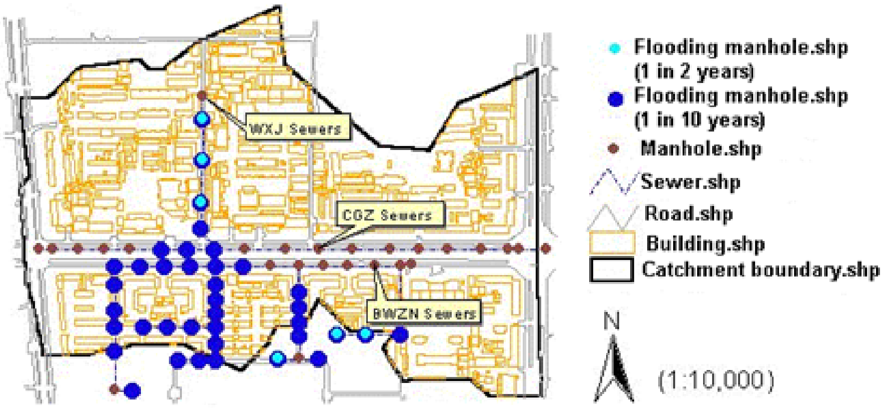


Figure 5.29 Flooding manholes of BWZ sewers (Model II)

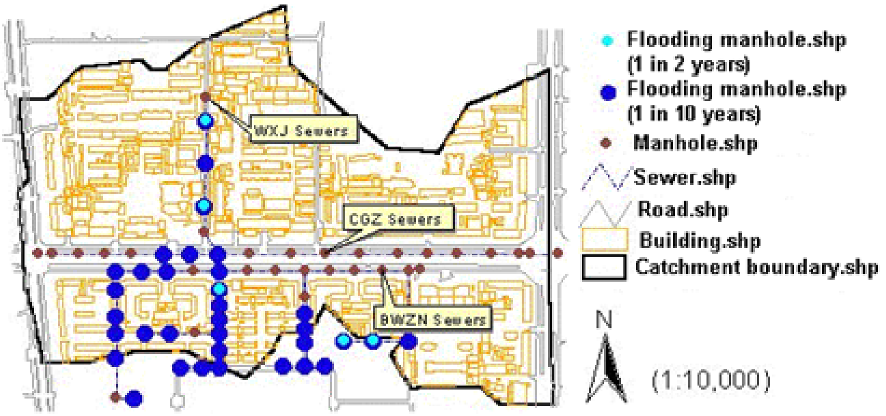


Figure 5.30 Flooding manholes of BWZN sewers (Model III)

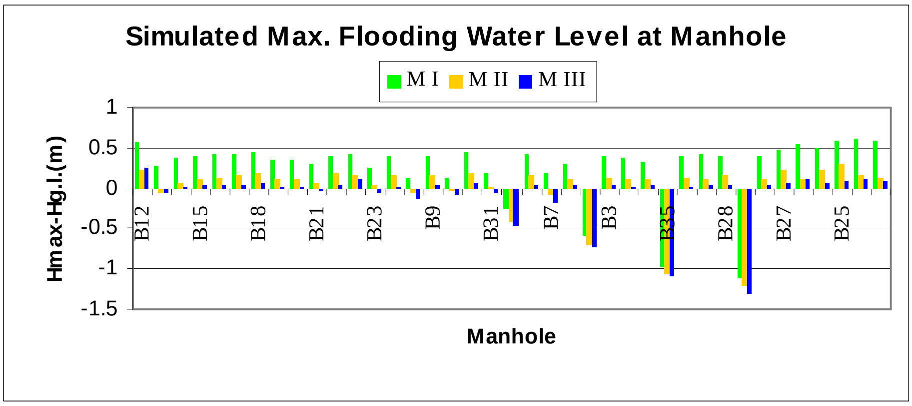


Figure 5.31 Simulated maximum flood water level of manholes in BWZN catchment (rainfall of 1 in 10 years)

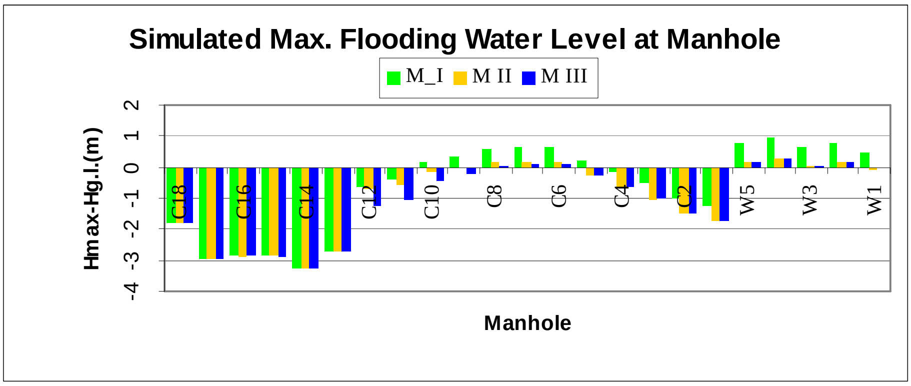


Figure 5.32 Simulated maximum flood water level of manholes in CGZ and WXJ catchment (rainfall of 1 in 10 years)

Table 5.6 Summary of flooding simulation of BWZ catchment

Recurrence interval (1 in n year)		**Model I**		**Model II**		**Modell III**	
		Flooded manhole	**Hmax. (m)**	**Flooded manhole**	**Hmax. (m)**	**Flooded manhole**	**Hmax. (m)**
120 min.	2	W1-5; B36-37.	0.55m at W4;	W2-4; B25; B36-37.	0.14m at W5	W2; W4; B11; B36-37.	0.14m at W4
	10	W1-5; 36 flooded manholes on BWZN; C5-10 on CGZ.	0.95m at W4	W2-5; 31 flooded manholes on BWZN; C6-8 on CGZ.	0.26m at W 4.	W2-4; 28 flooded manholes on BWZN; C6-8 on CGZ.	0.28m at W4.
24h	20	No surface flooding	—	No surface flooding	—	No surface flooding	—

According to the simulation, the lateral sewers on WXJ Street all reach their capacities when rainfall is at frequency of 1 in 2 years. Only few manholes are flooded in BWZN subcatchment as the same rainfall occurs. When rainfall at frequency of 1 in 10 years falls, almost all lateral sewers and manholes are full of their capacities and consequently flood water comes to the surface. Several main sewers along CGZ main road get flooded as well.

Finally, it is concluded that the capacities of sewers on WXJ Street are only sufficient for rainfall events less than 1 in 2 years. Sewers in BWZN catchment can convey stormwater of 1 in 2 years. The main sewers along CGZ road have the capacity of transporting safely storm water under 1 in 10 years.

In addition, the flood water levels from these three models are rather different. As displayed in Fig. 5.31 and Fig. 5.32, Model I gives the highest flooding water level, and Model III calculates the lowest flood water levels for most manholes. With respect to modeling principles, modeling structure and the geometrical representation of the flooded areas, the results from Models II are regarded as being the most reliable.

5.7 Summary

Main developments and results of Chapter five:

Two urban flooding models have been developed based on MOUSE. Including MOUSE surface fictive flooding model, three models are introduced and applied in this chapter. They are:

Model I: MOUSE fictive surface flooding tank;

Model II: Integrated “basin” model;

Model III: Dual drainage flooding model.

Model I is a special facility included in the MOUSE program to deal with flooding problem when it occurs during simulation. It is designed to control the water balance at flooding manhole(s), but it cannot simulate the flow hydraulic behavior of the surface water. A virtual tank up to $1000A_m$ surrounding the flooded manhole will be automatically activated as flooding occurs. However, such a tank neither represents the flood area nor the flood routes in reality, so that improvement needs to be made.

On the basis of Model I, Model II, the integrated “basin” model, is developed to define the flood water level and volume on the surface. It treats the manhole and the corresponding surface storage as a basin to keep the entire storm water within the basins. As flooding occurs, the floodwater is the water stored on the surface from the ground level of a basin, which is equal to the ground level of the original manhole, to the highest water level at the basin. In addition, the model considers manhole and connecting surface flooding area as a whole, which guarantees a continuous water accumulation in the basin. In other words, no additional linking structure between manhole and surface is needed. Moreover, the surface storage of the basin is extracted from the terrain surrounding the flooding manholes, which makes the water levels in basins close to the real situations on the surface. However, the basin functions as a storage tank, and surface flow routine is not available yet.

The model III, dual drainage flooding model, is developed to simulate flooding both in sewers and on the surface. In this model, the two layers, i.e. the underground sewers and the surface channels, are connected by fictitious weirs at each manhole. The flow in connecting sewers is transferred by a connecting manhole. Similarly, fictitious manholes are allocated on the surface to transfer flow in the surface channels. The longitudinal profile of surface channels proceeds along the layout of manholes, and cross sections of the channels are extracted from the DEM at the location of each manhole.

Two case studies, Fredlybekken in Trondheim, Norway, and Baiwanzhuang (BWZ) in Beijing, China, have been applied to examine the developed models and check the sewer capacities for given design storms.

The sewer capacities in the Fredlybekken catchment have been checked for floods at several combinations of block rainfall intensity and durations. Where, rainfall with 90 and 120 minutes duration gives the most critical flooding situation. Operational attention or modification is suggested for sewers from manhole 447632 to 25983.

In the BWZ case study, synthetic design storms of 1 in 2 years and 1 in 10 years with 10 minutes time resolution during 120 minutes, as well as synthetic rainfall of 1 in 20 years with 1 hour time resolution during 24 hours are applied to the flooding simulation. The simulation results show that the capacities of lateral sewers on WXJ Street are insufficient to transport stormwater of 1 in 2 years; the capacities of lateral sewers on BWZN subcatchment can convey stormwater from rainfall of 1 in 2 years except one sewer section from manhole B36~B37. The main sewers on CGZ road can transport the storm discharge from rainfall of 1 in 10 years, but measures have to be taken to protect flooding from manholes C6-C8.

Restrictions and deficiencies of the simulations in Chapter five, suggestions for future research

Simulated flood water levels from the three models are rather different. Model I calculates the highest flood water levels, while model III gives the lowest ones. According to the modeling structure and the geometrical representation of flooded areas, Model III is the best among these three models. However, the necessarily complicated structures, their options and initial conditions may lead to inaccuracy of the calculation. Therefore, the results from Model III should be checked carefully.

In the Trondheim case study, there are two major flooding conditions: heavy rainfall in summer and autumn; rainfall plus snowmelt in late winter or early spring. However, this study focuses on the development of flooding models in sewers and connecting surfaces, where a simple hydrological model was applied, and in which no snowmelt routine was included. Therefore, only summer and autumn rainfall events were selected for model calibration.

However, it is possible to model winter flooding, i.e. taking snow melt into consideration, if a rainfall-runoff module with snow routine is connected to the modeling package.

In addition, the Trondheim case study has good topographic data, but the measurement of the inverted level of the manholes is not completed yet. Therefore, three meters difference from the top of a manhole to its bottom is assumed at manholes, where the measured levels are not available. As a result, the flooding simulation should be updated when measured levels are available. Besides, the observed discharge is only available at the outlet of the Fredlybekken catchment. Therefore, the modeling calibration is obviously insufficient. Due to the above two reasons, the flooding simulation of Fredlybekken were carried out only on main sewers.

If possible, the sewer discharge should be observed at several places of the sewer systems in order to calibrate the established models properly.

Moreover, one particular feature in the Trondheim case is that most of buildings are built with basements. The storage volume in basements is not included in the developed flooding models. In case of basement flooding, the storage of the basements will alleviate the flooding on the surface but cause damage in these basements.

Chapter 6

Flood Damage Evaluation and Flood Mitigation

It is difficult to avoid flooding completely because of its stochastic characteristics. However, man can reduce the risk of flooding by taking various mitigation measures.

6. FLOOD DAMAGE EVALUATION AND FLOOD MITIGATION

Chapter six focuses on the last two topics of flood management: FLOOD DAMAGE EVALUATION and FLOOD MITIGATION. Under these topics, special concern is given to flood mitigation in urban drainage systems. Two case studies are introduced to examine the promoted mitigation measures.

6.1 Introduction

Flooding is the consequence of natural phenomena. It is difficult to avoid flooding completely due to its stochastic characteristics of occurrence. However, the risk of flooding can be reduced to some extent. In addition, it is important to assess flood damage properly in order to make emergency flood plan and to implement flood mitigation measures.

Over time, government and publicans have learnt living with floods in addition to traditional flood defense. Therefore, sustainable water resources conservation has become a concerned topic, particularly in areas prone both floods and drought in different periods, such that flood control and drought mitigation should be considered as a whole.

6.2 Flood Damage

6.2.1 Flood Damage Category

Flood consequences range from loss of life, damage of private property and public facilities as well as adverse influence on daily life, such as power cuts, interruption of water and gas systems, halting of traffic and environmental deterioration. In addition to the damage at flood inundation sites, the indirect impacts to activities in other areas, and ever the prolonged impacts into the future should also be concerned.

Walesh (1989) divided flood consequences into two categories: direct and indirect, then tangible damage and intangible losses under each category (see table 6.1).

6.2.2 Flood Damage Assessment

Flood damages are generally estimated at two levels: regional level and single house level. Government and local authorities usually use the regional method to evaluate flood damage in large flood areas. Municipalities and insurance companies need to assess the damage to single flooded houses for flood compensation.

Table 6.1 Types of flooding damage (Walesh, 1989)

Form of losses	Tangible damage		Intangible losses	
	Private	**Public**	**Private**	**Public**
Direct	Loss of properties; Loss of animals, crops and livestock; Loss of commercial and industrial contents and lands; Cost of cleaning, repairing or replacing of residential & other contents.	Loss of public properties; Loss of commercial and industrial contents and lands; Cost of repairing or replacing water, power, roads, bridges, culverts, sewers, park, public lands and other facilities.	Loss of life; Health hazards; Psychological stress caused by current flood.	Disruption of normal community activities; Interruption of traffic, power, water, gas, telecommunication system; Loss of archaeological or cultural site(s); Deterioration to environment.
Indirect	Cost of temporary evacuation and relocation; Loss of wages; Loss of production and sales; Cost of purchasing and storing flood-fighting equipment and materials; Incremental cost for life	Incremental costs to governmental units and other institutions as a result of flood fighting measures; Cost of post-flood engineering and planning studies and of implementing structural and non-structural management measures.	Reluctance by individuals to inhabit flood-prone areas; Psychological stress caused by possibility of future floods.	Reluctance by business interests to continue development of flood-prone, thereby adversely affecting the community tax base.

6.2.2.1 Regional Method

For pre-flooding defense, e.g. flooding warning and deciding people who have to be evacuated, the following factors are important:

- Probable rainfall and probable flood water level;

- Potential inundation areas and people at risk.

Unlike pre-flooding estimation, post-flooding damage is generally assessed by the following indicators:

- Loss of life;
- Inundation areas and affected people;
- Direct property damage;
- Costs for flooding defense and rescue;
- Affected activities;

The regional method is commonly used for flood damage assessment in river floodplains. Chen (1999) and Wan (1999) presented several methods of evaluating the indicators mentioned above.

6.2.2.2 Single Property Damage

As flood happens, damage might be caused in flooded buildings. In such a case, flood compensation consists of following two parts: the direct property damage counted in each flooded house or public building; and the remedial expense calculated to repair the damaged items, such as water pipes, sewage drains and damage to the building itself etc.

Walesh (1989) presented a method to assess flood damage of single house by constructing frequency~stage~damage curves for different types of structures. Herath, Dutta and Musiake (1999); Wang and Lu et al. (2001) introduced method of flood damage evaluation based on property distribution in urban district using GIS. Konig, Sægrov and Schilling (2002) analyzed the flood damage relates to individual flooded houses. They are valuable references for other flooding cases. However, flood compensation must be assessed by experts according to the losses on flooding sites.

6.2.3 Urban Flood Damage: Trondheim Case Study

Flooding damage has been described in Chapter one and section 6.2. However, the damage varies greatly from case to case. Taking Trondheim municipality as an example, the average annual sewer damage compensation paid by municipality is about 1.44million Norwegian Crown (NOK) (see Fig.3.6). In addition, the damage compensation per case paid by Trondheim municipality is, on average, no more than 10,000 NOK, and the excess damage is paid by insurance companies. When large floods occur as in 1997, which means that the rainfall was heavier than the designed storms that sewers can accommodate, then the damage is covered by the government, or by insurance companies. Therefore, in addition to the compensation paid by Trondheim municipality, two insurance companies, ***if*** and ***Gjensidige***, also paid large amounts of compensation for flood related damage (if, 2000; Gjensidige, 2000).

6.3 Flood Mitigation

As described in the above section, floods have severe adverse influences on objects and activities in flooding and flooding affected areas. Therefore, effective mitigation measures should be taken to reduce the risk of flooding and alleviate the flood damage.

6.3.1 Flood Mitigation Measures of River Basins

In river floodplains, flood mitigation measures are generally classified into three categories: structural measures, non-structural measures and living with floods, see table 6.2.

Table 6.2 River flooding mitigation measures (Saul, 1992)

Category	Measures
Structural measures	Storage facilities: reservoirs, lakes and other artificial retention tanks Dams, river channel embankments, earthen platforms and polders built in floodplains
Non-structural Measures	Regulations and policies Flood defense: flood forecasting, warning and Evacuation and emergency rescue Flood insurance programs
Living with flood	Avoid floodplain occupacy Restricting floodplain use for wildlife habitat Land conservacy

6.3.2 Flood Mitigation Measures of Urban Catchments

Unlike the river floodplains, urban catchments are relatively small and floods are caused by local drainage problems. For given rainfall, runoff from urban catchment depends greatly on the degree of imperviousness and the soil infiltration. Further on, the drainage of the runoff depends on the topography and the capacity of drainage system.

During rapid urbanization, particularly in developing countries, the percentage of impervious areas of urban catchments is sharply increasing, consequently both the total volume of runoff and peak flow increase. Additionally, the existing sewers deteriorate and loose part of their capacities due to sedimentation and other operational problems, and it is difficult to rehabilitate those sewers because of financial limitation and disturbing residents' activities. Therefore, the risk of flooding is increased, and effective mitigation measures have to be taken into consideration.

Regarding to the causes of urban flooding, the common flooding mitigation measures focus on the following aspects:

- Reduce the impervious areas;
- Increase the soil infiltration;
- Modify the sewers of insufficient capacities;
- Construct water detention or retention facilities.

The first two measures are intended to reduce runoff at the source, while the latter two are supposed to increase the sewer capacities to convey or store the stormwater that otherwise would contribute to flood. In addition, sufficient supervision and maintenance is always essential in order to reduce the risk of flooding, which has been described in detail in the Chapter three.

6.4 Urban Flood Mitigation: Case Studies

The flood mitigation measures introduced in the section 6.3 above will be examined in the following two case studies in combination with the flooding simulation in Chapter five.

6.4.1 Trondheim Case Study

Regarding to the flooding situation in Trondheim, the effectiveness of two flooding mitigation measures, reducing impervious areas of a catchment and increasing the existing sewer capacities, are examined in the Trondheim case study.

6.4.1.1 The Impacts of Catchment Imperviousness on Flooding

According to the statistics of land use for Trondheim-Fredlybekken (Chapter five), the average percentage of imperviousness of this catchment is about 26%. It told us that the degree of urbanization in this catchment is relatively lower comparing with other areas, for example Beijing-Baiwanzhuang catchment (Chapter five). However, it is increasing gradually in recent years, and over a longer period, its hydrological effects can be significant. Therefore, it is essential to check the impact of urbanization on flooding, and to give recommendations to compensate for the impact, if possible, and for new development plan.

In combination with the flooding simulation in Chapter five, the impact of catchment imperviousness is illustrated by comparing current imperviousness with a 10% reduction, rainfall of 1 in 10 years and 1 in 20 years in 90 minutes are applied for the simulation. The results are displayed in Fig. 6.1~ Fig. 6.5.

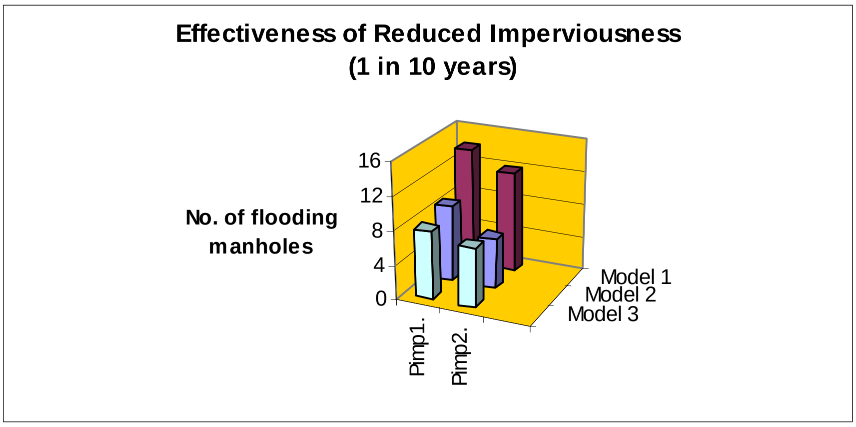


Figure 6.1 The effectiveness of 10% reduction of catchment imperviousness with block rainfall of 1 in 10 years

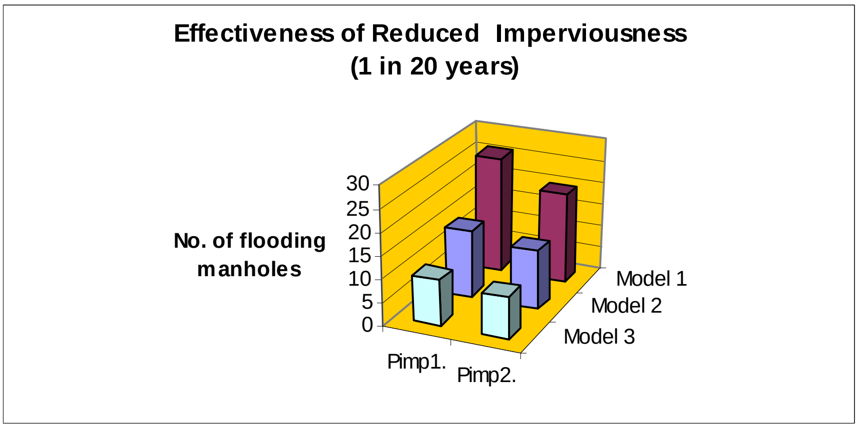


Figure 6.2 The effectiveness of 10% reduction of catchment imperviousness with block rainfall of 1 in 20 years

Fig. 6.1 and Fig.6.2 illustrate the change of the number of flooding manholes comparing original and 10% reduced imperviousness of each subcatchment. The following Fig.6.3~Fig.6.5 display the difference of maximum floodwater level from the three models. These results indicate that the impact of catchment imperviousness on flood is sensitive, and people should be awere of it when they rebuild old urban areas, and make land use plan for new developing areas.

However, it is difficult to reduce the impervious areas in highly developed urban cactments. So that alternative solutions have to be considered to solve the current flooding problem.

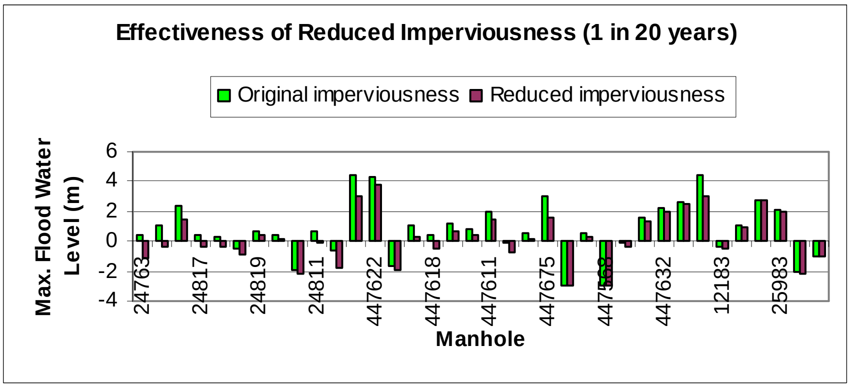


Figure 6.3 The effectiveness of 10% reduction of imperviousness with block rainfall of 1 in 20 years (Model I)

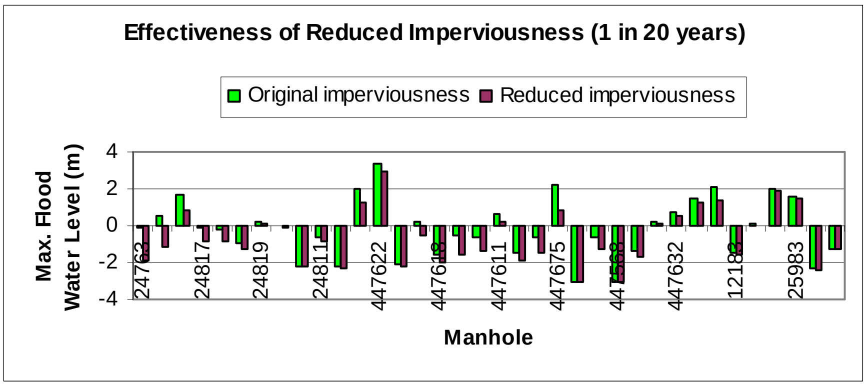


Figure 6.4 The effectiveness of 10% reduction of imperviousness with block rainfall of 1 in 20 years (Model II)

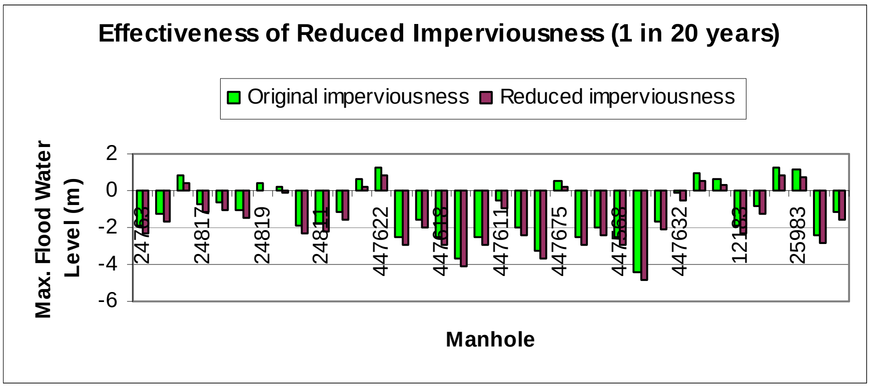


Figure 6.5 The effectiveness of 10% reduction of imperviousness with block rainfall of 1 in 20 years (Model III)

6.4.1.2 The Effectiveness of Increasing the Sewer Capacities

According to the flooding simulation of Fredlybekken case study in Chapter five, the trunk sewers from manhole 447632 to manhole 25980 have higher risk of flooding. In the original sewer system, there are two parallel sewer lines at downstram of manhole 25980 but only line at upstream of manhole 25980. Therefore, the sewer capacities in this section are potentially insufficient during large discharge period. Thus they are optimised in this study. Instead of changing the size of existing sewers, a fictive parallel line of sewers, which have the same size as the existing ones, are added to the existing sewer system. The effects are displayed in Fig. 6.6 ~Fig. 6.10.

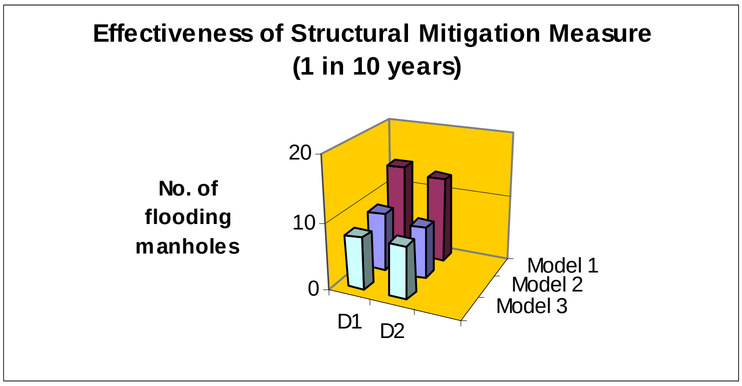


Figure 6.6 The effectiveness of enlarged sewer capacity for block rainfall of 1 in 10 years

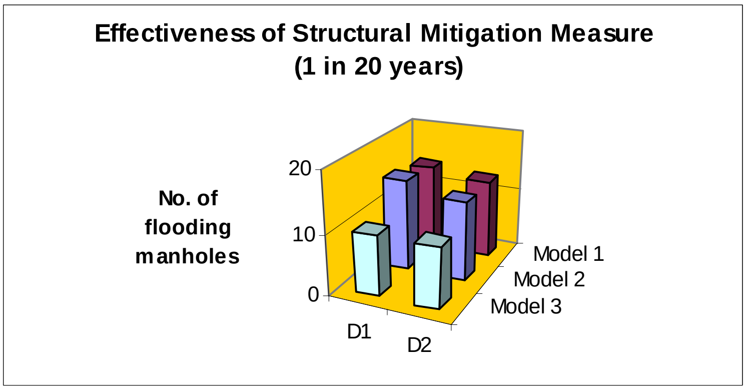


Figure 6.7 The effectiveness of enlarged sewer capacity for block rainfall of 1 in 20 years

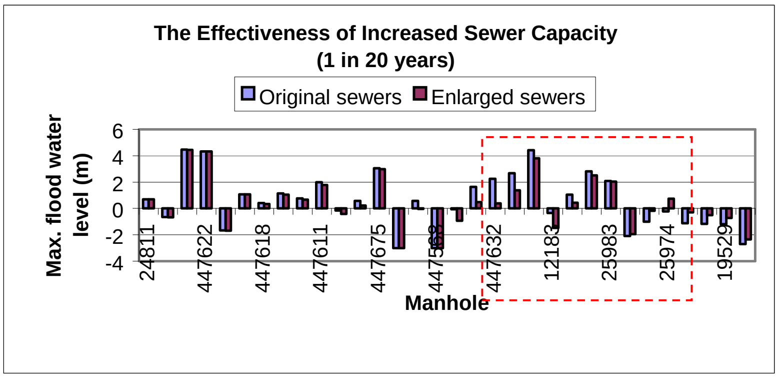


Figure 6.8 The effectiveness of increased sewer capacity for rainfall of 1 in 20 years (Model I)

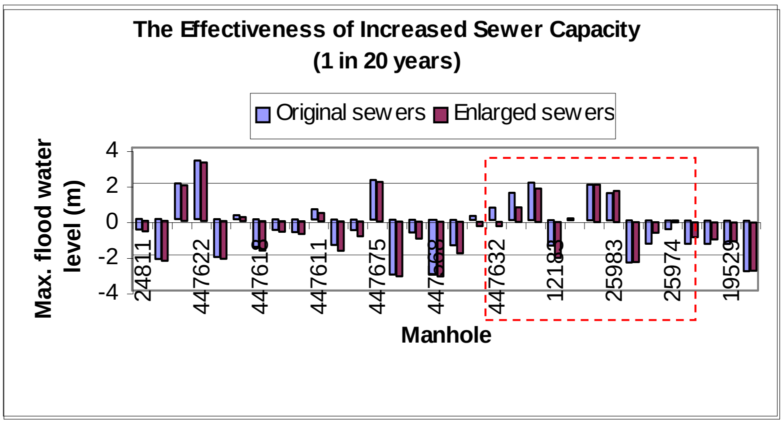


Figure 6.9 The effectiveness of increased sewer capacity for rainfall of 1 in 20 years (Model II)

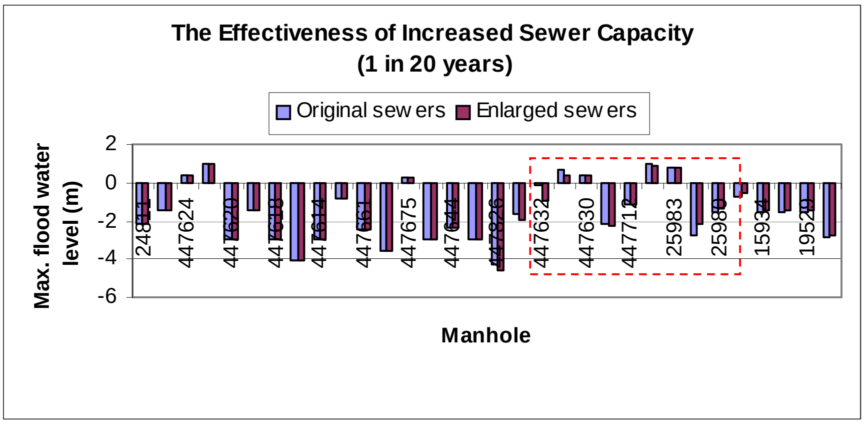


Figure 6.10 The effectiveness of increased sewer capacity for rainfall of 1 in 20 years (Model III)

Fig. 6.6 and Fig. 6.7 illustrate the change of flooded manholes before and after the modification of sewer capacities. Fig. 6.8~6.10 display the difference of maximum flood water level. The highlight parts with red dash-line are where the sewers are optimised. It is indicated that the flood water level of the optimized sewers are reduced, meanwhile, however, the water levels of downstream sewers is increased, but there is no flooding from downstream sewers, because the downstreams sewers have very large capacities in this case study.

6.4.1.3 Discussions of Flood Mitigation of Fredlybekken Case Study

Two flooding mitigation measures are examined in the Trondheim-Fredlybekken case study: the effectiveness of reducing catchment imperviousness and increasing capacities of the existing sewers. According to the simulation and analysis above, keeping lower catchment imperviousness is a good solution for flood control, because it is able to reduce the risk of flooding at the source, i.e. reducing the value of runoff. It is a solution so called “source control”. Regarding to today’s land use of Fredlybekken catchmnet, i.e. 30% imperviousness, the risk of flooding is not high for rainfall less then 1 in 20 years within 1-hour. For those sewers that have higher risk of flooding when rainfall becomes heavier, a structural flood mitigation measure of increasing sewer capacities is tested. The simulation indicates the flood water levels of optimised sewers are reduced, but the adverse effect is that the water levels of downstream sewers is increased though there is no flooding from downstream sewers.

It is concluded that keeping the percentage of imperviousness of Fredlybekken catchment under 30% and increasing the sewer capacities from manhole 447632 to 25980 are two possible solutions for flood mitigation in the Trondheim-Fredlybbekken catchment. However, it should be cautious enlarging the sewer sizes to aviod deterirotating flooding situation of downstream sewers.

6.4.2 Chinese Case Study

The Beijing-BWZ catchment, applied as a case study for flooding simulation in Chapter five, is also used for flooding mitigation. Compared with Trondheim-Fredlybekken catchment, the flooding situation of BWZ catchment is different because of the different sewer systems, their design standards and the land use.

Regarding the probable risk of flooding of BWZ catchment, the effectiveness of the following mitigation measures are examined:

- Changing the catchment imperviousness;
- Increasing the soil infiltration;

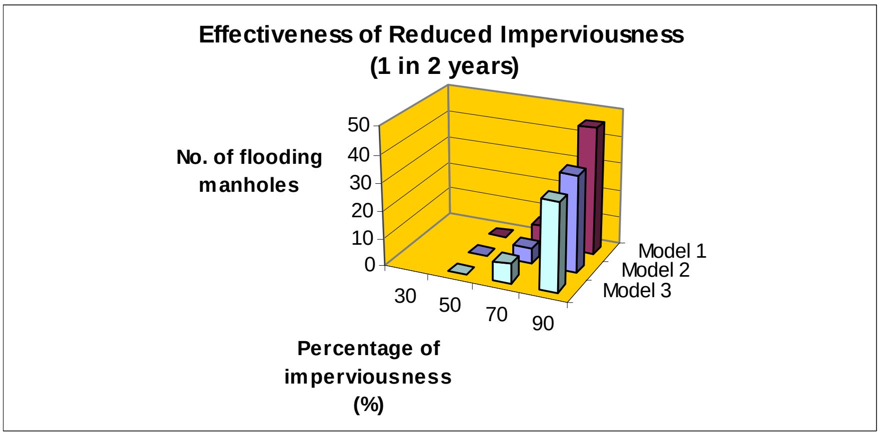
- Replacing the existing sewers on WXJ lateral sewers by large size sewers to ensure that the lateral sewers have a capacity for flooding of 1 in 2 years.
- Constructing off-line retention water tanks at the main sewers of CGZ6-8 to ensure the main sewers having capacity to transport stormwater generated from rainfall of 1 in 10 years.

6.4.2.1 The Effectiveness of Catchment Imperviousness

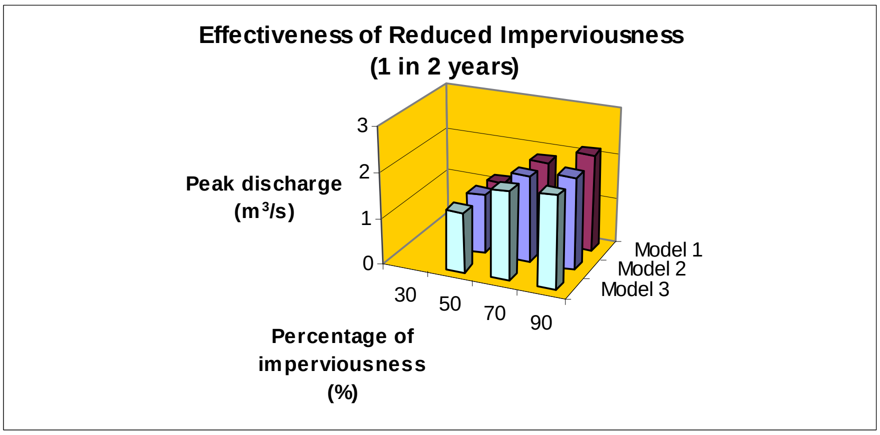
Keeping other parameters in the rainfall-runoff model constant, flooding simulation is carried out assuming the percentage of catchment imperviousness of 90% (the current value), 70%, 50% and 30% (the value in 70s) individually. The results are displayed in Fig. 6.11 and 6.12.

Fig. 6.11 (a) presents the number of flooding manholes for rainfall of 1 in 2 years. Where, when the percentage of imperviousness is under 50%, no manhole is flooded. However, when the catchment imperviousness increases to 70%, about 10% manholes are flooded and more than 50% manholes are flooded when catchment imperviousness increases to 90%. Fig. 6.11 (b) and (c) displays the change of peak discharge and discharge time series at outlet of BWZN subcatchment.

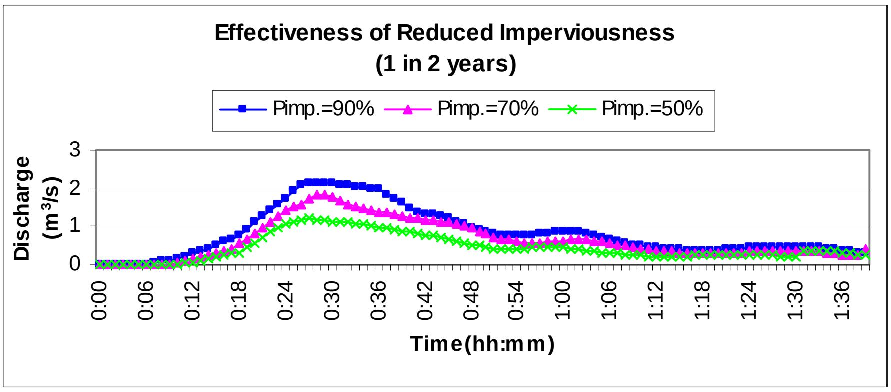
As displayed in Fig. 6.12 (a) for rainfall of 1 in 10 years, there is no flooding manhole when the percentage of catchment imperviousness is 30%. However, 25% manholes are flooded when the imperviousness increases to 50% and more than 50% manholes are flooded with 70% catchment imperviousness. The number of flooding manholes remains almost the same when the percentage of imperviousness increases from 70% to 90%. This is because most of the manholes of lateral sewers are at capacities with 70% of imperviousness. Therefore, the number of flooding manholes will be almost the same for lateral sewers with even a higher percentage of imperviousness, and meanwhile only few main sewers are flooded when catchment imperviousness increases to 90%. The changing of peak flow and flow hydrograph are displayed in Fig. 6.12 (b) and (c) and numerical results are summarized in table 6.3.



(a). Number of flooding manholes

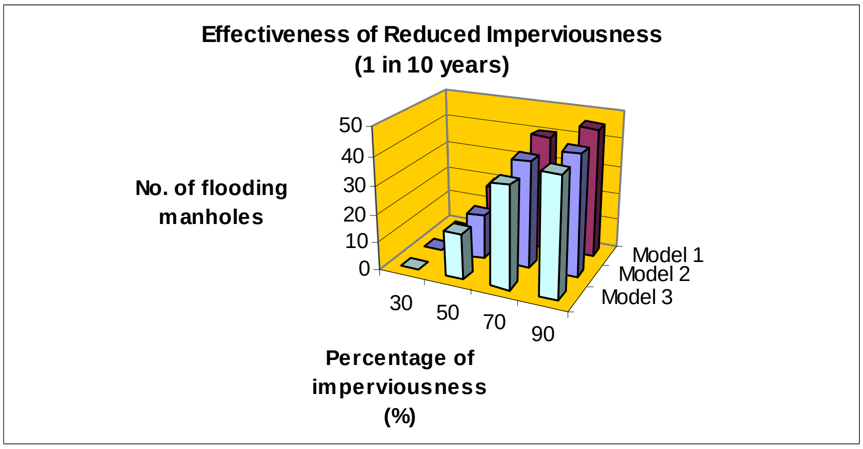


(b). Peak discharge

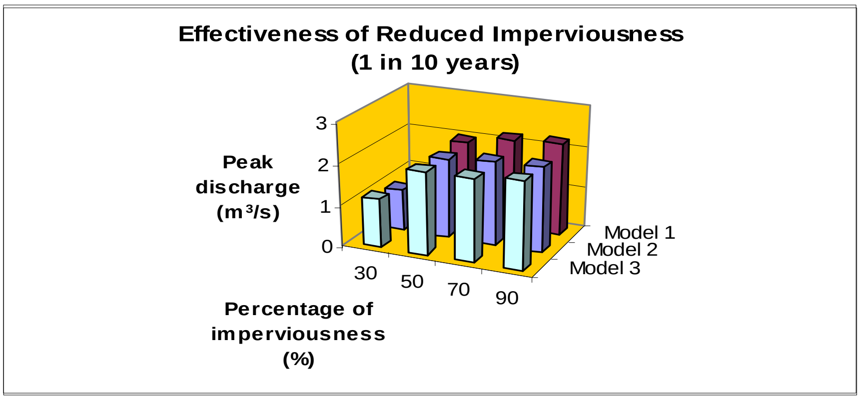


(c). Hydrograph at BWZN sewer outlet

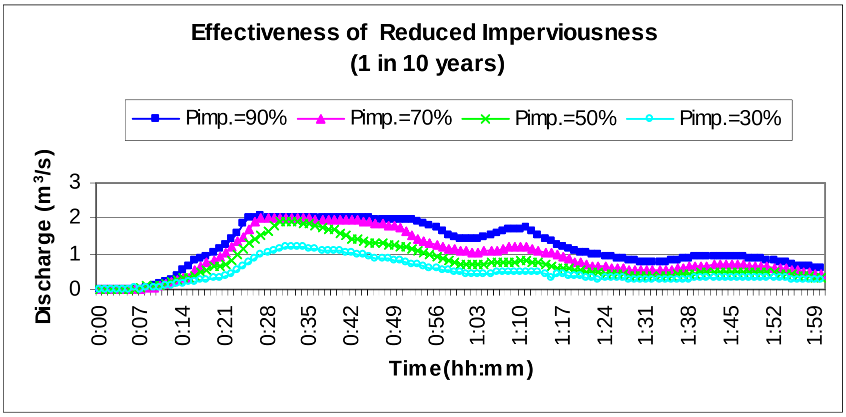
Figure 6.11 Effectiveness of catchment imperviousness for rainfall of 1 in 2 years



(a). Number of flooding manhole



(b). Peak discharge



(c). Hydrograph at BWZN sewer outlet

Figure 6.12 Effectiveness of catchment imperviousness for rainfall of 1 in 10 years

Table 6.3 Summary of flooding mitigation of BWZ case study: the impacts of catchment imperviousness

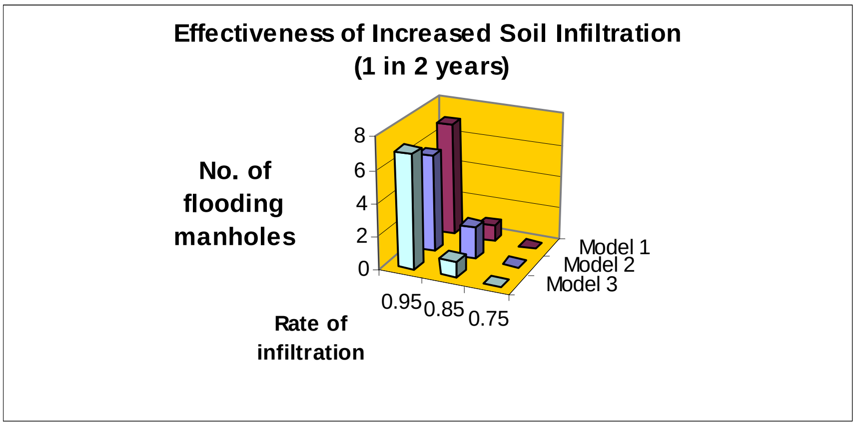
Flooding frequency (1 in n years)	**Flood index**		**Model I**				**Model II**				**Model III**		
			90%	**70%**	**50%**	**30%**	**90%**	**70%**	**50%**	**30%**	**90%**	**70%**	**50%**
2	No. of flooding manholes	WXJ	5	5	0	—	3	3	0	—	4	2	0
		BWZN	35	2	0	—	29	3	0	—	25	5	0
		CGZ	6	0	0	—	3	0	0	—	3	0	0
	Peak discharge (m^3s)	BWZN	2.149	1.837	1.205	—	2.204	1.887	1.303	—	2.013	1.931	1.311
10	No. of flooding manhole	WXJ	5	5	5	0	4	4	3	0	5	5	3
		BWZN	34	34	12	0	34	31	13	0	34	28	13
		CGZ	7	3	3	0	5	3	0	0	3	3	0
	Peak discharge (m^3s)	BWZN	2.261	2.201	2.007	1.191	2.083	2.047	1.948	1.048	2.140	2.024	2.000

6.4.2.2 The Effectiveness of Increased Soil Infiltration

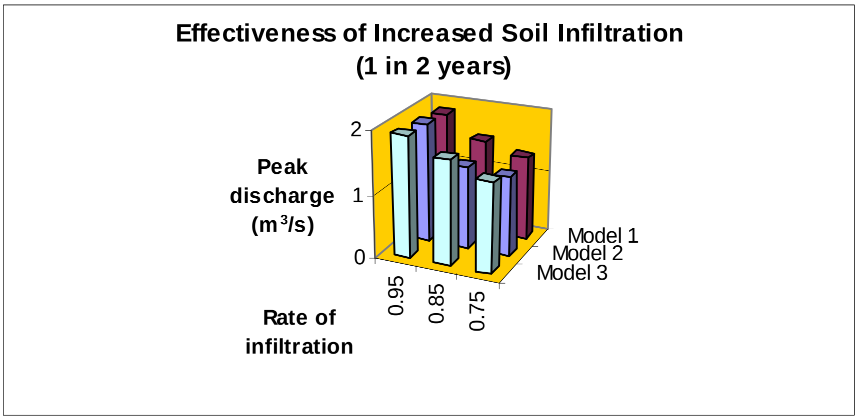
Reduction of catchment imperviousness is an effective mitigation measure to reduce the risk of flooding. It is, however, difficult to implement in highly developed urban areas, such that other alternatives have to be considered. In turn, the effectiveness of increasing soil infiltration is examined, which could be achieved replacing the current paved areas by using percolated materials (Tveit and Zhu et al., 1996; Thorolfsson, 1997; Fujita, 2002).

In the rainfall-runoff model A of Chapter five, runoff is assumed generated from only impervious areas, the reduction due to soil infiltration, envaptranspiration and imperfect imperviousness is expressed by a lumped hydrological reduction factor. In the flooding simulation of Chapter five, a constant value of 0.95 is applied. Here, other two hydrological reductions of 0.85 and 0.75 are examined and the results are displayed in Fig. 6.13 for rainfall of 1 in 2 years and Fig. 6.14 for rainfall of 1 in 10 years.

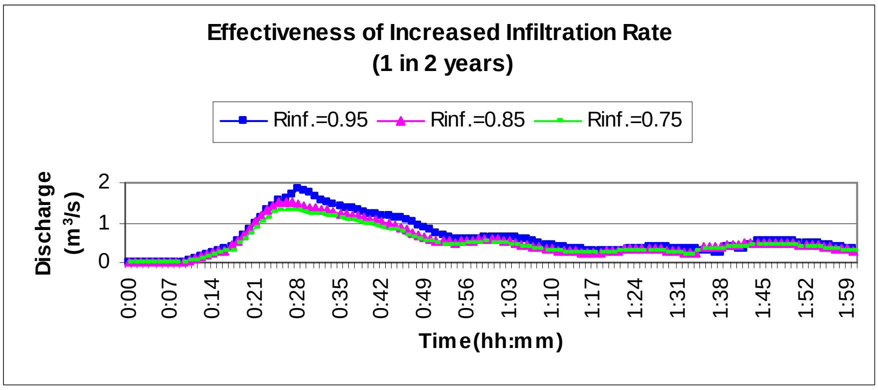
Fig. 6.13 (a) illustrates that the number of flood manhole reduces to zero for design rainfall of 1 in 2 years when the hydrological reduction factor is reduced from 0.95 to 0.75. However, as displayed in Fig. 6.14 (a), the reduction of flooding is very minute for rainfall of 1 in 10 years. The reductions of discharge are displayed in Fig. 6.13 (b) and (c) for rainfall of 1 in 2 years, and Fig.6.14 (b) and (c) for rainfall of 1 in 10 years. They indicate that the effectiveness of increasing soil infiltration is relatively less sensitive, especially for rainfall of 1 in 10 years, such that the other flood mitigation measures are still needed.



(a). Number of flooding manholes

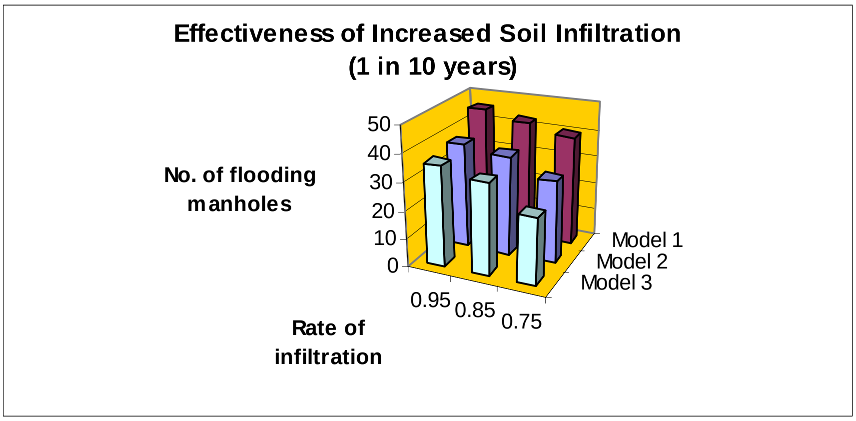


(b). Peak discharge at sewer outlet

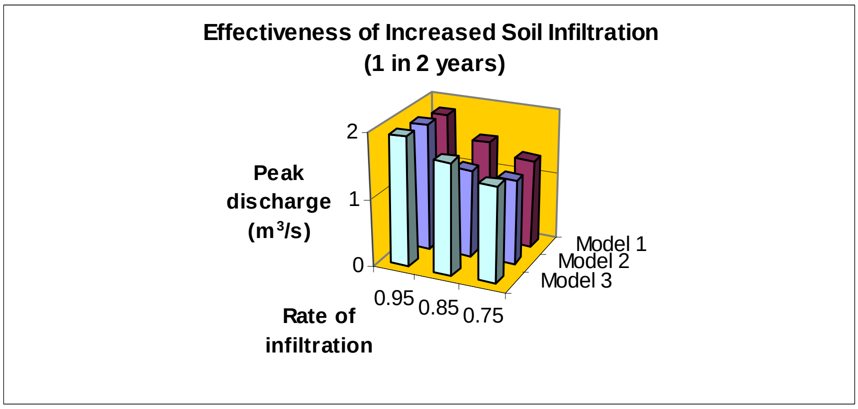


(c) Hydrograph at BWZN sewer outlet

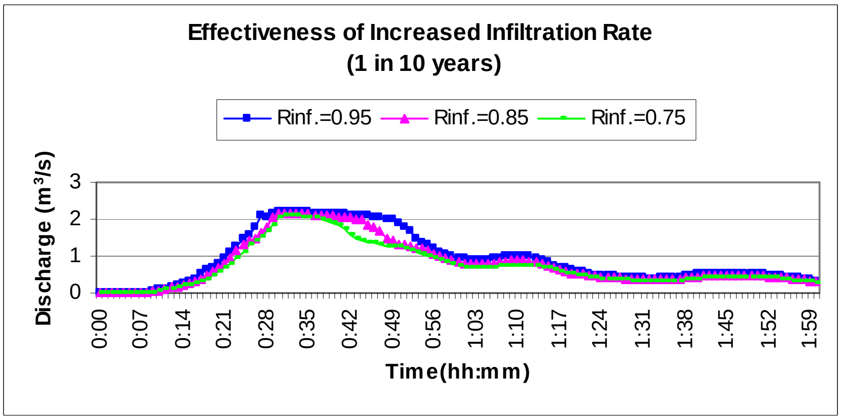
Figure 6.13 Effectiveness of increased soil infiltration for rainfall of 1 in 2 years



(a). Number of flooding manholes



(b). Peak discharge



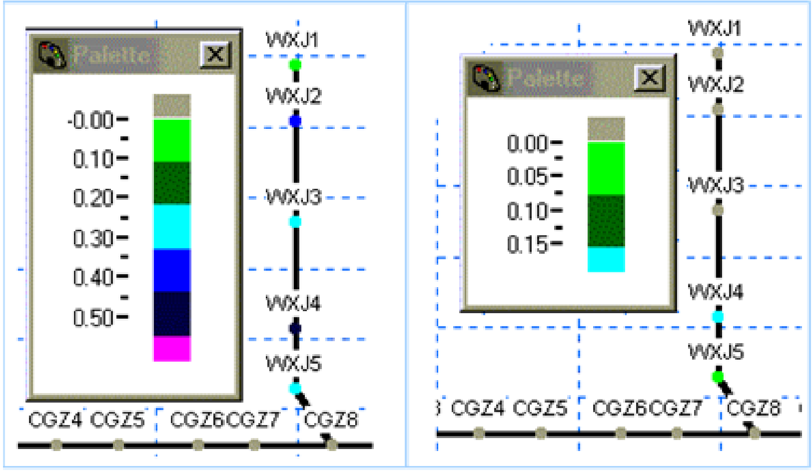
(c). Hydrograph at BWZN sewer outlet

Figure 6.14 Effectiveness of increased soil infiltration for rainfall of 1 in 10 years

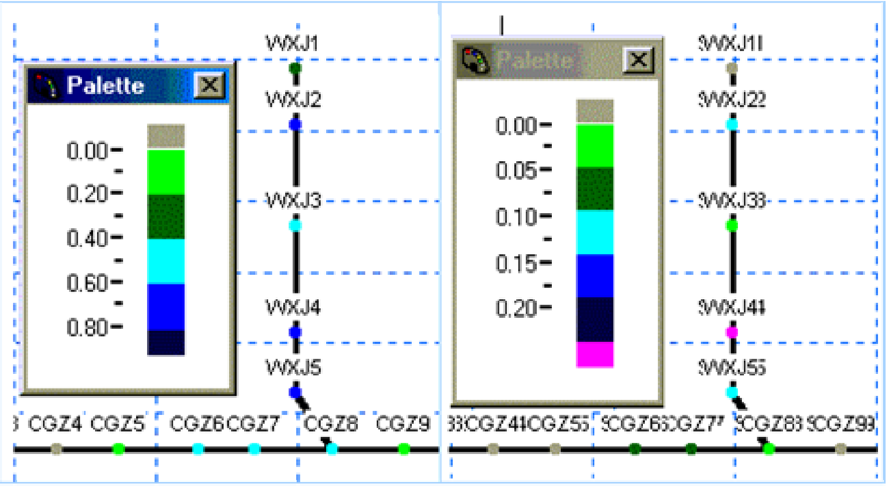
6.4.2.3 The Effectiveness of Structural Mitigation Measures

According to the flooding simulation in Chapter five, the sewers in BWZN catchment have capacities to drain stormwater of 1 in 2 years rainfall except one section between manhole 36 and 37. The capacities of sewers on WXJ Street are insufficient to drain stormwater of rainfall of 1 in 2 years and sewers on CGZ Road can transport less stormwater of 1 in 10 years rainfall, where three manholes are flooded. Flood mitigation measures of reducing the percentage of catchment imperviousness and increasing the rate of soil infiltration have been examined. Through the simulation, the risk of flooding can be reduced to some extent. However, on the one hand, it is difficult to implement these two measures in highly developed urban areas; on the other hand, the mitigation merely depending on soil potentials is limited. Consequently, two other mitigation measures are, in turn, examined to ensure the lateral sewers are able to drain stormwater safely for rainfall of 1 in 2 years, and to ensure main sewers have the capacities to drain stormwater for rainfall of 1 in 10 years.

Enlarging sewers on WXJ Street Assuming the sewer diameters are increased from 0.6m and 0.7m to 1.0m, as displayed in Fig. 6.15 (a) at 70% of catchment imperviousness for rainfall of 1 in 2 years, all the manholes are flooded on WXJ original sewers, while there is very small flooding from manhole 4 and 5 with enlarged WXJ sewers. Fig.6.15 (b) displays the flooding situation of enlarged sewers when the percentage of catchment imperviousness increases to 90%, where manholes WXJ2-5 are still flooded. The legends in Fig. 6.15~6.18 illustrate the flood water level.



(a). Pimp. =70%: Original sewers (left); Enlarged sewers (right)



(b). Pimp. =90%: Original sewers (left); Enlarged sewers (right))

Figure 6.15 Flooding mitigation of WXJ sewers for rainfall of 1 in 2 years

For sewers in BWZN catchment As displayed in Fg.6.16, flooding occurs at manhole 36 and 37 for rainfall of 1 in 2 years. Problem could be solved locally replacing the vulnerable sewer 36-37, or replacing the branch sewers from 36 to 39 by larger sewers, if necessary, to avoid flooding shifted to sewers downstream.

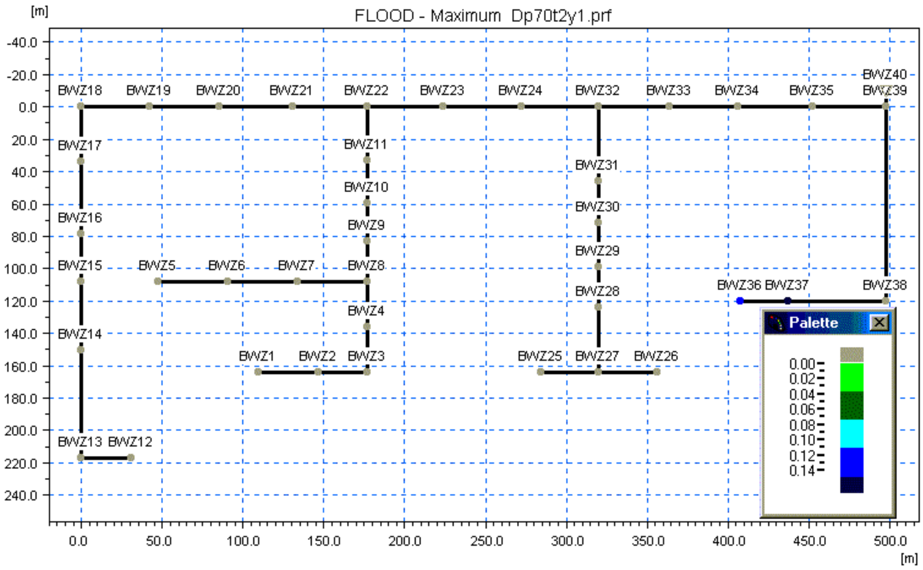


Figure 6.16 Flooding simulation result of BWZN sewers of 1 in 2 years

For main sewers on CGZ Street In case of flooding of 1 in 10 years, as displayed in Fig.6.17, the mitigation measure has to be considered to protect flooding from manhole CGZ6-9 on CGZ main sewers. Meanwhile the lateral sewers in BWZN along the main road (Fig. 6.18) should be considered as well.

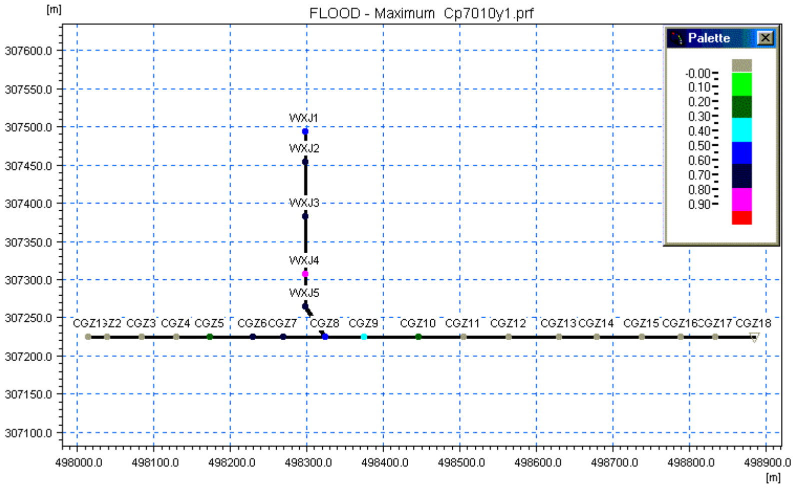


Figure 6.17 Flooding of CGZ sewers for rainfall of 1 in 10 years

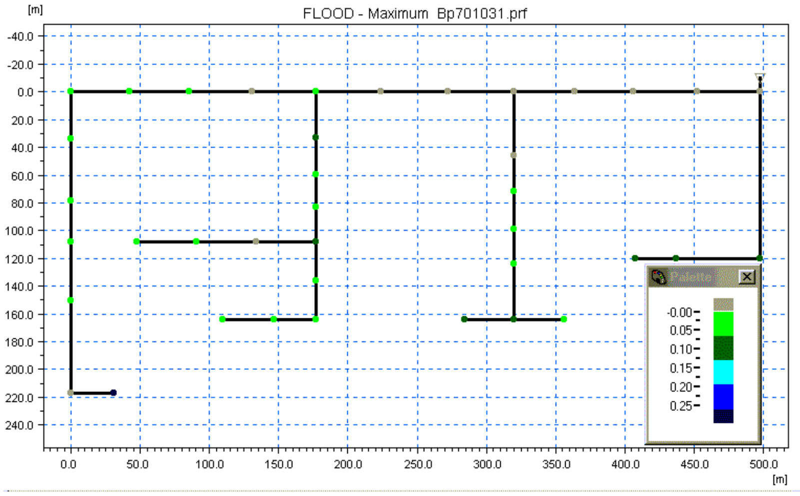


Figure 6.18 Flooding of BWZN sewers for rainfall of 1 in 10 years

Considering stormwater reuse and reducing the flooding of connecting sewers without deteriorating flooding situation of sewers downstream, an off-line storage tank is inserted to original sewer system as displayed in Fig. 6.19. It works based on water level control at connected manholes. As the water level at these manholes reaches the critical level of flooding, then the extra stormwater will be diverted to the storage tank by an overflow weir. The stored water can be pumped back to the system via pumps after the flooding ceases, or be provided for other uses. In the case of BWZ catchment, the off-line storage tank can also provide capacity for BWZN sewers (Fig. 6.19). The potential floodwater that might be diverted into the storage tank is illustrated in Fig. 6.20. The stormwater on-line and off-line storage facilities have been widely and successfully implemented in Japan (Funayama, Shinkawa, et al., 2002).

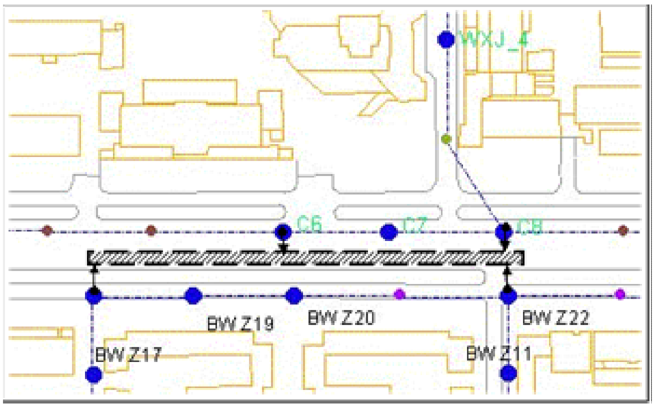
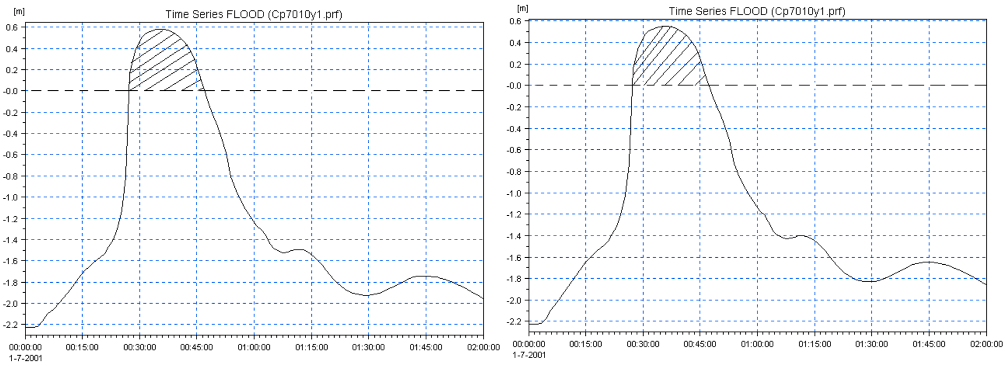
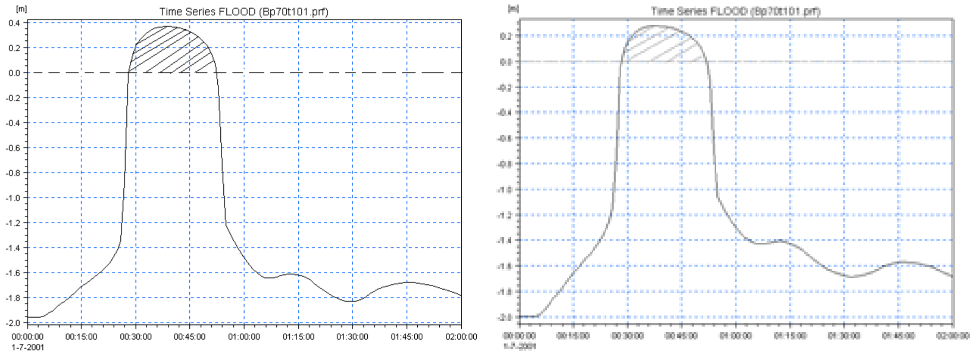


Figure 6.19 Sketch of an off-line storage tank



(a). CGZ 6-7

(b). CGZ 7-8



(c). BWZN 18-19

(d). BWZN 22-23

Figure 6.20 The effectiveness of the off-line storage tank

6.4.2.4 Discussions of Flood Mitigation of BWZ Case Study

Four flood mitigation measures have been examined in the BWZ case study. The effectiveness of reducing the catchment imperviousness is the most effective if it could be achieved in real catchment. Increasing the rate of soil infiltration is sensitive for light rainfall, for example, rainfall of 1 in 2 years. The flooding situation of WXJ lateral sewers for rainfall of 1 in 2 years can be reduced by increasing the current sewer sizes to 1.0m. Replacing BWZN sewer from manhole B36 to B37 (B39) can protect BWZN sewer from flooding of 1 in 2 years' rainfall. In addition, considering the water situation in Beijing, an off-line storm water storage tank was tested for CGZ main sewers from C6-C9, which might be an advisable solution because it not only reduces the risk of flooding but also stores the stormwater for other uses.

6.5 Summary

When flooding happens in urban areas, either on the main road, or in the residential districts, damage in deluged houses and other habited areas, as well as adverse impacts on activities in the flooding areas are inevitable. Traffic may be halted, and lines for supplying electricity, water and gas may even be broken. Therefore, flooding mitigation must be taken into consideration.

Two flooding mitigation measures, i.e. reducing catchment imperviousness and enlarging the sewer capacity, were examined in the Trondheim case study. Through the analysis, it is effective to reduce the risk of flooding by reducing the catchment imperviousness. The simulation also indicates that keeping catchment imperviousness under 30% is a good solution for flood control in the Trondheim case. The sewer capacities from manhole 447632 to manhole 25980, where it is indicated having higher risk of flooding, are increased. Through the simulation, the flood water levels of optimised sewers are indeed reduced, while the water levels of downstream sewers are increased though there is no flooding from downstream sewers. It tells us that it is possible to reduce the local flooding problem by enlarging the sewers there, however, it should be cautious to aviod deterirotating flooding situation of downstream sewers.

Four different flood mitigation measures were examined in the BWZ case study. Reducing the percentage of catchment imperviousness is the most effective one. In addition, increasing the soil infiltration is sensitive for light rainfall, for example, rainfall of 1 in 2 years. In addition, two other mitigation measures, enlarging the sewer size and designing an off-line stormwater storage tank, were tested. The simulation indicated that increasing the sewer size to 1.0m on WXJ Street could reduce the flooding situation for rainfall of 1 in 2 years. Local solution of replacing BWZN sewer from manhole B36 to B37 (B39) can protect BWZN sewer from flooding of 1 in 2 years' rainfall. An off-line stormwater storage tank was examined to protect the main sewers from flooding of 1 in 10 years; meanwhile the stored floodwater can also be provide for other purpose.

Overall, the combination of non-structural and structural flood mitigation measures is the best solution for flood control. Thus, a sustainable solution of living with flooding could be achieved.

Chapter 7

Main Results, Conclusions and Suggestions for Future Research

One has definitely got a lot of results from a period of research. Some may turn out as seeds; others perhaps just as sermon.

7. MAIN RESULTS, CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

7.1 Main Results and Conclusions

The risk of urban flooding increases during the progress of urbanization. Floods cause severe consequences as they happen. This thesis set aims to find the potential flood hazards and to analyze how floods happen, further on, to develop models and procedures to calculate the propagation of the flow in sewers and on the surface. Advanced GIS technology was applied into the model development and flooding simulation. The final procedure of this study was to test the effectiveness of flood mitigation measures for giving recommendations to solve or compensate the flooding problems in urban catchments, or to make development plan of rebuilding the old areas or developing new areas. The research in this thesis achieved the following main results and lead to the subsequent conclusions:

1. A total of 68 potential hazards were identified in Chapter three. These hazards range from natural hazards, technical defects to man made mistakes and errors. These potential threats lead to urban floods having happened frequently and cause large amount of damage. In particular, they cause more inconvenience to municipality activities and residents' daily life. Therefore, attention should be paid to urban flooding in addition to large river floods.

2. The GIS-based analysis in Chapter four produced the following results:

    2.1 Watersheds and surface stream networks are two important products delineated from the DEM, which were illustrated in the Trondheim case study.

    2.2 It is possible to produce proper sizes of watersheds and suitable levels of stream networks applying GIS hydrological model to meet the needs of applications.

    2.3 The resolution of the grid DEM should be specified according to the needs of applications. A small grid size gives a more accurate representation of uneven terrain but generates a large amount of redundant data for representing uniform terrain in the same study area, and vice versa.

    2.4 The influence of buildings, which consist of part of "elevation contours", or "elevation points", on the delineation of watersheds and surface streams should be considered when people check the flow situations of small streams, branch or lateral sewers which connect to buildings.

Otherwise, it can be omitted when one is only interested in the main sewers and runoff from large subcatchments.

2.5 GIS also provides an ideal tool to analyze other digital data. Taking sewer data in the Fredlybekken of Trondheim case study as an example, they were checked carefully using GIS. The errors in the sewer database and defects in the existing sewers were identified.

2.6 GIS-based preliminary flooding analyses delineated the flood risk zones for the Trondheim case study in Norway and the Jingdezhen case study in China, which are valuable for making floodplain development plan and for further intensive flood simulation.

Concisely, GIS build a bridge between digital data and wide range of applications.

3. Two flood models, the “basin” model and the dual drainage model, were developed in Chapter five on the basis of the MOUSE program:

3.1 The MOUSE model consists of submodels of rainfall-runoff, pipe flow and a virtual surface flooding tank to deal with flooding problem when it occurs during simulation. It is designed to control the water balance at flooding manhole(s), but it cannot simulate flow on the surface. A virtual tank up to $1000A_m$ surrounding the flooded manhole will be automatically activated as flooding occurs. However, such a tank neither represents the flood area nor the flood routes in reality, so that improvement needs to be made.

3.2 The “basin” model consists of submodels of rainfall-runoff, pipe flow and the routine of basin. A “basin” treats manhole and surface flooding areas as one. The surface flood area is extracted from DEM. The floodwater in a basin is the water from the ground level of a manhole to the highest water level in the basin. The advantages of the “basin” model are its simple structure and comparatively reliable representation of flooded areas on the surface. However, a “basin” merely performs as a storage tank, no hydraulic routine to simulate surface flow between neighboring basins.

3.3 Further on, the dual drainage flood model was developed in Chapter five combining several structures in the MOUSE program. It consists of rainfall-runoff model, pipe flow model and surface channel flow model. In addition, fictive weirs were added to each manhole to transfer flow between sewers and surface channels, and fictive manholes were applied at the location of each manhole but stands on the surface to transfer the flow between neighboring surface channels. Therefore, the dual drainage model is able to simulate flow in underground sewers and on surface channels, and to calculate the flow exchange between these two layers. From the point of view of modeling structures, the dual drainage model is regarded as being the most advanced one.

4. The flooding capacities of existing sewer systems in two case studies were checked by three models: the MOUSE model, the “basin” model and the dual drainage model. The flooding simulation in the Trondheim-Fredlybekken catchment in Norway was carried out using the constant rainfall intensities with recurrence intervals of 1 in 10 years, 1 in 20 years and 1 in 50 years respectively. The flooding simulation of Beijing-BWZ catchment in China was carried out using available synthetic design rainfall of recurrence intervals of 1 in 2 years, 1 in 10years and 1 in 20 years. The simulation results indicate that the present sewer capacities in these two case studies are less than the design capacities. Therefore, flood mitigation measures should be considered.

5. Both non-structural and structural flood mitigation measures were examined in Chapter six applying the same case studies as flood simulations:

   5.1 The effectiveness of reducing catchment imperviousness was proved to be an effective mitigation measure to reduce the risk of flooding by reducing the value of runoff from its generation, i.e. at the source. The percentage of impervious areas of a catchment should be kept under a certain level, for example 30% in Trondheim. The current catchment imperviousness in the BWZ catchment was very critical. The test results could give recommendation to the city planners when they restore the old urban areas and making development plan for new areas.

   5.2 Increasing the rate of soil infiltration can be achieved by constructing infiltrated paved areas. The changing of soil infiltration of 0.01 and 0.02 were tested in Beijing-BWZ catchment. It was proved to be sensitive for light rainfall, for example rainfall of 1 in 2 years.

   5.3 The capacities of sewers with high risk of flooding in Trondheim-Fredlybekken catchment were increased by adding extra sewers into the existing sewer system. The flood water levels of these sewers were reduced, however, the water levels of downstream sewers were increased but no flooding occurs from these sewers. This is because the flow capacities of downstream sewers are very large in the Fredlybekken. This study also told us that one should be cautious increasing the sewer size to avoid deteriorating flooding situation of downstream sewers.

5.4 An off-line stormwater storage tank was tested in Beijing-BWZ catchment. It was designed by water level control to protect main sewers at CGZ road from surface flooding. The stored stormwater can be pumped back to the sewer system after flooding ceases, or it can be provided for other uses.

5.5 Comparing with on-line pipes added in the Trondheim case study, the advantage of the off-line stormwater storage tank is able to reduce the risk of flooding without increasing the flooding of sewers downstream.

6. It cannot be over emphasized that appropriate management and sufficient supervision are always essential to reduce the risk of flooding from operational obstacles in all stages of drainage system development and operation.

Overall, the research in this thesis concludes that the combination of structural and non-structural flood mitigation measures is regarded as the best solution for flood control, or in other words, urban development, land use and flood control should be considered as one.

7.2 Suggestions for the Future Research

The research presented in this thesis primarily focuses on the subject matters of finding out the risk of urban flooding, the use of GIS in flooding simulation, flood model development, flooding simulation and mitigation. However, four years period is limited, and consequently the results are not yet perfect. Improvement ought to be made in future.

The suggestions for future research are divided into two main parts: the improvements toward the studies in this thesis and the ideas not being included in this thesis but optimistic for the development of the studied subjects.

1. Regarding studies carried out in this thesis, the following improvements are suggested for future research:

1.1 Floods may be caused by joint events. To decide about the frequency of flooding of joint events is, however, very complicated. The study in the thesis proceeds simply by considering few events with known frequency. It should go forward to embrace more flooding scenarios. Meanwhile, the present frequencies should be corrected when the observed data series are longer.

1.2 GIS builds a bridge between digital data and hydrological as well as hydraulic analysis, which makes it possible for hydrologists and hydraulics to use the digital data in many ways. However, the requirements for digital data and their characteristics vary with models, or programs, which lead to large amount of time in transforming data from one format to another, or adding the characteristics that models need. It cannot be over emphasized that the better understanding of the application, the better database will be produced. Further on, the collaboration of data producer and program developer or users is encouraged.

1.3 Moreover, GIS-based hydrological analysis should proceed to compile the vertical characteristics of soil, if available.

1.4 The dual drainage flood model developed in Chapter five should be carefully checked together with MOUSE developers of DHI. Particularly, the connecting and disconnecting of the MOUSE surface flooding tank and the weir options.

1.5 The flood simulation for the Fredlybekken catchment in the Trondheim case study should be corrected when the measured invert levels of manholes are available. Likewise, the flood simulation should go further to catchment level III, i.e. smaller catchment, in order to know the risk of flooding of lateral sewers. Moreover, winter flooding situation should be studied as well in the Trondheim case.

1.6 For flooding mitigation in the Trondheim-Fredlybekken catchment, adding extra sewers to the existing sewer system to increase the capacities of transporting stormwater is a common measure taken in practice. The sizes of these sewers should be further checked carefully to ensure that the flooding situation of sewers downstream does not deteriorate.

2. In addition to the improvements suggested to the research presented in this thesis, the following ideas might be integrated into future research as well:

2.1 The dynamic characteristics of flood hazards should be considered because natural events, technical properties of physical systems and human behavior all vary with time. Thus, it is incomplete to neglect the impacts of time effect.

2.2 In addition, the time in GIS digital data are important as well. A digital database is generally built assuming static geographical feature condition at a certain time. It is a known fact, however, that geographic features evolve through time. Many of them change as a result of natural processes; but in other cases, they change as a result of human intervention. Land cover, surface terrain, stream networks are examples that may change over time, and that may have significant impacts on urban hydrology and flooding analysis. However, the developed models and methods merely take the spatial variation of characteristics into consideration, further research should also analyze the risk of urban flooding over time.

2.3 Design flooding frequencies for major and minor drainage systems differ between in cities and countries. The protection standards of rivers are generally higher than sewers. Higher standard, such as flooding frequency of 1 in 100 years, has been applied to protect cities from river flooding, but less than 1 in 10 years for sewers. Obviously, there exists a gap between these two standards. According to river protection standards, cities should be safe when rainfall does not exceed the river’s limit. However, the city will be flooded because of limitation of sewer capacities. Then the question is: how do we cope with such a problem that standards do not match in minor and major drainage systems in the same areas?

Sustainable urban water management is a concerned topic of research and management. Flood control is one of the branches. Improvements of the existing models and problems have to continue and challenges of the new tasks arise during the development and over time…

SUMMARY

In spite of the great efforts made in flood control and protection, we still witness severe flood disasters: less common but large river flooding and more frequent small urban floods, which disturb cities' activities and citizens' lives in several ways besides the economic damage. As such, the basic questions were put forward to:

- Where do the hazards of urban flooding come from and how do floods happen?
- Do we have adequate methods and models to analyze the mechanism of floods in the present dynamic society?
- Do we have effective measures to alleviate the flood problems as soon as we know the risk?

This thesis answered the above questions in a stepwise manner through the following chapters:

Chapter one described flood-related problems: the global damage, the causes and the increasing risk. It illustrates the objectives of flood management, where emphasis was given to urban flood control. The aims of the present study and the organization of the thesis were introduced in this chapter as well.

Chapter two was literature review. It introduced the basic concepts of flooding, described the mechanism and characteristics of urban flooding and the state-of-the-art of urban drainage systems (Appendix B and C). The research progress of risk analysis, urban flooding model development, GIS in flooding analysis were overviewed. As a result, the needs for further development were obtained in the last part of this chapter.

Chapter three was one of the core parts of this thesis. It sought answers to the following questions***: Why*** do floods happen? ***How*** do they happen? ***How often*** do they happen? ***What*** are the potential consequences? ***How*** do we alleviate the flooding problems and mitigate the potential consequences? A total of 68 potential flood hazards were identified. Among them, root causes and contributing factors were distinguished by the fault tree method and probable flooding scenarios were discovered by event tree analysis. In addition, the theory and formulae of probability and statistics were introduced to estimate flooding frequency. Flooding consequences, risk evaluation and mitigation were discussed as well. On these bases, a case study of estimating flooding frequency was carried in the Trondheim, Norway.

Experiences told us that large river flooding is a tragedy. Sewer flooding is less catastrophic compared to large river flooding. However, it happens more

frequently and affects the cities' activities and citizens' lives in many aspects. Therefore, it was concluded that management attentions should be paid to flooding from sewer systems in addition to large river flooding, and men should also pay attention to the interaction of sewers, rivers and the sea, if such a situation exists.

Information is definitely indispensable for scientific analyses. Geographical Information System (GIS) is a one of the most powerful tools to collect, produce, store, analyze and process digital data. Chapter four is GIS-based analysis. It introduced the basic concepts of GIS. Focus was given to Digital Elevation Model (DEM) and its applications in hydrological analysis. Two important hydrological elements, watersheds and stream networks on surface, were delineated. The resolution of grid, the size of watersheds and the levels of stream networks, the influence of structures on surface were studied individually. In addition, a GIS-based method of preliminary flooding analysis was introduced in combination with two case studies. Moreover, the sewer data were analyzed on the template of GIS, where the errors in the database and defects of existing sewers were identified.

The analysis in Chapter four provided basic products for flooding simulation in Chapter five.

Chapter five focused on flood model development of urban drainage systems. Where, two flood models, the "basin" model and the dual drainage model, were developed on the basis of the MOUSE program.

The MOUSE model consists of submodels of rainfall-runoff, pipe flow and a virtual surface flooding facility to deal with flooding problem when it occurs during simulation. It is designed to control the water balance at flooding manhole(s), but it cannot simulate flow on the surface. A virtual tank up to $1000A_m$ surrounding the flooded manhole will be automatically activated as flooding occurs. However, such a tank neither represents the flood area nor the flood routes in reality, so that improvement needs to be made.

On the basis of the MOUSE program, a "basin" model was developed. Compared to the MOUSE surface flooding tank, the "basin" model includes the volumes of surface flooding areas extracted from DEM, which represent better the surface flood areas and flood volume than the fictitious flood tank in the MOUSE. The dual drainage model was further developed to simulate the flow in underground sewers and on surface channels, and to describe the water interaction of these two layers. From the point of modeling structure, the dual drainage flood model was regarded the most advanced one. All these three models, the MOUSE model, the "basin" model and the dual drainage flood model were examined through two case studies; and then applied to flooding simulation to check the flow capacities of existing sewers in two case studies.

Chapter six went forward to flooding mitigation. Several mitigation measures were examined through the two case studies. The effectiveness of changing the percentage of catchment imperviousness and increasing the rate of soil infiltration were tested. The effect of catchment imperviousness was proved to be very sensitive. The impact of increasing soil infiltration is effective for light rainfall. These two flood mitigation measures were proved being effective to reduce the risk of flooding by reducing the value of runoff at the sources. They are valuable recommendations for flood control while making plan to restore the old urban areas and developing new areas. In addition, structural flood mitigation measures, increasing sewer size and constructing off-line storage tank, were examined as well. The simulation in the Trondheim-Fredlybekken case study indicated that increasing on-line sewer capacities could reduce the risk of flooding of connecting sewers. However, the sizes of larger sewers have to be designed carefully to avoid shifting flooding to downstream. Unlike adding the on-line sewers, the off-line stormwater storage tank designed for Beijing-BWZ case study can reduce the flooding of connecting sewers without deteriorating the flooding problem of sewers downstream. In addition, the stored stormwater can be provided for other purpose.

Chapter seven summarized the main results and conclusions attained from this study and suggestions were given for future research.

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APPENDICES

Appendix A Global Flooding Album

Several flooding scenarios from different regions in the world are collected and presented in this appendix.

Figure A.1 Flooding in Dhaka, Bangladesh, 1987 (Kalken and Mark, 1999)

"*Flood in Bangladesh is a part of the normal cycle of the seasons. Depending on its nature, magnitude and duration, flood is considered both as an asset and as a hazard.*"

— Rafiqual and Rumi (2002)

(a) The Mississippi River lapped at the City of Keokuk on July 7, 1993
(Photo by Robert Buchmiller, USGS)

(b) A flood-ravaged road (Photot by Brian Glenister)

Figure A.2 Flooding in Mississippi river, 1993 (Mississippi, 1993)

"*In the wake of the great flood, unprecedented numbers of people retreated from the banks of the Mississippi, deeply shaken by the river's fury and power. But the vast majority of riverbank dwellers have chosen to stay, keeping alive many of the issues raised in the film.*"

— Lessons from Mississippi flooding

Adreſſeaviſen

1. APRIL 1997 UKE 14 NR. 73 TIRSDAG 231. ÅRGANG LØSSALG KR. 10

Millionskader etter flom

Rundt 100 hus fikk vannskader i Trondheim

– Det er helt vanvittig! Hvem hadde trodd dette skulle skje midt i Trondheim? spør Henrik Carstens (43) på Nidarvoll. Han sitter i sønnens vesle seilbåt og titter inn i garasjen. Der står familiens to nesten nye biler under vann. Det voldsomme regnværet og snøsmeltingen i Trondheim og Midt-Norge i går førte til en flom som gjorde at Carstens og mange andre fikk store vannskader på sine eiendommer. Flommen skadet rundt 100 hus bare i Trondheim, men det meldes om flomskader på hus og veier fra mange steder både i Trøndelag og Møre og Romsdal. Skadene kommer opp i flere millioner kroner.

Side 16 og 17

BIL-MARINA: *Henrik Carstens brukte sønnens båt for å komme seg bort til garasjen der familiens to biler sto under vann. Bare skiboksen berget.*
Foto: BENT RAMBERG

(a). Flooding in Trondheim, Norway, 1997
(Adresseavisen, 01/04/1997)

(b). Flooding in Oslo, Norway, 2003 (Aftenposten, 12/04/2003)

"In Norway, rain, often in combination with snow melt, is the chief cause of floods"

—Living With Floods (NVE, 2000)

(c). Flooding in River Glomma at Lauta, Norway, 1995
(Photo by Hallvard Berg)

(d). Flooding in River Leira at Frogner, Norway, 2000
(Photo by Hallvard Berg)

Figure A.3 Flooding in Norway

"Living with floods is a summary of the key results of Norwegian research programme, HYDRA- on Floods"

— NVE (Hydra, 2000)

Figure A.4 Flooding in Britain, 2000 (http://www.flooding in britian_2000)

Floods threaten the ancient city:

"Rising flood waters which caused thousands of people to be evacuated from the ancient city of York in northern."

"More than 140 flood warnings are in force in England and Wales."

"The main problem now is that the ground is saturated with water so any amount of rain -- even a small fall -- will complicate the situation even more."

— CNN News (04/11/ 2000)

(a). Flooded residential areas in Guangxi **(b).** Flooded tram in Chongqing

(c). Flooding in Beijing **(d)**. Bridge is broken by flooding

(e). Flooding in Xinjiang **(f)**. Flooding in Fujian

Figure A.5 Flooding in China, 2002 (Web news/2002)

In June 2002, many cities in China were flooded due to the incessant heavy rainfall. Governments and publicans concern on the capacity of drainage systems. — Beijing Daily (2002)

Figure A.6 Flooding in Europe, August 2002
(http://www.news.bbc.co.uk/2/hi/europe/2193167.stm)

"Around 100 people are thought to have died in severe flooding in central Europe. Several hundred thousand people have been moved into emergency accommodation while they wait for the waters to subside. Troops and civilians have joined forces in a massive sandbagging operation along the Danube and other rivers." — Europe flood chaos (2002)

Appendix B Components of Urban Stormwater Drainage Systems

TableB.1 Components of urban stormwater drainage systems (Walsh, 1989)

Components	**Functions**	**Comments**
Catchment and subcatchment	**a.** Contribute to surface runoff after a reduction due to the imperfect imperviousness from impervious surface; **b.** Permit interception and infiltration and provide for surface runoff after self-saturated from pervious surface.	Paved open surface, roof tops and associated surface with vegetable cover
Swale and open channel	Receive and transmit surface runoff to subsurface storm sewer systems.	Swale and open channels may be natural, constructed or a combination.
Culvert	Provide for the passage of storm water flowing beneath highways, streets and private drives and driveways.	
Roadway with roadside ditch or curb and gutter	**a.** Provide, during minor runoff events, for the collection of surface runoff and its conveyance and then transmit surface runoff to subsurface storm sewer systems. **b.** Provide, during the major runoff events, for transport or temporary storage of storm water and conveyance to minimize the inundation problems.	
Inlet	Provide, primarily during minor runoff events, for storm water transition between the surface and subsurface components.	
Manhole	**a.** Provide for the intersection of storm sewers having different grade, elevation, direction, or size; **b.** Permit access to the storm sewers for inspection, maintenance, repair and system expansion.	
Storm sewer	Provide, during minor runoff events, for the collection and conveyance of storm water and provide for temporary storage during the major runoff events.	

Detention facilities	**a.** Provide, in a normally dry area or enclosure, for the temporary storage of storm water for subsequent slow release to downstream channels or storm sewers; **b.** provide for the settling of sedimentation and other suspended materials in storm water, thus reducing the load of potential pollutants on receiving water.	A detention facility is normally dry, or contains very little water and designed to fill only during runoff events.
Retention facility	Provide, in a reservoir or natural lake that normally contains a substantial volume at a predetermined conservation pool level, for the temporary storage of additional storm water for subsequent slow release to downstream channels or storm sewers; **b.** provide for the settling of sedimentation and other suspended materials in storm water, thus reducing the load of potential pollutants on receiving water.	The volume of water contained normally in a retention storage facility serves recreational and aesthetic functions.
Detention/ Sedimentation basin	Trap suspended solids, suspended and buoyant debris and absorb the potential pollutants, which are varied by storm water.	

Appendix C Collection of Design Standards for Drain and Sewers Outside Buildings

* The standards are arranged in alphabetic order

Austrian standard

Design storm frequency (1 in n years)	Location	Design flooding frequency
1 in 1 years	General areas of the city	No
1 in 5 years	City center	Rainfall of 1 in 5 years is checked in one city.

Chinese standard

Design storm frequency (1 in n years)		Location	Design flooding frequency
Beijing	3 in 1 – 2 in 1	Residential areas and roads	No design flooding frequency is suggested
	2 in 1 – 1 in 1	Dangerous areas	
	1 in 1 – 1 in 2	City center and main roads	
	1 in 2 – 1 in 3	Cross section of main roads	
	1 in 3 – 1 in 10	Important areas	
Shanghai	2 in 1 – 1 in 1	General city areas	No design flooding frequency is suggested
	1 in 1 – 1 in 5	Industrial area	
Chongqing	1 in 1 – 1 in 2	Small area (A<30ha)	No design flooding frequency is suggested
	1 in 5	Residential area (A=30~50ha)	
	1 in 5 –1 in 10	Large or important area	

European Standard (EN 752-4)

Design storm frequency (1 in n years)	Location	Design flooding frequency (1 in n years)
1 in 1	Rural areas	1 in 10
1 in 2	Residential areas	1 in 20
1 in 2 1 in 5	City centers/ Industrial /commercial areas -with flooding check -without flooding check	1 in 30
1 in 10	Underground railway/underpasses	1 in 50

Germany standard (ATV-A 118)		
Design storm frequency (1 in n years)	Location	Design surcharge frequency (1 in n years)
1 in 1	Rural areas	1 in 2
1 in 1-1 in 2	Residential areas	1 in 3
1 in 2 1 in 5	City centers, Industrial /commercial areas -With flooding check -Without flooding check	<1 in 5
1 in 5-1 in 20	Underground railway/underpasses	< 1 in 10
Japanese standard		
Design storm frequency (1 in n years)	Location	Design flooding frequency (1 in n years)
1 in 5-1 in 10	Urban areas	No design flooding frequency. New pipes or runoff control facilities such as infiltration facilities and storage ponds are constructed for flooding.
Dutch standard		
Design storm (l /s. ha.)	Location	Flooding Checking
60	Flat area	0.2m free board between maximum water level in manhole and ground level
90	Inclined area	
110		Flooding
Norwegian standard		
Design storm frequency (1 in n years)	Location	Design flooding standards
1 in 10-1 in 15	Urban areas	No acceptable flooding frequency, the problems are fixed locally.

Thailand standard

Design storm frequency (1 in n years)	Location	Design flooding frequency
1 in 2	For secondary/lateral sewers	No
1 in 5	For primary/mail sewers	No

The United Kingdom (UK) standard

<table>
<tr><td rowspan="4">Designing new systems</td><td>Design surcharge frequency (1 in n years)</td><td colspan="2">Location</td><td>Design flooding frequency (1 in n years)</td></tr>
<tr><td>1 in 1</td><td colspan="2">Average slope of site > 1%</td><td rowspan="3">1 in 30</td></tr>
<tr><td>1 in 2</td><td colspan="2">Average slope of site ≤ 1%</td></tr>
<tr><td>1 in 5</td><td colspan="2">Sites where consequences of flooding are severe</td></tr>
<tr><td rowspan="4">Updating existing systems</td><td rowspan="2">Location</td><td colspan="3">Flooding checking frequency (1 in n years)</td></tr>
<tr><td>Trigger for early rehabilitation</td><td>Target for updating</td><td>New design</td></tr>
<tr><td>Inside occupied premises</td><td>2 in 10</td><td>1 in 30</td><td>1 in 50</td></tr>
<tr><td>Streets</td><td>2 in 1</td><td>1 in 20</td><td>1 in 25</td></tr>
</table>

The United States (USA) and Canada standard (ASCE, 1992)

Land use	Design storm return period (Frequency)	Design flooding frequency
Minor Drainage Systems:		
• Residential	2-5 years	No available
• High value general commercial area	2-10years	
• Airports (terminals, roads, aprons)	2-10years	
• High value downtown business areas	5-10years	

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Appendix D Description of Digital Data of Trondheim Case Study

D.1 Introduction of SOSI Data Format

At the national level, SOSI format is the first and most concrete result of standardisation work under the auspices of the Department of Environmental Protection of Norway. The digital data of Trondheim case study are produced in SOSI format.

The formal core of the SOSI-format is not basically limited to geographic information, and certainly not only to coordinate data. It is a very general format which may be used in many contexts, e.g. to represent economic and statistic information as readily as geographic information. This basis must be so broad, for geographic information is itself a very broad concept, encompassing e.g., administrative and personal data in the Norwegian registry of real estate, address and buildings, as well as coordinate data for topographic maps, The set of attributes including in the concept geographic information is anything but static.

Every database may be considered as consisting of two basic parts:

- The data, or the information, which lies in the database or file structure;
- An underlying data model or data structure to which the information adheres;

The standard consists of three parts:

- Basic syntax;
- Standard elements and guidelines for practical use;
- Object catalogue including data models together with thematic and attribute codes.

D.2 Structure of SOSI File

SOSI file consists of following components:

- HEADER Identifies information about the whole file;
- DEFINITION LIST specifies the characteristics included in the data group, take a group of people: name, address (consisting of township number, street ID code, house number and postal code) for example:
- DATA include names, values and attributes;
- END ends the data-file.

D.3 Data Group and Code System in SOSI Data Files

Taking the data groups used in the Trondheim case as example, this part introduces several data groups and the code systems in SOSI format (Table F.1). Where, the Norwegian terminology and corresponding English translation are included.

Table D.1 Sample of code systems of SOSI data

Data group	**Codes**	**Norwegian terms**	**English terms**
Topography	2001	Høydekurve	Elevation contour
	2003	Forsenkningskurve	Countersink contour
	2101	Terrainpunkt	Terrain point
	2102	Høydepunkt/kolle	Elevation points/ Top of the mill
	2200	Terrainlinje	Terrain lines
River	3001	kystkontur	Coast contour
	3009	kystterskel	Coast boundary
	3099	Fiktivt-havdel	Fictive ocean division
	3101	Innsjø-kontour	Lake contour
	3109	Innsjø-terskel	Lake boundary
	3201	Kant elv/bekk	Edge of river/creak
	3203	Kant kanal/grøft	Edge of channel/ditch
	3209	Elv-terskel	River boundary
	3211	Midt elv/bekk	Central line of river/creak
	3213	Smagroft midt (<1m)	Central line of small ditch
	4051	Off. Godkj.grensemerke	Unknown border mark
	4053	Kors	Cross
	4054	Ror	Control surface/point
	4055	Grensestein/roys	Border stone
	6701	Fyr	Light house
	6702	lykt	Ground plant
Building	5001	Takkant	Roof edge
	5002	Veggliv	Brick wall
	5003	Bygningsdel	Building division
	5005	Bygård	Flat
	5041	Overbygg	Super structure
	5061	Veranda	Stairs

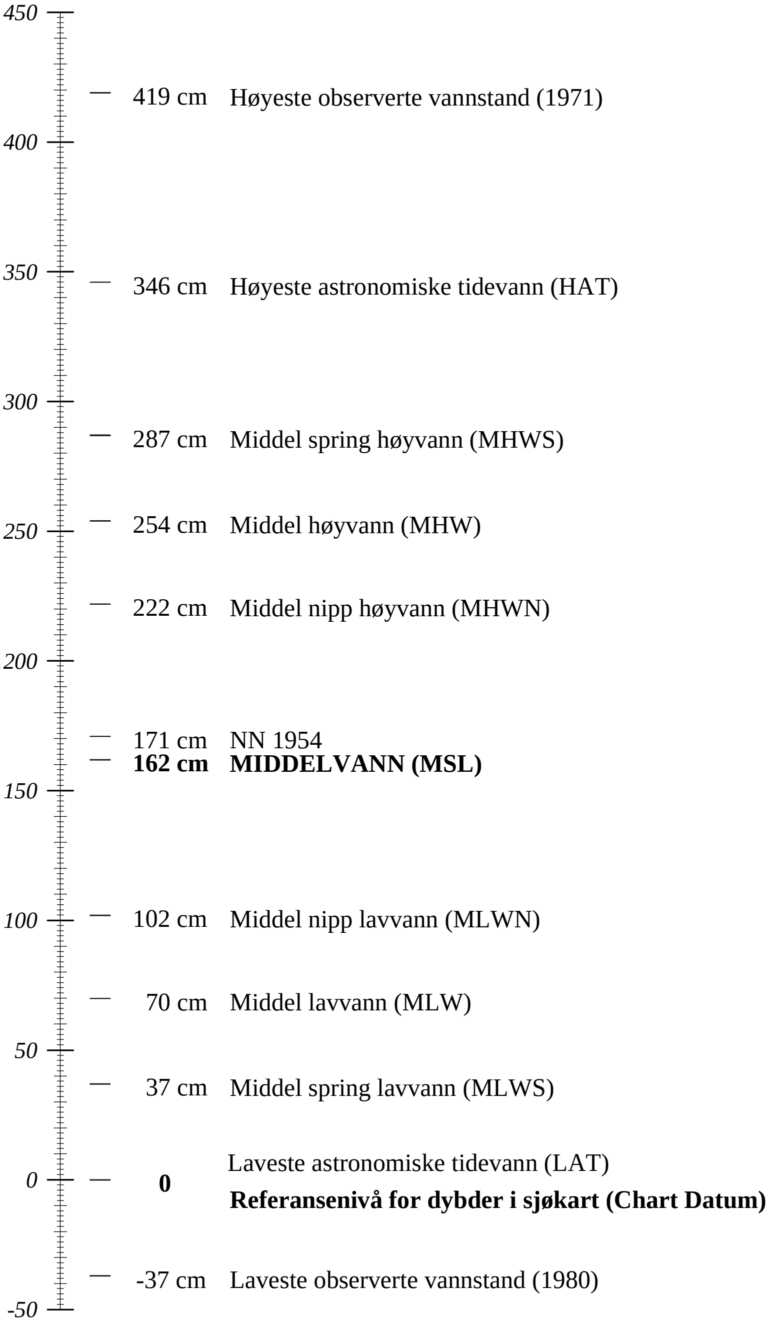
	5081	Taksprang	Roof crowd
	5820	Mønelinje	Roof
Road	7002	Vegkant	Edge of road
	7003	Midt veg	Central line of road
	7007	Annet vegareal	Other road area
	7013	Midtdeler/trafikkoy	Central part/traffic pier
	7021	Kjørefeltavgreanseing	Border of driving area
	7041	Sentralinje gangbru	Central line of path bridge

Appendix E Different Elevation Systems versus Water Level at Trondheim Fjord

Different elevation systems versus water level at Trondheim fjord are illustrated in the Fig. E.1. This sketch is made by the Department of Norwegian National Map (Statenskartverk) and updated on 31.12.2002 (Torresen, 2003).

TRONDHEIM

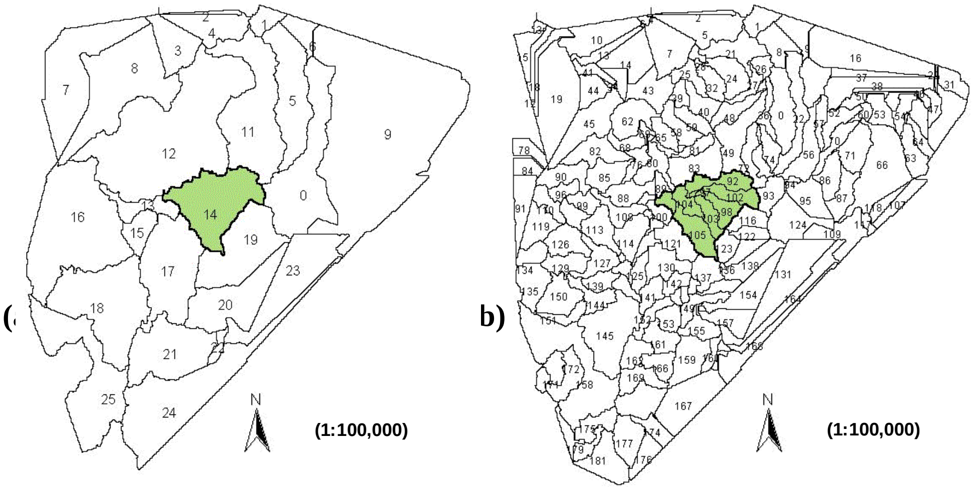
Nivåskisse med de viktigste tidevannsnivåene samt observerte ekstremverdier.
Alle verdier er gitt i cm relativt til sjøkartnull.



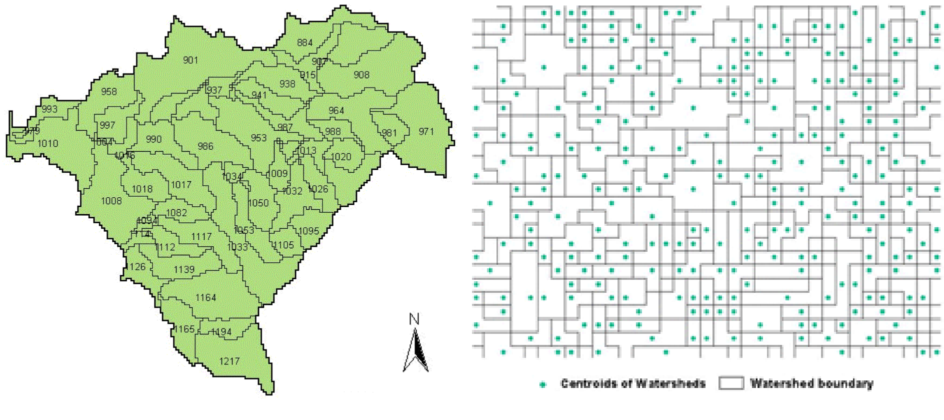
419 cm	Høyeste observerte vannstand (1971)
346 cm	Høyeste astronomiske tidevann (HAT)
287 cm	Middel spring høyvann (MHWS)
254 cm	Middel høyvann (MHW)
222 cm	Middel nipp høyvann (MHWN)
171 cm	NN 1954
162 cm	**MIDDELVANN (MSL)**
102 cm	Middel nipp lavvann (MLWN)
70 cm	Middel lavvann (MLW)
37 cm	Middel spring lavvann (MLWS)
0	Laveste astronomiske tidevann (LAT) **Referansenivå for dybder i sjøkart (Chart Datum)**
-37 cm	Laveste observerte vannstand (1980)

Appendix F Watershed and Surface Stream Networks Derived from DEM for the Norwegian-Trondheim Case study

Different solutions of watersheds, surface stream networks derived from GRID DEMs, as well as the influence of buildings on the delineation are displayed in this appendix.



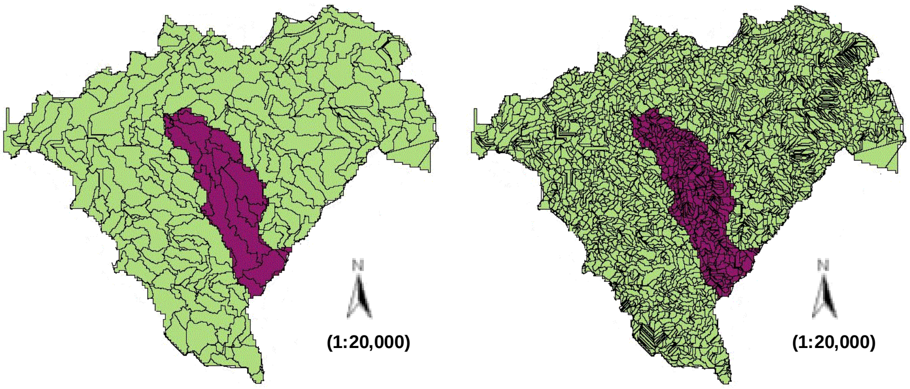
(a). Watersheds (Min_10,000 cells) **(b).** Watersheds (Min_1,000 cells)



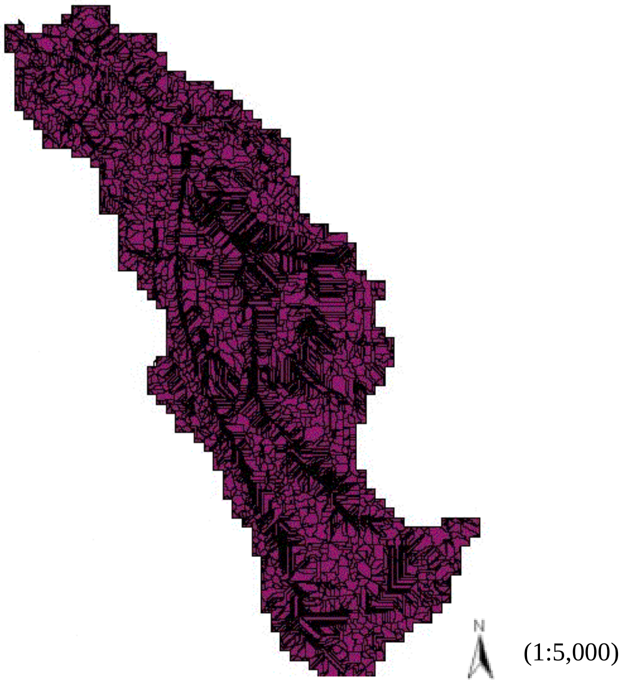
(1:20,000) (1:2,000)

(c). Watersheds (Min_100 cells) **(d).** Watersheds (Min_1 cell)

Figure F.1 Watersheds delineated from GRID DEM (cell size: 20m*20m)



(a). Watersheds (Min_10,000 cells) **(b).** Watersheds (Min_1,000 cells)



(c). Watersheds (Min_100 cells)

Figure F.2 Watersheds delineated from GRID DEM (cell size: 1m*1m)

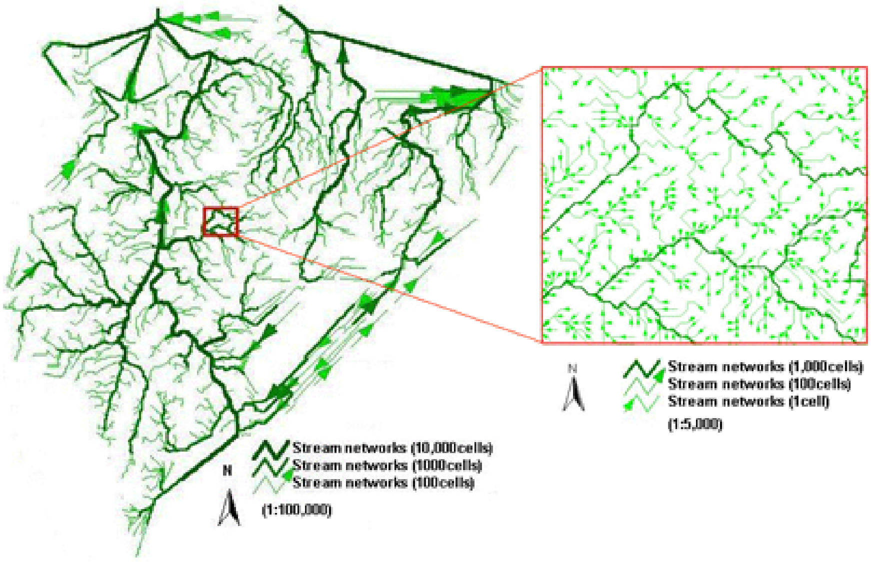


Fig. F.3 Surface stream networks delineated from GRID DEM
(Cell size: 20m*20m)

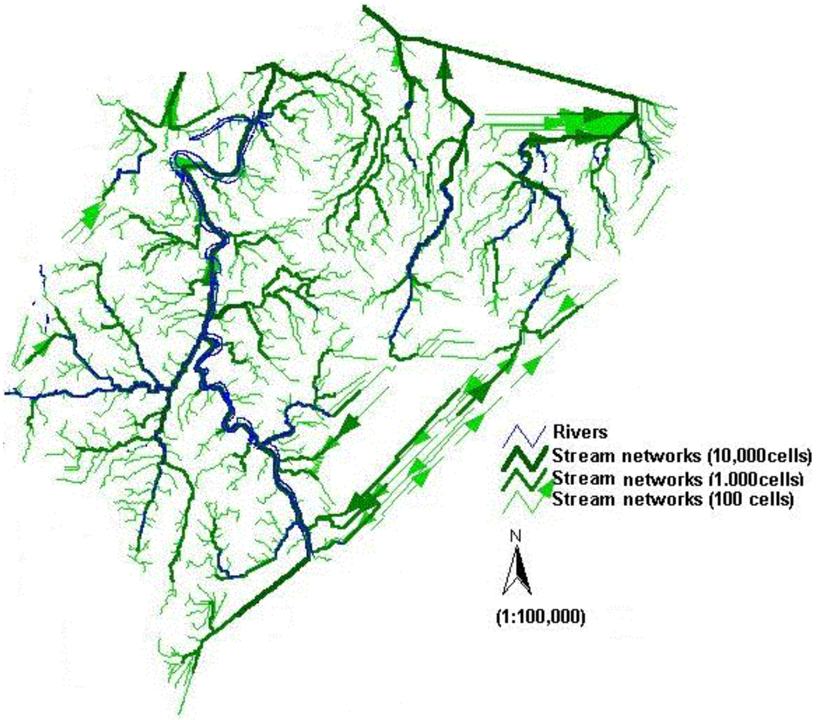
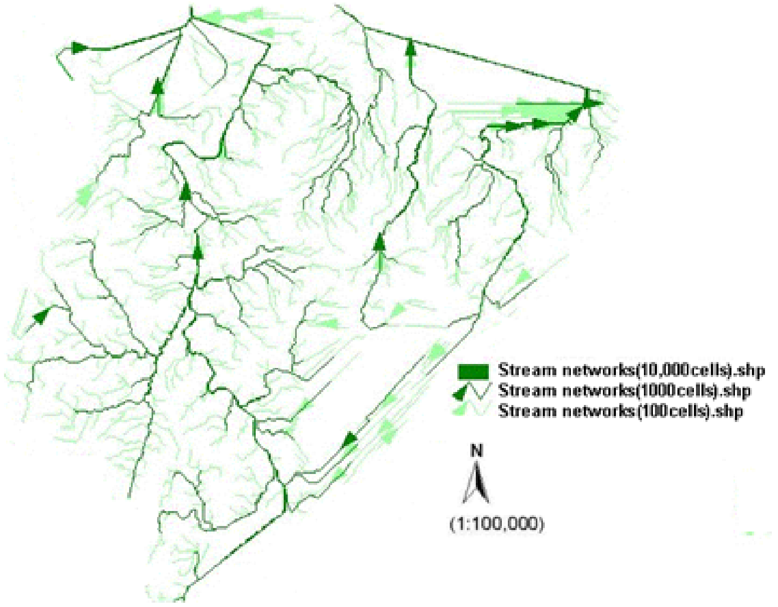
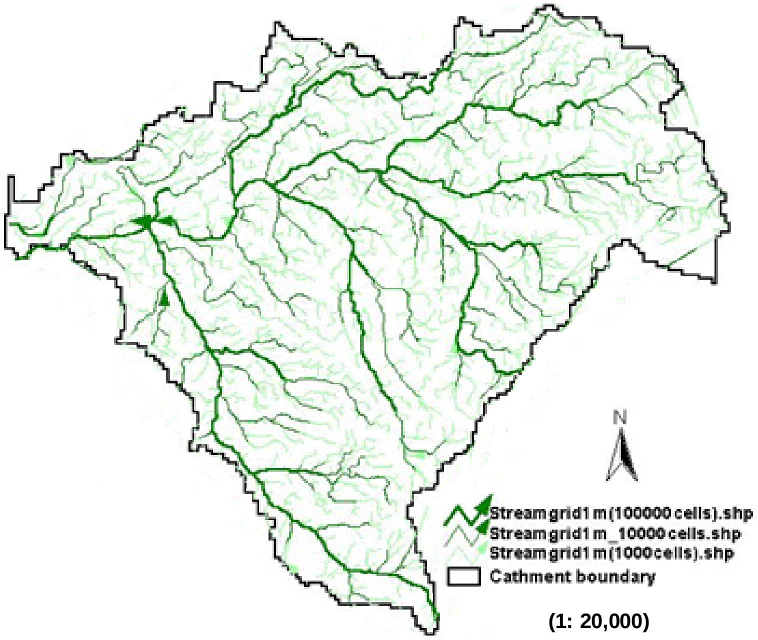


Fig. F. 4 Natural Rivers and delineated streams from GRID DEM
(Cell size: 20m*20m)

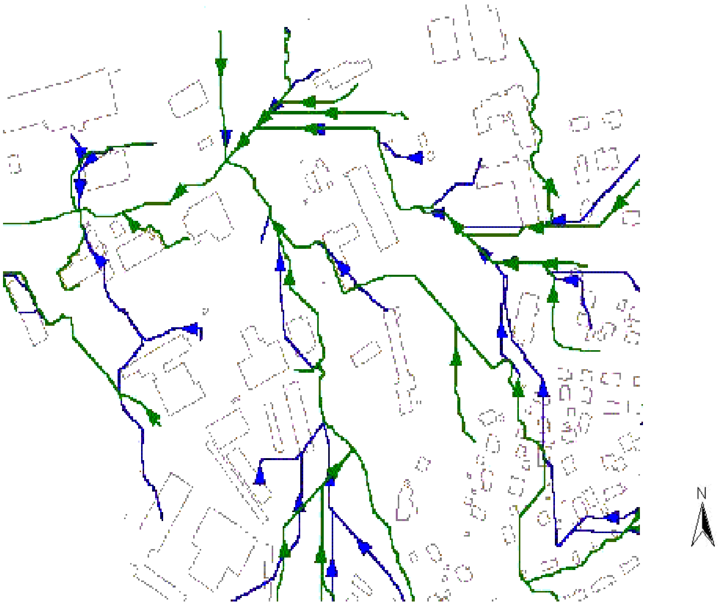


(a). Surface stream networks at different levels
(Cell size: 20m*20m)

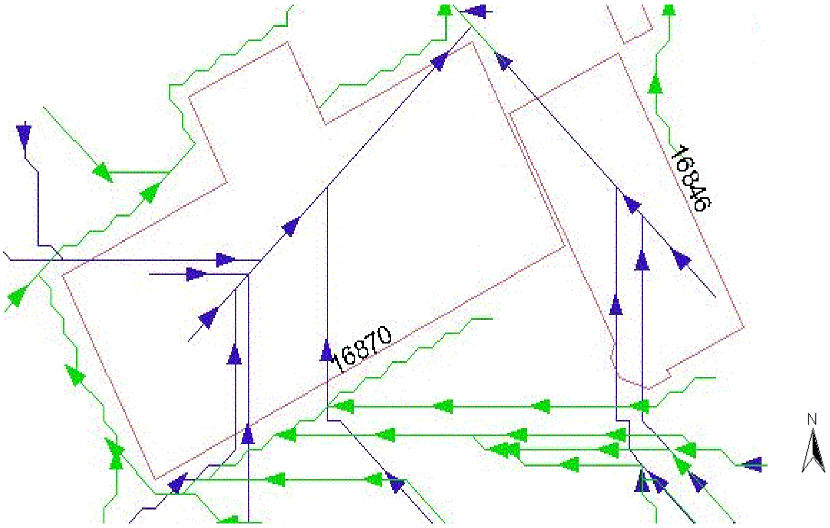


(b). Surface stream networks with different levels
(Cell size: 1m*1m)

Figure F.5 Surface stream networks delineated from GRID DEM

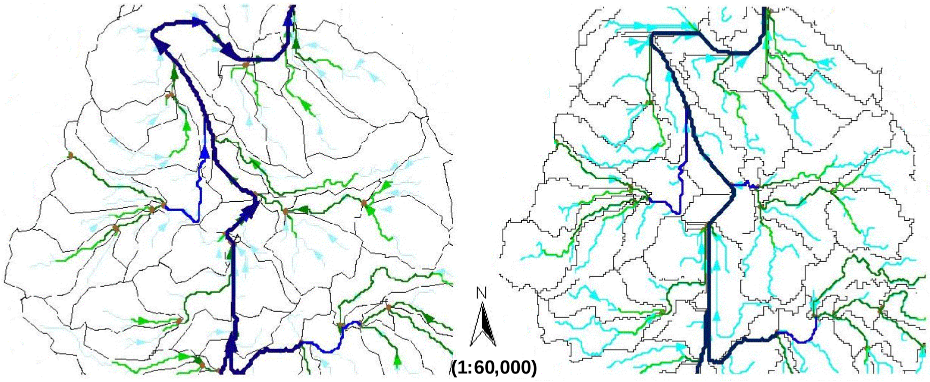


(a). Major streams delineated from GRID DEM without (blue) & with (green) considering buildings on surface (Min_5,000 grids)



(b). Minor streams delineated from GRID DEM without (blue) & with (green) considering buildings on surface (Min_100 cells)

Figure F.6 Influence of buildings on the delineation of stream networks
(Grid cell size: 20m*20m)



(a). Major streams and watersheds without including buildings

(b). Major streams and watersheds with buildings in the delineation

(Grid cell size: 20m* 20m)

Figure F.7 Influence of buildings on the delineation of surface streams and watersheds

Appendix G The Status of Sewer Systems in the Fredlybekke Catchment

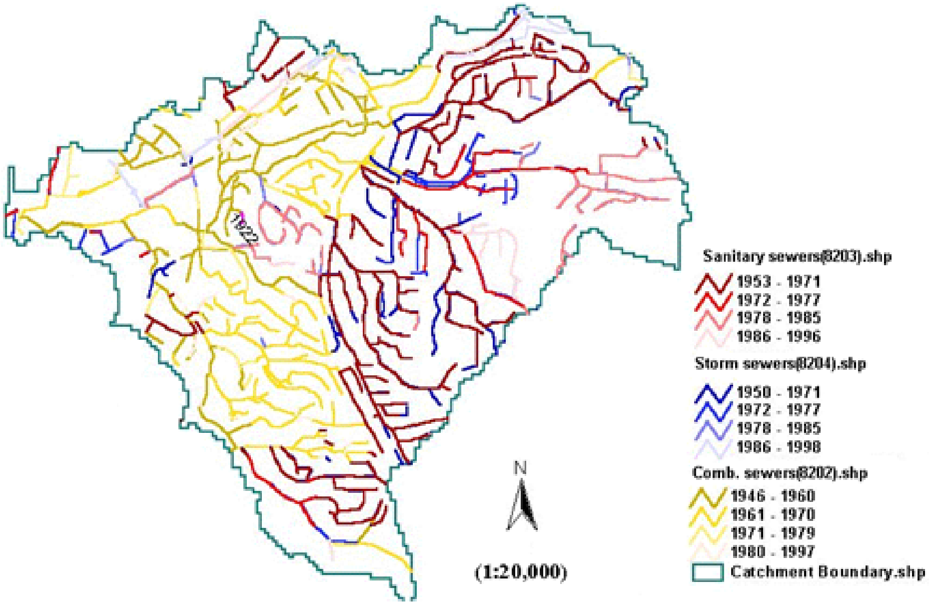


Figure G.1 Construction time of sewers

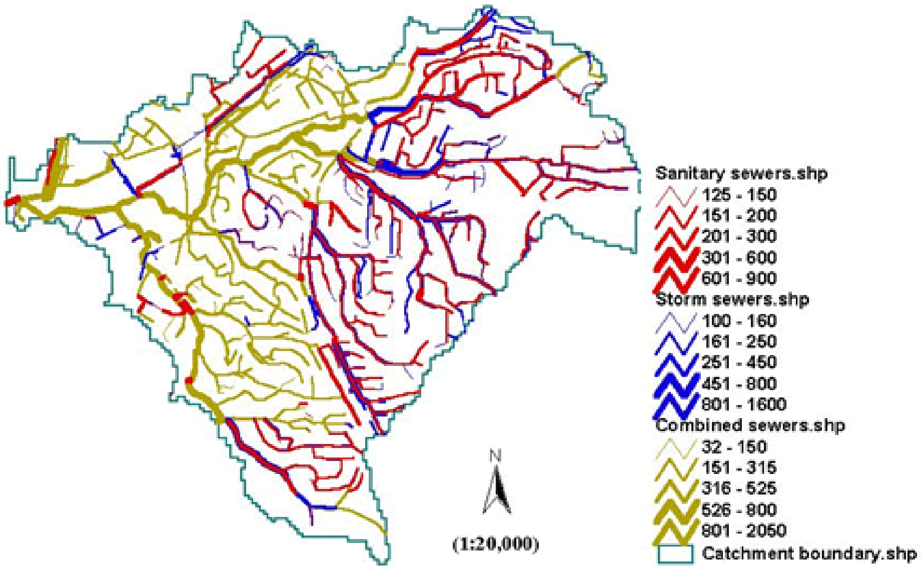


Figure G.2 Dimension of sewers

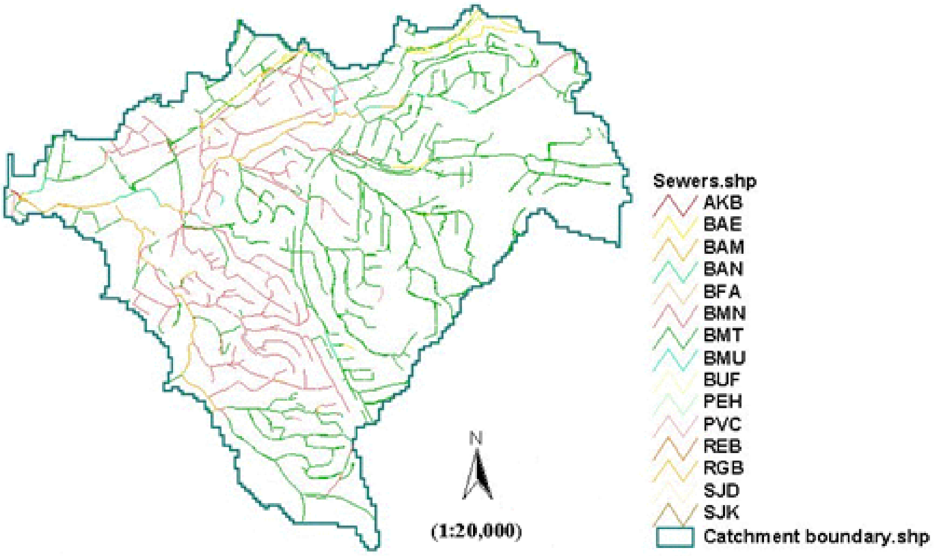


Figure G.3 Sewers material

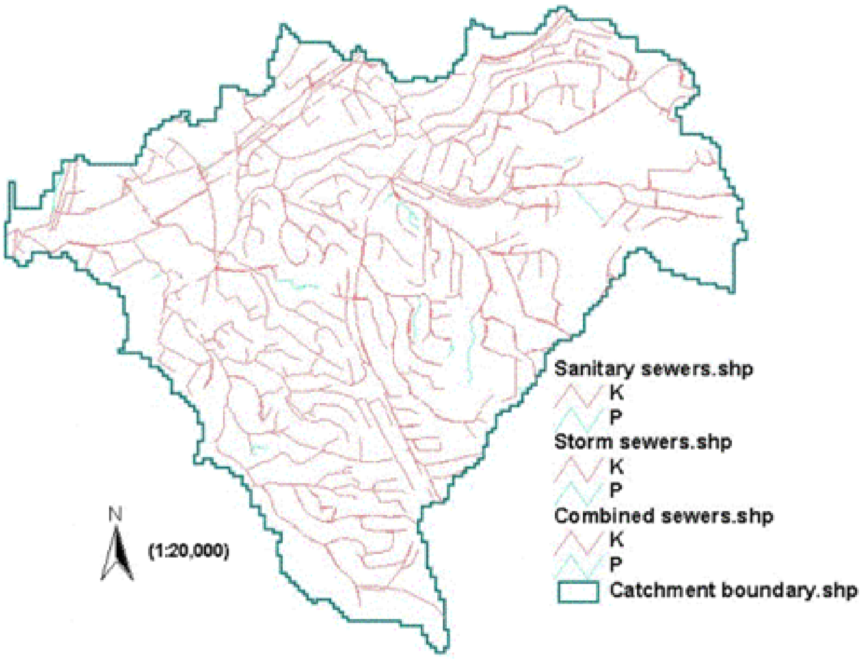


Figure G. 4 Sewer owners
* (K: Public sewer; P: Private sewer)

Table G.1 Explanation of notation of sewer materials

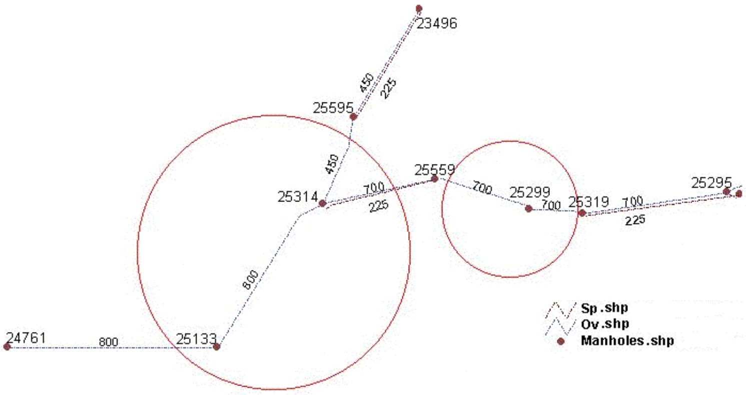
Sewer material	Explanation	
	Norwegian	**English**
AKB	(Avløp) Betong kanal	(Sewer) Concrete canal
BAE	Betong amert falsrør, (Enkelt amert)	Concrete groove fold pipe (groove only)
BAM	Betong amert falsrør m/fot, NS 462	Concrete groove fold pipe with heel
BAN	Betong amert falsrør, NS3026	Concrete groove fold pipe
BFA	Betong amert falsrør, BN	Concrete groove fold pipe
BMN	Betong mufferør, NS461	Concrete bell pipe (1890-1948)
BMT	Betong mufferør, tykkvegede NS3027 eller BN	Concrete bell pipes, thick walled
BMU	Betong mufferør, NKIF-norm	Concrete bell pipes (1949-1965)
BUF	Betong uamert falsrør, NS3028/BN	Concrete ungrooved fold pipe
PEH	Polyetylen med høy densitet	High density polyethylene sewer
PVC	Polyvinylklorid	Plastic sewer (PVC)
REB	Betong renov. med skjøt.injisert akrylamidgel	Concrete renovation with gel
RGB	Betong renov. med Inpipe-strømpe	Concrete renovation with inside stocking
SJD	Støpejern, duktilt med innv. Mørtelforing og utv. Bitum. Sink og bitumen fra 1975-1978	Ductile iron pipe with internal and external protection
SJK	Støpejern, duktilt. Ingen beskyttelse, elle evt. Utvendig bitumen	Ductile iron pipe without protection

Table G.2 Explanation of notation of sewer types

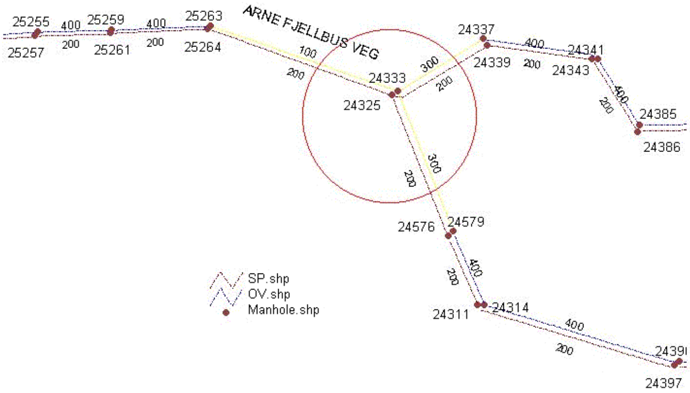
Sewers	Explanation	
	Norwegian	**English**
AF	Fellesavløp	Combined sewers
KF	Felleskanal	Combined Cannel
OL	Overløpsledning	Overflow pipes
OV	Overvannsledning	Stormwater pipes
PS	Pumpestasjon	Pumping station
SP	Spillvann avløp	Wastewater sanitary sewers
ST	Trykkeavløpsledning	Pressurised sewers

Table G.3 Checklist of suspected errors/deficiencies of existing sewers and their verification messages or comments

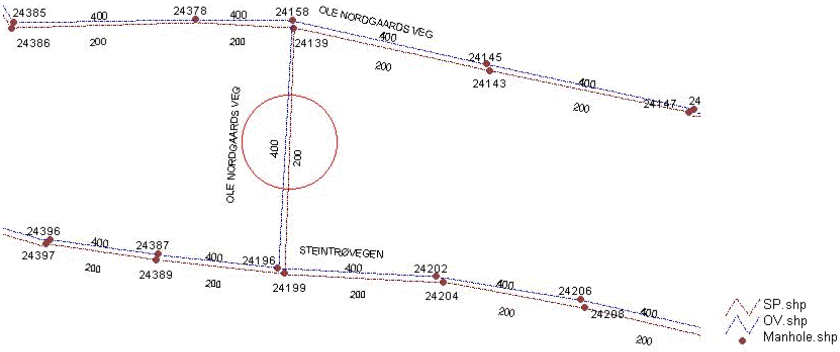
Street	Type of the sewers	Suspected error massages (SID)	No. of figures	Confirmations/Co
Othiliensborgvegen	Separate sewers: SP, OV	**1.** Missing SP sewers from node 25595 to node 24761; from node 25319 to 25559.	Fig. G.5 (a)	Having been fixed in sewer database
Arne Fjellbusveg	Separate sewers: SP, OV	**2.** Suspected errors / hydraulic bottleneck 24333.	Fig. G.5 (b)	These three sewers ha changed to 400mm.
		3. Suspected errors at Ole Nordgaardsvei sewers.	Fig. G.5 (c)	The connecting sewer removed from the dat
E.B.Schieldropsv.	Separate sewers: SP, OV	**4.** Complicated sewers connections from node 496209 to node 496220.	Fig. G.5 (d)	Water storage tanks
Blaklihøgda	Separate sewers: SP, OV	**5.** Suspected bottleneck at Blaklihøgda sewers.	Fig. G.5 (e)	Not clear yet
Utleirvegen	Mixed sewers: AF, SP, OV	**6.** Suspected errors from node 24969 to node 24960.	Fig. G.5 (f)	No error in sewer dat Check the real sewers
Torsveg	Combined sewers: AF	**7.** Suspected Error/bottleneck on Torsveg sewers from node 24655-24653-24814.	Fig. G.5 (g)	Having been fixed in sewer database
Tempenvegen	Combined sewers: AF	**8.** Suspected bottlenecks on sewers: 22955-22943; 22939-22935.	Fig. G.5 (h)	Not really hydraulic bottlenecks



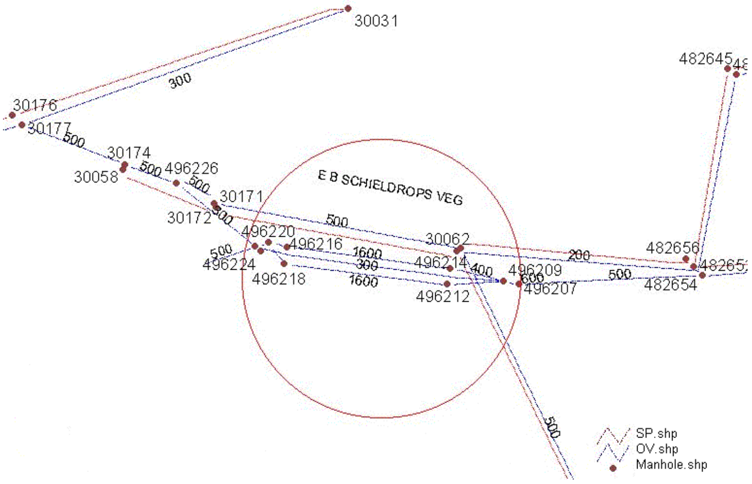
(a). Suspected errors in Othilienborgvegen sewers



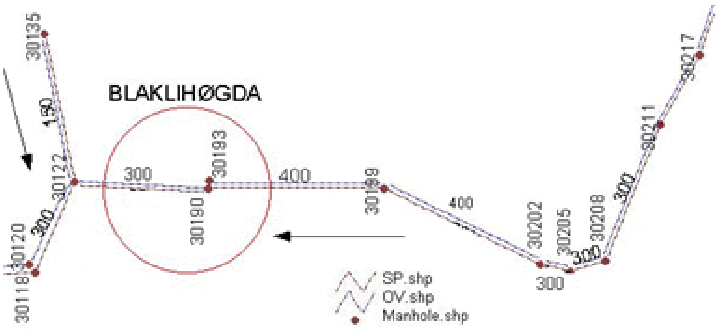
(b). Suspected sewer hydraulic bottleneck at Arne Fjellbusveg sewers



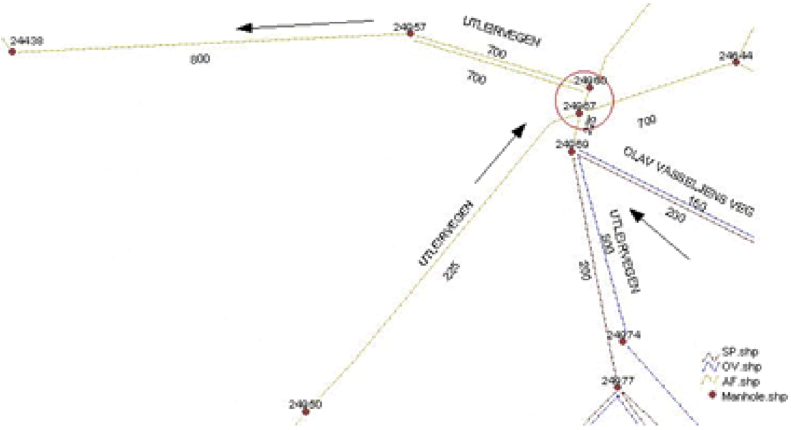
(c). Suspected errors at Ole Nordgaardsvei sewers



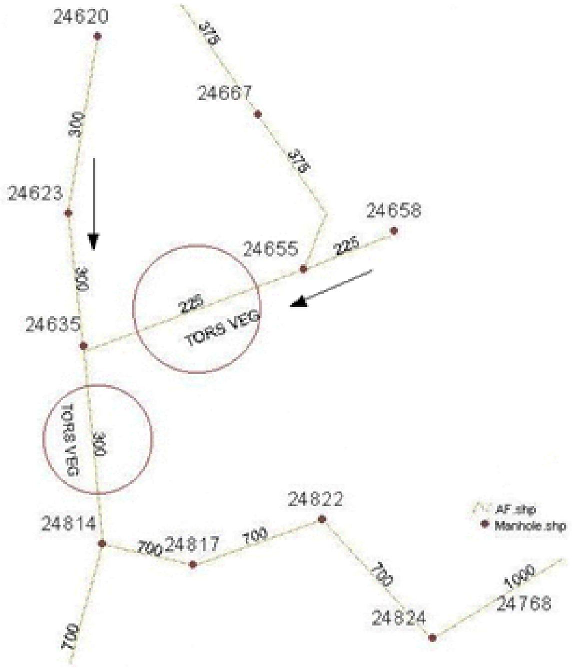
(d). Complicated sewers connection on E.B.Schieldropsveien



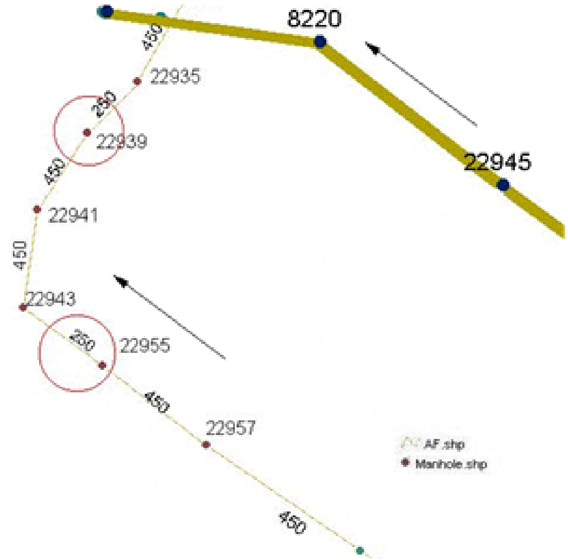
(e). Suspected errors/ bottleneck at Blaklihøgda sewers



(f). Suspected errors on Utleirvegen sewers



(g). Suspected sewer hydraulic bottleneck on Torsveg sewers



(h). Suspected bottlenecks on Tempenvegen sewers

Fig. G.5 Sample of suspected errors or deficiencies of existing sewer systems in the Trondheim-Fredlybekken case study

Appendix H Results of Flooding Simulation of Tondheim-Fredlybekken Case Study

H.1 IDF Curve

The Intensity-Duration-Frequency (IDF) curve of Trondheim-Fredlebekken case study and flooding simulation results for the sewers at level II of Fredlybekken catchment are given in this appendix.

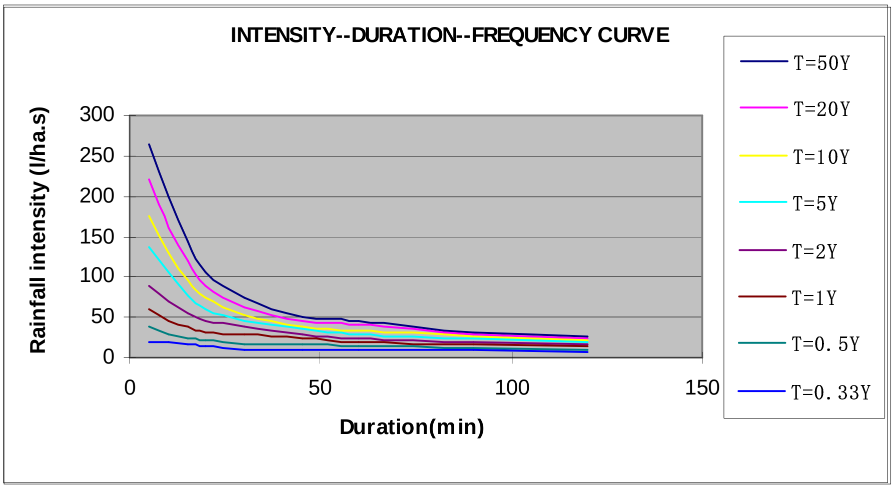


Fig.H.1 Intensity-Duration-Frequency (IDF) curve of Fredlybekken catchment (Deng & Nie, 2001)

H.2 Results of Flooding Simulation

The results of flooding simulation, flooding manhole and sewer pressure for constant rainfall of 1 in 10 years, 1 in 20 years and 1 in 50 years in 10, 30, 45, 60 and 120 minutes are gathered in this appendix. In the following maps, the left figures represent the flooding manholes and corresponding floodwater levels, while the right figures display the pressure of the sewers in meter.

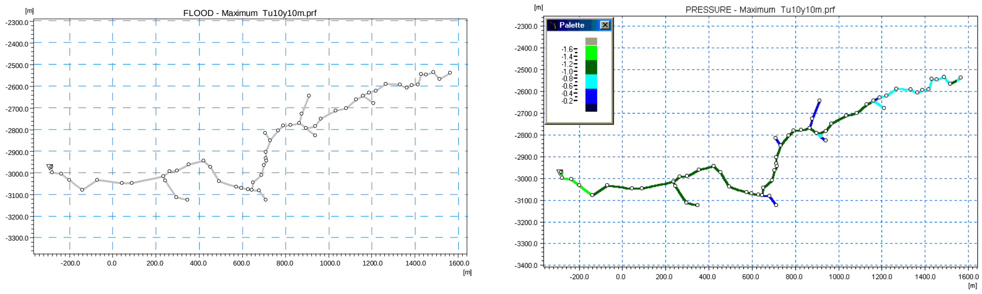


Fig.H.2 (a). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 10 years in 10 minutes

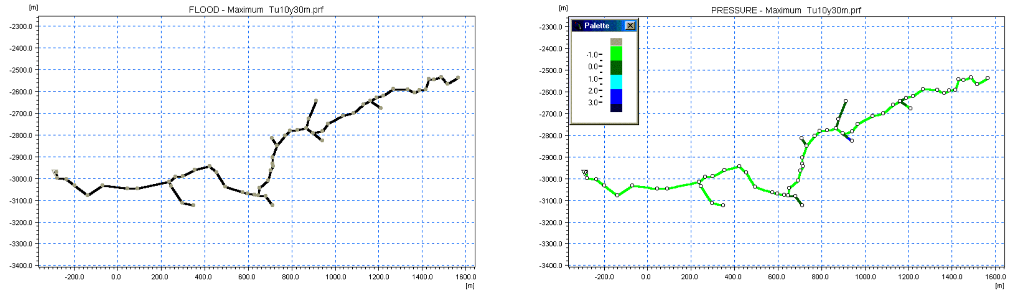


Fig.H.2. (b). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 10 years in 30 minutes

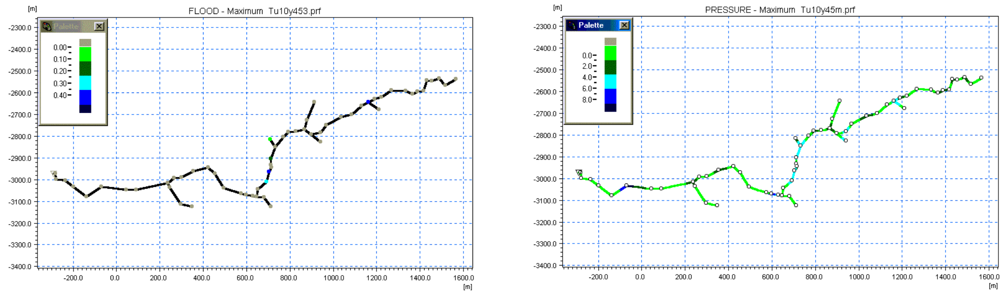


Fig.H.2. (c). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 10 years in 45 minutes

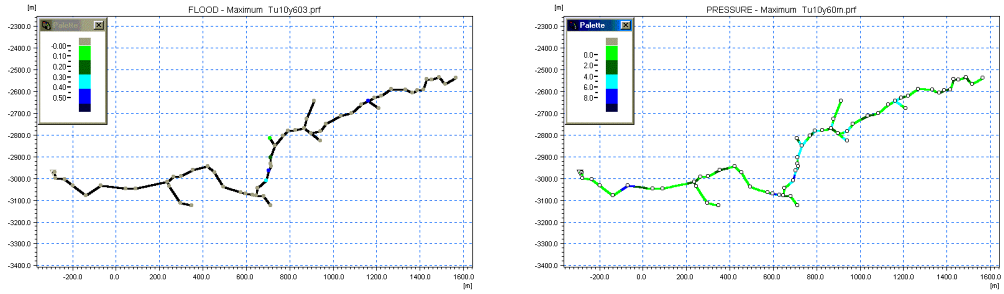


Fig.H.2. (d). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 10 years in 60 minutes

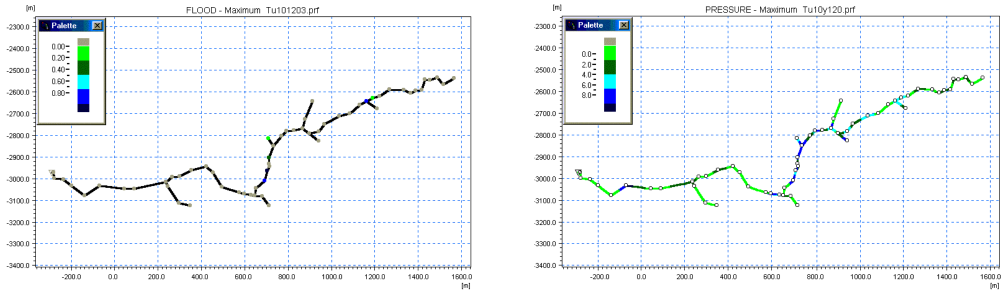


Fig.H.2. (e). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 10 years in 120 minutes

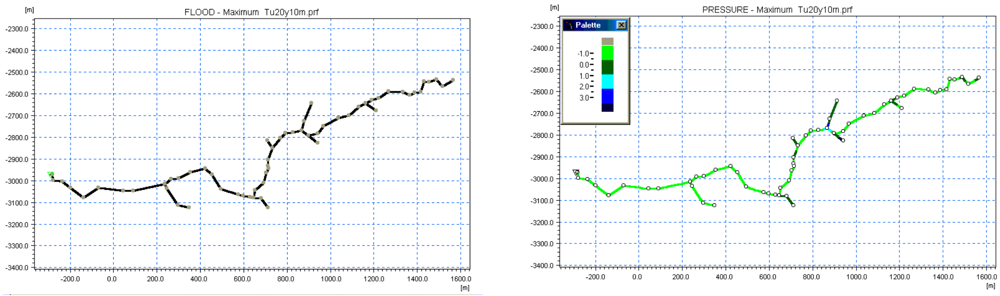


Fig.H.3 (a). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 20 years in 10 minutes

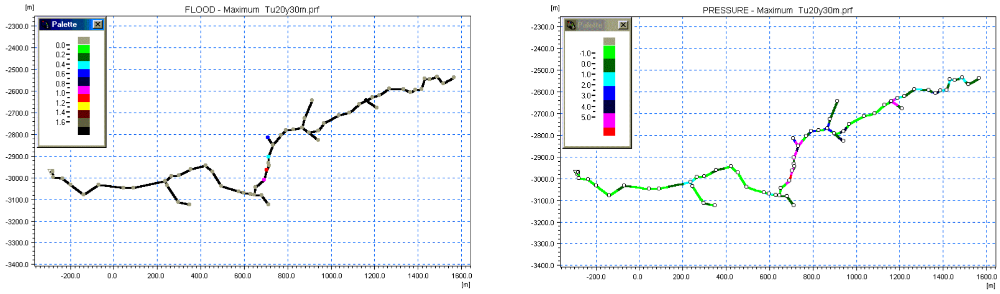


Fig.H.3 (b). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 20 years in 30 minutes

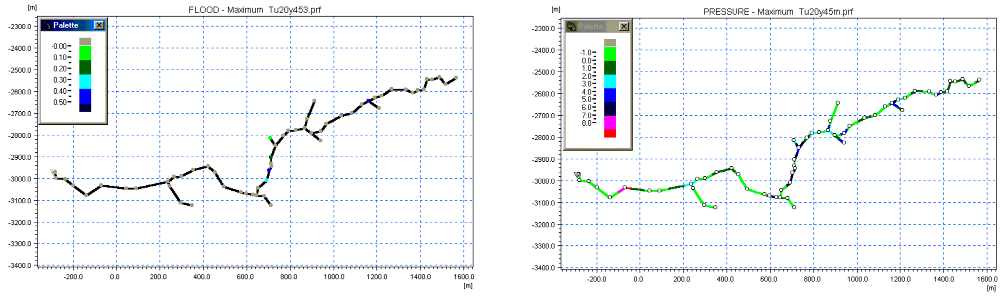


Fig. H.3 (c). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 20 years in 45 minutes

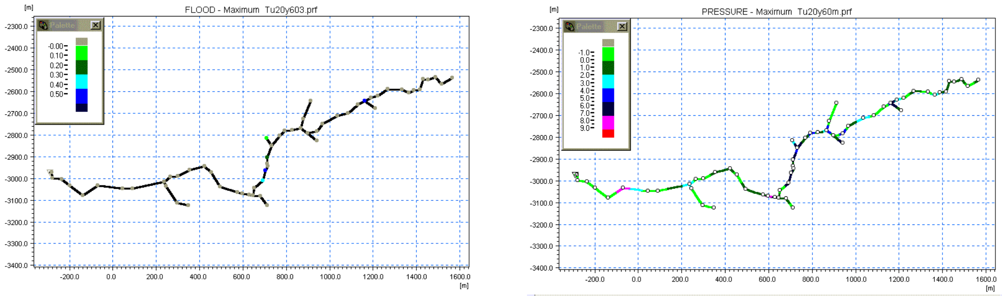


Fig.H.3 (d). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 20 years in 60 minutes

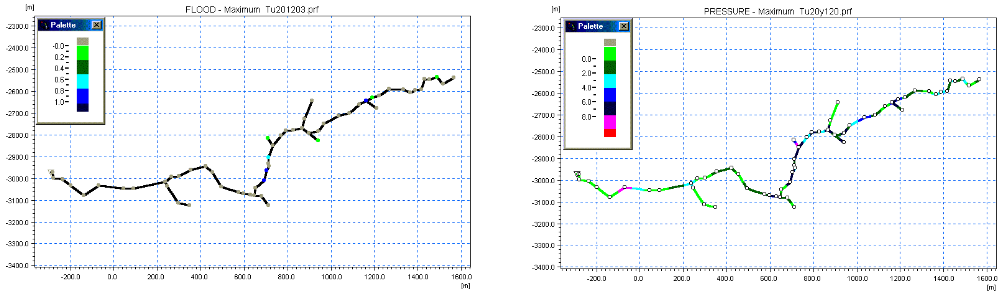


Fig. H.3 (e). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 20 years in 120 minutes

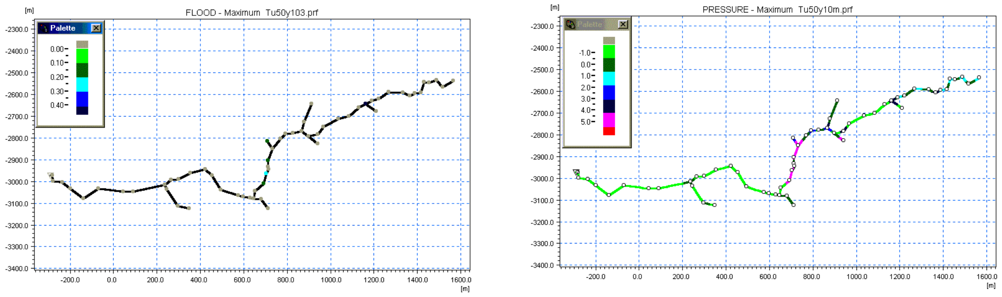


Fig. H.4 (a). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 50 years in 10 minutes

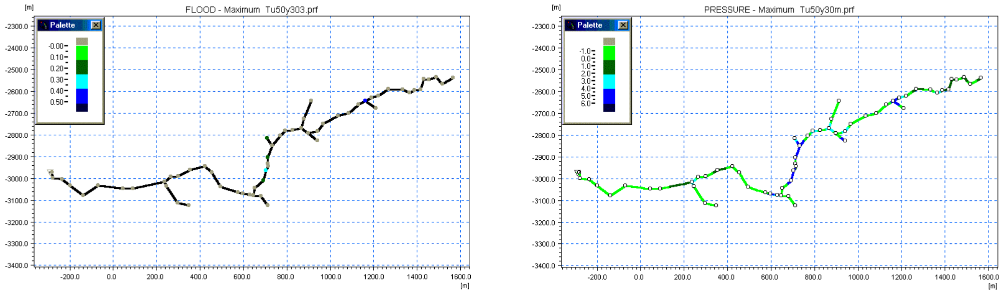


Fig. H.4 (b). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 50 years in 30 minutes

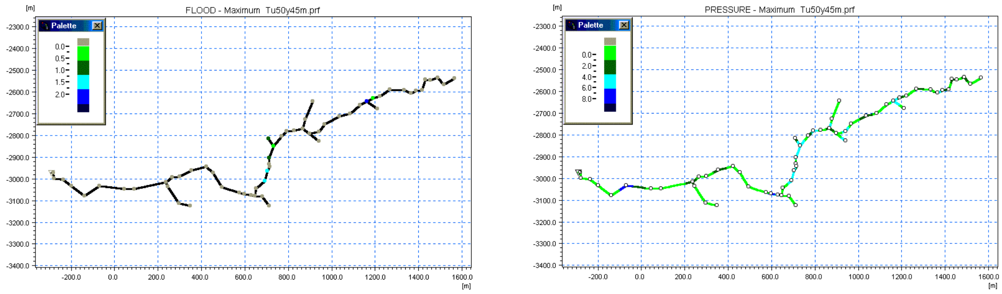


Fig. H.4 (c). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 50 years in 45 minutes

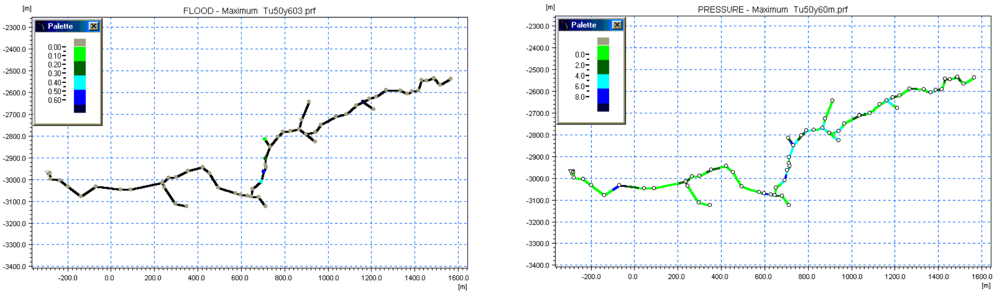


Fig. H.4 (d). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 50 years in 60 minutes

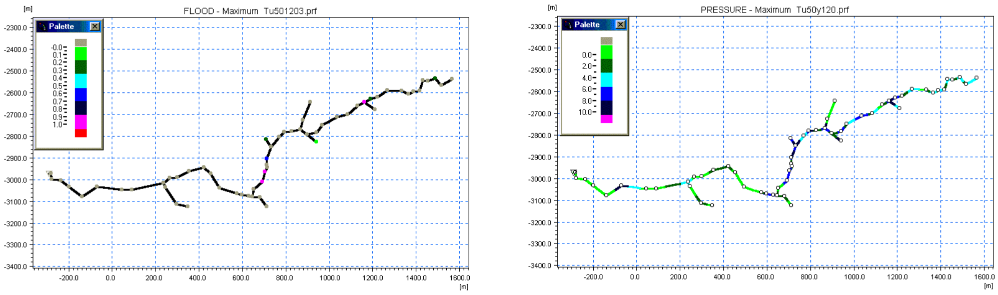


Fig. H.4 (e). Flooding manhole (left) and sewer pressure (right) of rainfall of 1 in 50 years in 120 minutes

Appendix I Description of Digital Data of Beijing-BWZ Case Study

The digital data of BWZ case study is provided by the Institute of Surveying and Mapping of Beijing, China. It is produced in Arc/info format in the scale of 1:2000. The data themes applied in this case study are described in the following table I.1.

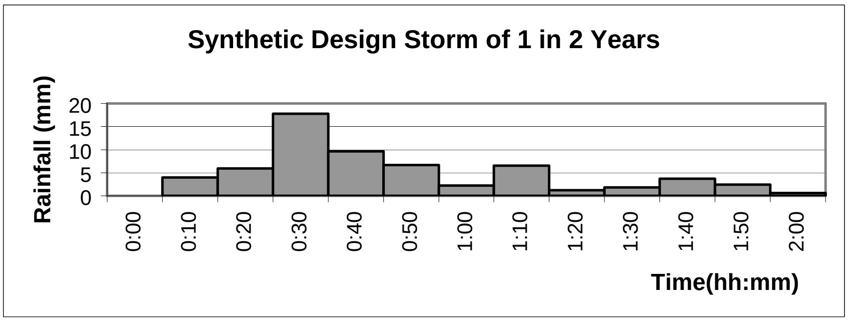
Table I.1 Description of digital data of BWZ case study

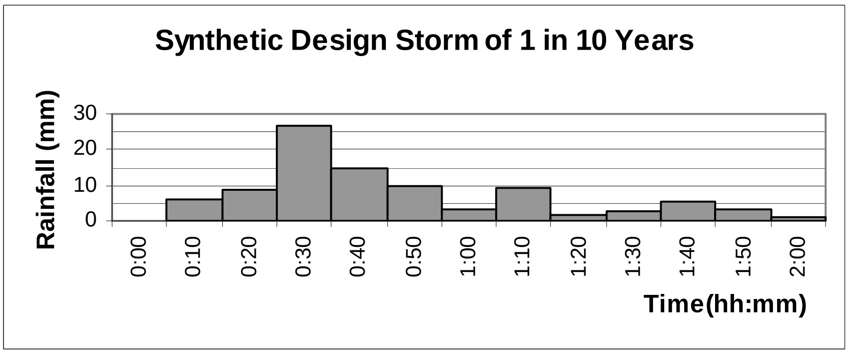
Data themes		**Spatial objects**	**Spatial objects**
1	BID	Buildings	Polyline
2	TRFNET	Central line of road	Polyline
3	ROADP	Road area	Polygon
4	ROAD	Border of road	Polyline
5	WALL	Walls	Polyline
6	CONTOUR	Contour points	Point
7	VEGLP	Vegetation	Point, Polyline
8	ANNO	Information	Point
9	COVERALL	Graphical notes	Point, polyline
10	COVERZJ	Point notes	Point

Appendix J Synthetic Design Storms and Flooding Simulation Results of Beijing-BWZ Case Study

J.1 Synthetic Design Storms

The synthetic design storms applied for flooding simulation in Chapter five and flooding mitigation in Chapter six for Beijing-BWZ case study are displayed in the following Fig. J.1 (a), (b) and (c).





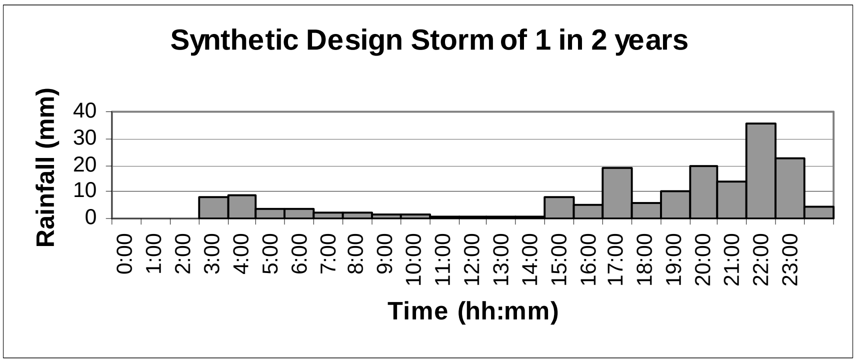
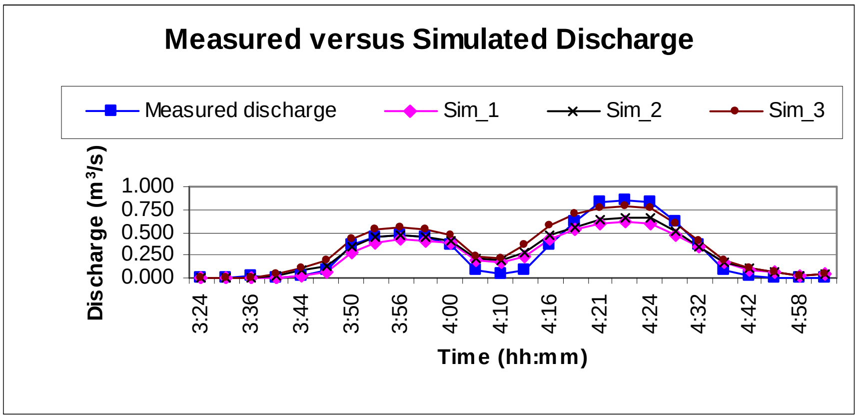
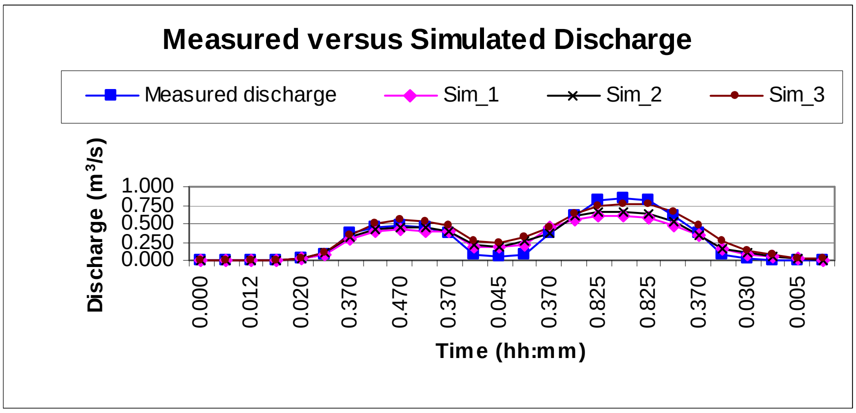


Figure J.1 Synthetic design storms of the BWZ case study

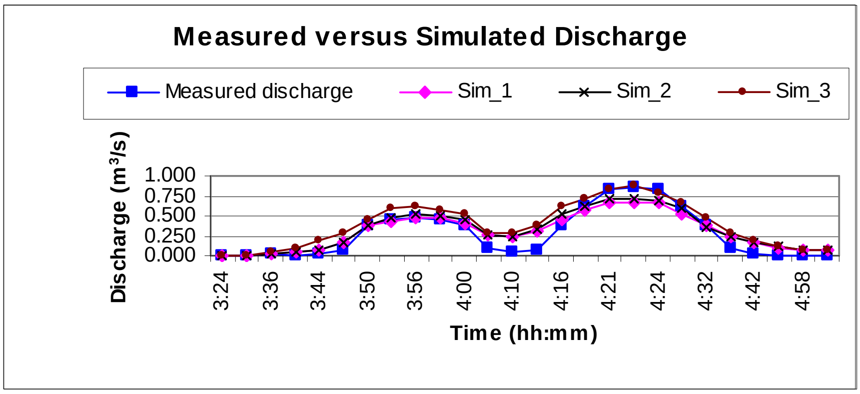
J.2 Model Calibration of BWZN Case Study



(a) Results of Model I



(b) Results of Model II



(c) Results of Model III

Figure J.2 Results of modelling calibration at node 22 of BWZN catchment

Appendix K Governing Hydraulic Equations and Solution Schemes of the MOUSE Pipe Flow

K.1 Saint Venant Equations

One dimensional Saint Venant equations are globally applied as governing equation for describing free surface hydraulic behaviors, which is derived by following assumptions (Sturm, 2001):

- The vertical acceleration is negligible so that the shallow water approximation applies, which results in a hydrostatic vertical pressure distribution, and the water depth, y, is small compared to the wave length;

- The channel bottom slope is small, so that $\cos\theta \approx 1.0$, and $\sin\theta \approx \tan\theta = S_0$, the channel bed slope, where, θ is the angle of the channel bed relative to the horizontal and the channel bed is stable, so that the bed elevations do not change with time.

- The flow can be represented as one-dimensional with (a) a horizontal water surface across any cross section, such that the transverse velocity is negligible and (b) an average boundary shear stress can be applied to the whole cross section.

- The frictional bed resistance is the same in unsteady flow as in steady flow, so that the manning or Chezy equation can be used to evaluate the mean boundary shear stress.

With reference to the control water volume in Fig. K.1, the continuity equation is expressed by:

Eq. K -1 $$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_L$$

Where, A is the cross-sectional area of flow, Q the flow rate of any cross section and q_L the lateral inflow rate per unit length.

Similarly, the momentum equation is derived as:

Eq. K -2 $$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(\alpha \frac{Q^2}{A}) + \frac{\partial}{\partial x}(gyA) = gA(S_O - S_f) + q_L v_L \cos\phi$$

Where $Q = A \cdot V$, the flow rate; $S_f = {}^{\tau_0}\!/\!_{\gamma R}$, the friction slope; $R = A / P$, the hydraulic radius and q_L the lateral inflow rate per unit length with velocity, v_L, and the angle, ϕ, of flow with respect to the x direction.

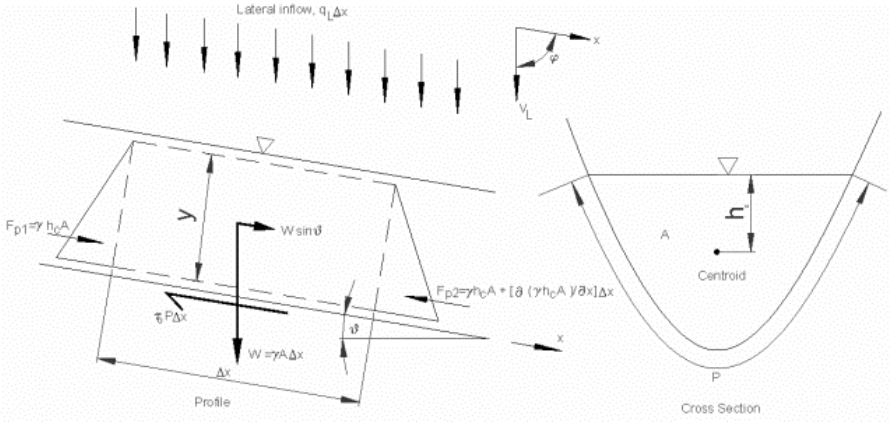


Fig. K.1 Control water volume of one dimensional Saint venant equation (Sturm, 2001)

Above equation (K.1) and (K.2) are applied to MOUSE pipe flow calculation with lateral inflow $q_L = 0$.

K.2 The Implementation Algorithm of Saint Venant Equation in MOUSE

The two governing equations in MOUSE are solved by an implicit finite difference method. The numerical scheme of Double sweep algorithm ensures the preservation of the mass balance and the compatibility of energy levels in the network nodes (DHI, 2000).

K.2.1 Computational Grid

The transformation of above two equations to implicit finite difference equation is performed by on a computational grids consisting of alternating Q, discharge, and h, water level, points (Fig. K.2).

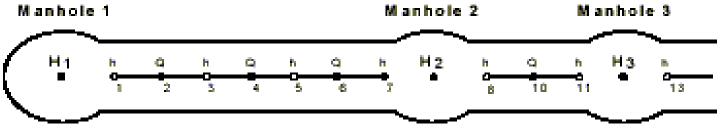


Fig. K.2 A sample of computation grids of sewer networks (DHI, 2000)

In each conduit, the Q and h points are equally spaced with distance Δx. equal to:

Eq. K-3 $$\Delta x = \frac{l}{N-1}$$

Where, l is the length of conduit.

The computational grids are automatically generated by the program with user-defined number of grid points.

K.2.2 Numerical schemes

The implemented numerical theme is a 6-points Abbott-scheme displayed in following Fig. K.3.

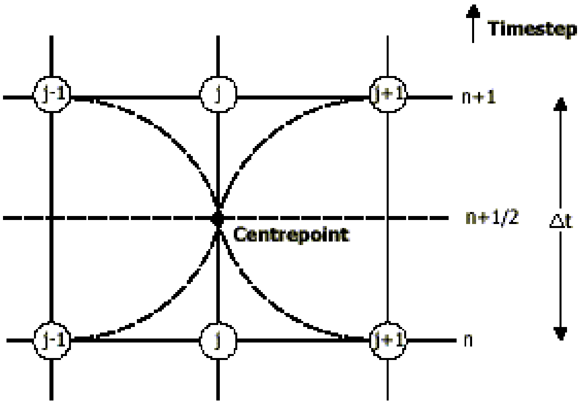


Fig. K.3 Centered 6-points Abbott scheme (DHI, 2000)

As only Q has deviation with respect to x direction, the continuity equation is centered on an h-point (see Fig. K.4).

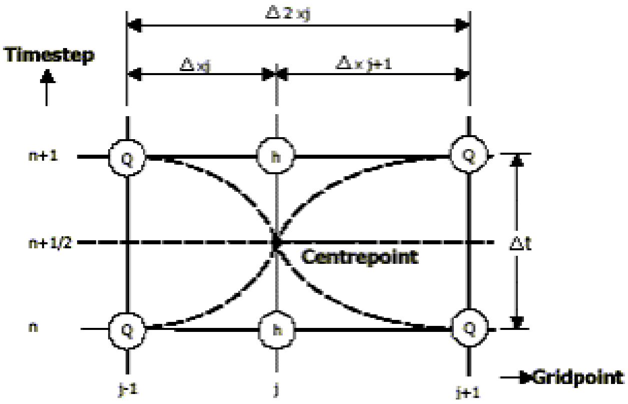


Fig. K.4 Continuity equation I Abbott scheme (DHI, 2000)

Such that, the finite difference of continuity equation is transferred into the following format:

Eq. K-4 $\alpha_j Q_{j-1}^{n+1} + \beta_j h_j^{n+1} + \gamma_j Q_{j+1}^{n+1} = \delta_j$

Where, α, β, γ, δ are intermediate parameters, which depend on Q and h at time step n+1

Unlike continuity equation, the momentum equation is centred on h-points (Fig. K.5).

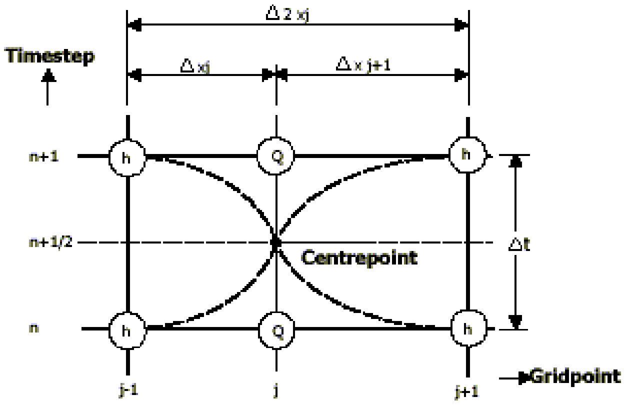


Fig. K.5 Momentum equation in Abbott scheme (DHI, 2000)

The finite difference format of momentum equation is expressed as below:

Eq. K-5 $\alpha_j h_{j-1}^{n+1} + \beta_j Q_j^{n+1} + \gamma_j h_{j+1}^{n+1} = \delta_j$

Where, α, β, γ, δ are intermediate parameters, which depend on Q and h at time step n+1.

K.2.3 The “Double Sweep” Algorithm

Using, instead of Q and h, a general variable Z, the general format of above equation (K-4) and (K-5) can be changed to the format below:

Eq. K-6 $\alpha_j Z_{j-1}^{n+1} + \beta_j Z_j^{n+1} + \gamma_j Z_{j+1}^{n+1} = \delta_j$

Where, the variable, Z, becomes Q at even grid points or h at odd grid points.

The general equations can be illustrated in a matrix format in Fig. K.6 below:

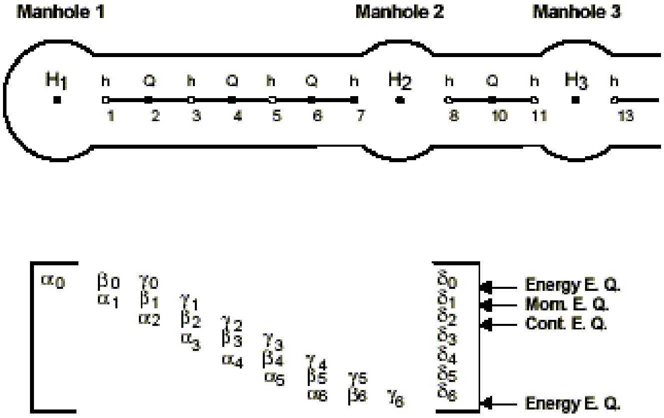


Fig. K.6 Breach matrix with coefficients derived from the node energy level, momentum and continuity equation (DHI, 2000)

Appendix L Basic Structures in the MOUSE Program

The MOUSE structures and options that are relevant to flooding model development in Chapter five are described in this appendix.

L.1 MOUSE node

Manhole, a common node in the MOUSE program (Fig. L.1 (a)), is defined by X- and Y- coordinate, the diameter of round manhole, the ground level and inverted level of the manhole, the outlet shape and the critical level.

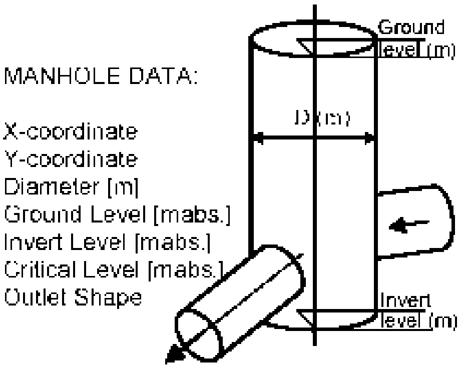


Fig. L.1 (a). Node defined in the MOUSE program (DHI, 2000)

“**Basin**”, another type of node defined in the MOUSE program, is illustrated in following Fig L.1 (b). Where, a “basin” is defined by X- and Y- coordinate, a group of parameters consisting of (H, A_c, A_s, K) which specify the storage volume of a basin at different time steps.

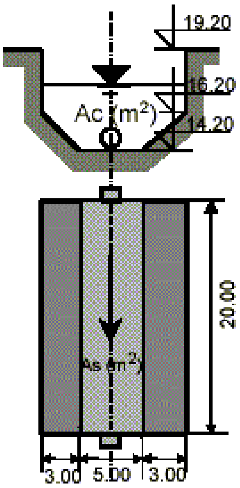


Fig. L.1 (b). Basin defined in the Mouse program (DHI, 2000)

L.2 Weirs

As displayed in following Figure L.2, two different types of weirs are defined in the MOUSE program. Such that both free overflow and submerged overflow can be simulated by the weirs.

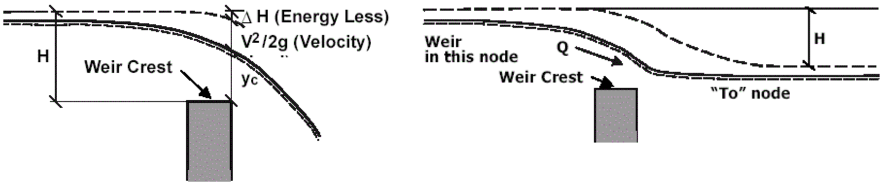


Fig.L.2 Overflow weir: free overflow (left) and submerged overflow (right) (DHI, 2000)

L.3 Fictitious slot

When the flow in sewers becomes pressurized during simulation, a fictive longitudinal slot is introduced in the crest of the pipe (Fig.L.3) to apply continually the Saint Venant equations.

Assuming the density of water ρ constant over the cross section, for a circular pipe, the density of the water can be expressed approximately as:

Eq. (L-1) $\rho \approx \rho_0 (1 + \frac{g(y-D)}{a_0^2})$

Where:

ρ_0 = the density of water for free surface flow [kg/m^3];

a = the speed of sound in water [m/s];

y = the water depth [m];

D = the pipe diameter [m].

The width of slot is specified as:

Eq. (L-2) $b_{slot} = g \frac{A_0}{a^2}$

Where, A_0 is the cross section area without extra pressure, *a* represents the speed of sound in water, and it is in the order of 1000[m/s] for most pipes.

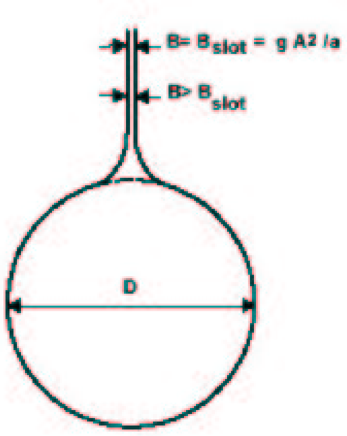


Figure L.3 Fictitious slot in the MOUSE program (DHI, 2000)

L.4 Flow Resistance

L.4.1 Friction losses in free surface flow links

Head losses caused by the friction resistance in free surface flow links are introduced as friction slope derived from the Manning's equation below:

Eq. (L-3) $$I_f = \frac{n^2 Q|Q|}{A^2 R^{4/3}}$$

Where,

n = roughness coefficient;

Q = pipe discharge, [m^3/s];

A = flow area, [m^2];

R = hydraulic radius, [m], ($R=A/P$, where P is the wetted parameter, [m]);

L.4.2 Head losses from nodes

L.4.2.1 Heal loss at node inlet

Assuming that the water levels in the inlet conduit and in the manhole, or other node, are the same, such that the head loss of the flow entering and expanding in the nodes amounts to the difference of the velocity heads in the inlet conduit i and the node m:

Eq. (L-4) $$\Delta H_i = \frac{v_i^{\ 2} - v_m^2}{2g}$$

L.4.2.2 Head losses at outlet from nodes

The outlet loss from manhole j is summed up by the loss due to individual link k at the node, which is estimated by the formula below:

Eq. (L-5) $$\Delta H_j = \sum_k \zeta_{jk} \frac{v_j^2}{2g}$$

Where,

ζ_{jk} is the head loss coefficient at manhole j through individual link k. MOUSE distinguishes among the following situations:

- Flow resistance calculation of manhole consisting of 2 inlet links and 1 outlet link (Fig. L.4.1)

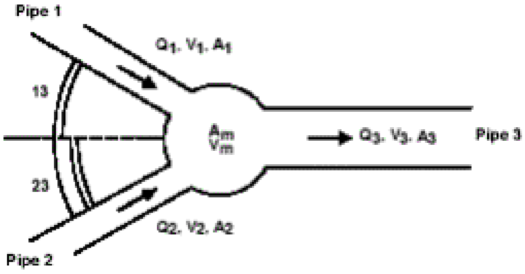


Figure L.4.1 Manhole consisting of 2 inlet links and 1 outlet link (DHI, 2000)

- Flow resistance calculation of manhole consisting of 1 inlet link and 2 outlet links (Fig. L.4.2)

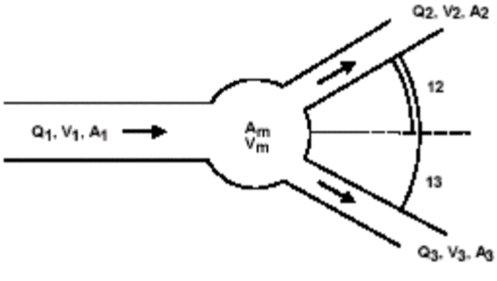


Figure L.4.2 Manhole consisting of 2 inlet links and 1 outlet link (DHI, 2000)

The head loss coefficient is calculated for each outlet link as follows:

Eq. (L-6) $$\zeta_{dir(j)} = \Sigma \frac{Q_i}{Q_j} \frac{\theta_{ij}^2}{90^2}$$

Where, i stands for inlet links, and j for outlet links.

- Flow resistance calculation of manhole with difference in elevation of inlet and outlet links (Fig. L.4.3)

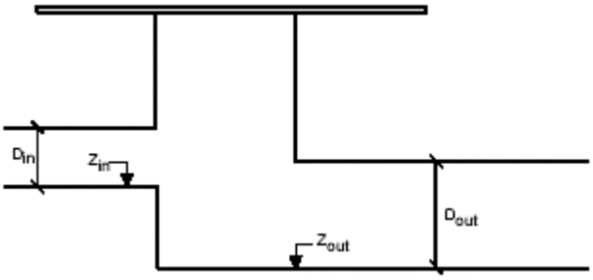


Figure L.4.3 Manhole with difference in elevation of inlet and outlet links (DHI, 2000)

The head loss is calculated by the following formula:

Eq. (L-7) $$\zeta_{level(j)} = \sum_{i=1}^{n} \frac{Q_i}{Q_j} \frac{(Z_j - Z_i) \cdot (Z_j + D_j - Z_i - D_i}{D_i D_j}$$

The total head losses through a node are summed up by the above relevant items in the equation (L-5).

Appendix M list of Publications

Papers published during the Ph.D study period are gathered in this appendix:

Nie, L.M., Schilling, W., Killingtveit, Å., Sægrov, S. and Ingrid S. (2002), *GIS Based Urban Drainage Analysis and Their Preliminary Applications in Urban Water Management*, Proceedings of the Ninth International Conference of Urban Drainage (9ICUD), 8-13 September 2002, Portland, Oregon, USA, published by ASCE, ISBN 0-7844-0644-8.

Nie, L.M., Sægrov, S. and Schilling, W., (2002), *GIS Based Urban Runoff Modeling*, Proceedings of the Ninth International Conference of Urban Drainage (9ICUD), 8-13 September 2002, Portland, Oregon, USA, published by ASCE, ISBN 0-7844-0644-8.

Nie, L.M., Schilling, W. and Zhou, Y.W. (2002), *Flooding Simulation and Mitigation in an Urban Catchment of Beijing, China,* Proceedings of 2nd International Symposium of Flood Defency (2ISFD), published by Science Press, ISBN 1-880132-54-0, PP.1372-1380.

Nie, L.M. and Schilling, W. (2001), *Development of Sustainable Water Management in Beijing, China,* Proceeding of International Symposium of Frontiers in Urban Water Management: Deadlock or Hope, published by IHP-V, Technical Documents in Hydrology No.45, UNESCO, PP.279-284.

Nie, L.M., Schilling, W., Royset, S. E. and Hovden, J. (2001), *Risk Analysis of Flooding of Urban Drainage Systems*, Proceedings of 29th International Congress of Water Association and Hydraulic Research (29th IAHR), published by Tsinghua University Press, ISBN 7-302-04676-X/TV, PP. 403-409.

Nie, L.M. and Schilling, W. (2000), *Ecological Flooding Impacts and Flood Control in China,* presented on the World Water Day of 20 March 2000, Norwegian Hydrological Research Program by NVE.