Study on pluvial flood processes with sensing and modelling of old urban drainage systems in the cities of developed and developing countries

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ABTRACT

Pluvial flooding is a critical issue in many cities worldwide and for flood mitigation measures the causes and characteristics behind pluvial flooding are of interest. Pluvial flooding occurs when the rainfall amounts exceed the capacity of storm water drains to collect the water and the capacity of the ground to absorb water. This is usually associated with short-duration storms. In the situation that the frequency of rainfall with strong intensity would increase due to climate change, risk reduction of pluvial floods is further challenge. However, it is hard to understand substantial characteristics of pluvial floods especially on the scale of city blocks, because they are seldom measured with instruments. It is also difficult to predict areas prone to the flood caused by heavy rainfall with a certain intensity. Indeed, even not in the climate change situation, insufficient capacity of a drainage system, which may be different from that of design, is also another important factor to cause pluvial floods to cope with these challenges. Modelling approach alone is not adequate to evaluate the causes and severity of pluvial floods.

If actual from that of design, the primary goals of this study, therefore, is to propose an effective data collection system for understand substantial characteristics of pluvial floods and applies it to models for identifying pluvial flooding processes including drainage models. Utilizing these results, the severity of pluvial flood is finally evaluated in relation to controlling factors.

In this study, I set Tsushima, Japan and Yangon, Myanmar as the target areas. These areas suffer frequently pluvial floods during monsoon seasons and typhoon approach. It could be described that the elevation, weather, drainage system, urban development and altitude of the citizens, which are characterized in each city, are strongly influenced on pluvial flood occurrence and severity. I presented the water logger monitoring system in urban storm drainage to identify the process of pluvial floods in both cities during heavy rain. It is also applied to preparation for inundation map with high resolution terrain data compared with simulation model results. I used New Integrated Lowland Inundation Model (open source) and InfoWorks ICM (commercial models) to assess the pluvial flood and to explore the effects of sediment depth and other factors in a different storm drainage system of each city that influence on flood severity.

Pluvial flood severity depends on not only rainfall intensity but also other controlling factors in the urban area such as sediment depth and garbage clogging inside drainage channels and water level variation of a river that receives the water from drainage systems. Pluvial flood severity is strongly related to sediment depth in the drains, and duration of flood is more sensitive affects than flood discharge. Flood inundation map is set based on joint impact of sediment and increased rainfall that shows where flooding may occur and how severe flood will be over a range of water levels in the urban city center.

We demonstrated that estimating local pluvial flooding process in an urban area using water depth loggers and a digital elevation model, which are cost-effective and do not require the latest technology. The results showed recorded water depths in storm water drainage systems could be applied for tracking the pluvial flooding process by combining it with high-resolution altitude distribution. The results of modelling demonstrated that considering with open channel storm drain can retain flood water than without considering open channel storm drain. Because considering with storm drain has less impacts of floods, while considering without storm drain has big impacts of floods.

Pluvial flood can occur typically coincide with sediment depth and garbage clogging inside drainage channels, garbage blockage at trash screen and water level variation of a river that receives the water from drainage systems according to the comparison of the logger and simulation results and site inspection. InfoWorks ICM provides faster calculating time, accurate flood characteristics of the simulation results like flood depth that can directly compare with logger depth, special feature like sediment in drain than New Integrated Lowland Inundation Model (NILIM). All of the simulations with different scenarios by applying InfoWorks ICM is more effective and efficient for flood risk evaluation and identification for this study. Effluent capacity of open channels is more sensitive in flooding than closed drain system. Indeed, the pluvial floods often occur closely to the open channel drainage system.

Flood risk management of developing countries have a lot of challenges, not only structural mitigation measures but also non-structural mitigation measures especially lack of land use regulation, enforcement of illegal waste disposal, and weakness of collaboration among different departments. I set pluvial flood risk management governance structure of Yangon, to reduce overlap and gap in responsibilities and to promote bridging concepts of visions for flood risk management plans and programs, clear rules of sharing responsibilities among different departments. I suggested some pluvial mitigation measures based on simulation results and field inspection that are reliable and achievable.

Chapter 1

INTRODUCTION

1.1 Backgrounds

Nowadays, flood has become one of the extreme catastrophic natural hazards with significant economic damage and loss of lives, particularly in urban areas (Zevenbergen et al., 2013; Hammond et al. 2015). Flooding in urban areas is especially related with pluvial flood (Tingsanchali 2012; Rosenzweig et al. 2018; Meng et al. 2019), usually occurs when the volume of surface water exceeds the conveyance capacity of the urban drainage system (Dawson et al., 2008; Pitt, 2008). Since recent decades, pluvial flood has been increasingly considered as a major hazard and presented a significant risk for urban areas (Fritsch et al. 2016; Rangari et al. 2018). Pluvial flooding is often assumed to only present a “nuisance”, with minimal impacts. However, there are many examples where it has resulted in direct loss of life, contaminant and pathogen exposure, significant property damage, and widespread of interruption in transportation networks or in other urban critical systems (Dogulas et al.,2010; Falconer et al., 2009). Furthermore, pluvial flooding generally occurs more frequently than fluvial flooding which might lead to comparative or higher economic risk (Moftakhari et al., 2017). In Japan, annual damage cost due to the pluvial flood is about USD 1 billion, as Figure 1.1 shows the temporal changes in both of annual fluvial and pluvial flood damages to general properties (MLIT, 2009). Here, general property includes housing, household appliances, depreciable and inventory assets for agricultural, fisheries and other businesses. The figure suggests that annual pluvial floods cause significant damages, and efforts for pluvial flood damage controls seem ineffective. Even well-prepared cities in terms of flood defense infrastructures, like Tokyo and Nagoya, suffer frequent pluvial flood damages (Sato, 2006; Fan and Huang, 2020). Cities in Japan are more vulnerable than before because of rapid urbanization with an ageing population, consequently decline in preparedness of local communities to fight flood disasters (e.g. Ikeda et al., 2007). Not only the big cities in Asian countries, but also those in Western countries have suffered from huge damages due to pluvial floods (Ofwat, 2002; Rosenzweig et al. 2018). In developing countries which make more risk for pluvial flooding, there are three major characteristics, compared to developed countries, as follows:(i) higher rainfall intensities, (ii) scarcer resources for drainage constructions, and maintenances and (iii) less effective solid waste management. They cause entering large amount of surficial solids, which degenerates drain capacity in the drainage system (Kolsky et al.,1999; Jha et al., 2012). So, pluvial flooding is one of the important issues in urban area and it is necessary to reduce its impacts on socioeconomic development of the countries. However, it is difficult to be identified pluvial flood processes because pluvial flood occurrences are complex phenomena. Although one of the main drivers of pluvial flood is extreme rainfall intensity, there are other drivers such as urbanization, inadequate drainage system, improper solid waste management, water level variation in receiving water bodies in urban areas (Pervin et al. 2019).

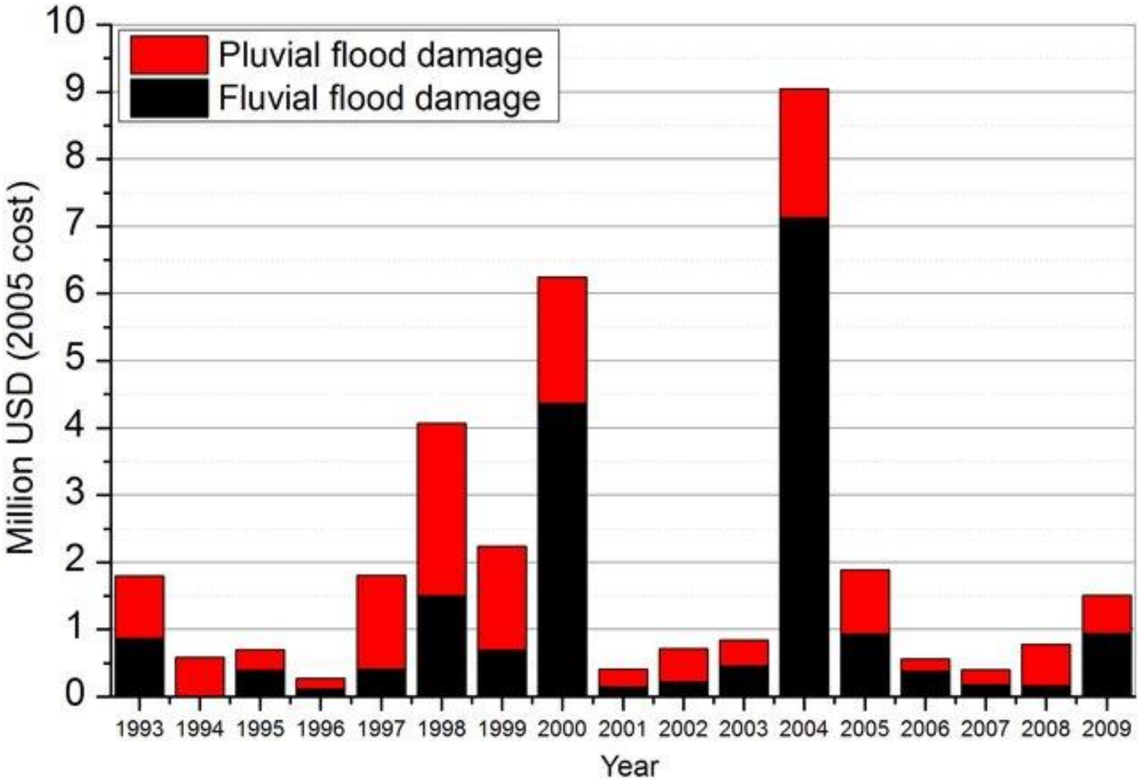

Figure 1.1 Historical general property damage description for pluvial and fluvial floods in Japan during 1993–2009.The pluvial flood occurrence is more constant than fluvial flood occurrence annually

The increased frequency and intensity of flood events in the world is partially credited with climate change-driven increase of extreme precipitation (IPCC, 2014). Global flood hazard is increasing as the direct consequences of climate variability (Milly et al., 2002). The other effects of urbanization on climate is the impact of rainfall. A number of studies have found rainfall increases in regions downwind of urban areas, with increases as high as 25% in some cases (Shepherd et al., 2002). Precipitation is the major parameter within climate change, causing the greatest flood impacts (Semadeni-Davies et al., 2008). Moreover, extreme rainfall leads to pluvial flooding in many cities without adequate warnings, affecting many people (Houston et al., 2011; Dale et al, 2012). Extreme precipitation with its convinced hazards pose huge threats to the economy, agriculture, infrastructure, and human lives (Spekkers et al., 2017). Climate change has a prominent effect on pluvial flooding and many researchers apply local climate models to predict the impacts of flooding and propose adaptation measures to reduce their socio-economic impacts (Löwe et al., 2017; Russo et al.,2020). Urban infrastructure planners and engineers should consider the forecasted changes in the occurrence of intense precipitation to adapt urban drainage systems as part of the reconstruction or retrofit of aging infrastructure. To meet the combined challenges of climate change and urbanization, the urban planners and engineers should carefully select adaptation measures that would require technical, economic and political commitment are needed (Semadeni-Davies et al.,2008; Yazdanfar and Sharman,2015).

Since the 20th century, the frequency and intensity of flood disaster have been larger than before. One of the main reasons is urbanization with land use / cover changing (LUCC) which has been made by human beings due to population growth and migration from rural areas to urban areas. Vegetated areas and natural streams have been replaced by houses, roads, artificial drainage systems and pavements which are impervious surfaces. Storm water flows into rivers faster in such environments than the natural conditions (Konrad and Booth, 2005). Major differences between the inundations in urban and rural areas are the existences of an impervious layers with the complexity of the road and building configurations (Lee et al., 2014). A better understanding and assessment of the impacts of land use changes on the watershed hydrologic processes are of great importance not only for the predictions and mitigations of flood hazards, but also for the planning the watershed management for sustainable development (Chen et al., 2009). Yu and Coulthard (2015) highlight that urban land covers and land uses, especially urban forms have extensive impacts on hydrological processes such as surface runoffs and infiltrations.

Pluvial floods are occurred due to the overflowing from urban drainage system receiving stormwater runoffs. There are three types of urban drainage systems such as combined sewer, separate sewer and open channel networks. Combined sewer carries both of wastewater from domestic and industrial environments and storm water in the same pipe (E. W. Steel, 1979). Figures 1.2 and 1.3 show schematically typical combined and separate sewer systems of a town, respectively.

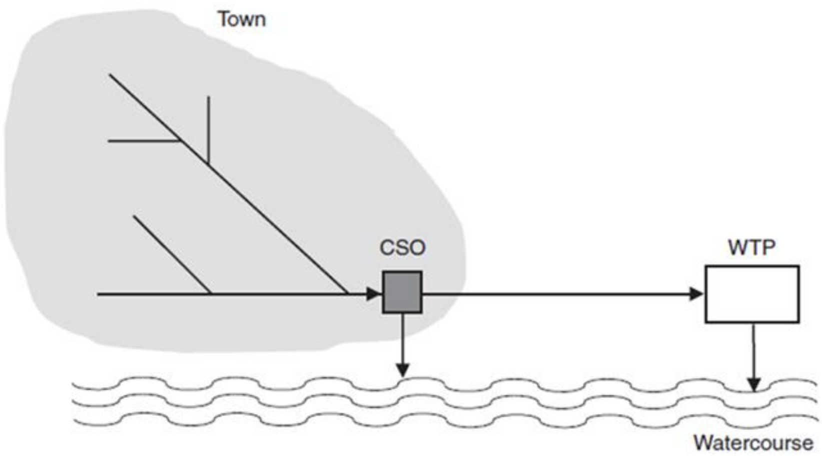

Figure 1.2 Combined system (schematic plan)

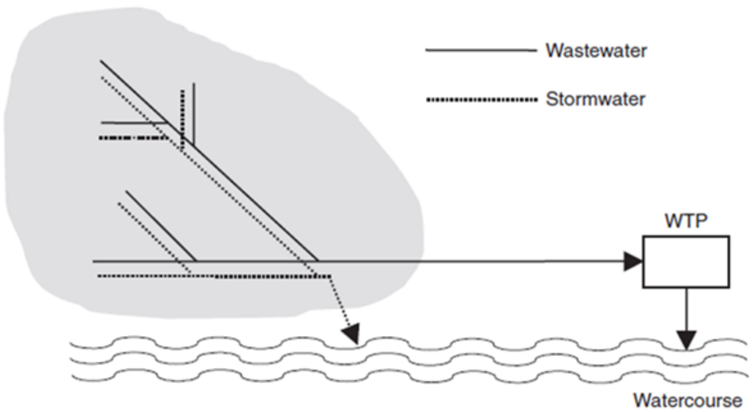

Figure 1.3 Separate system (schematic plan)

A storm water system with open channels for the discharge of rainwater exists in most urbanized areas in developing countries. The channels usually drain off rainwater into rivers or sometimes into the natural lake or ponds. Unauthorized discharge of domestic wastewater into the system leads to surface water pollution and diffusion of pathogens. Solid waste is also commonly disposed into these open channels (Figure 1.4).

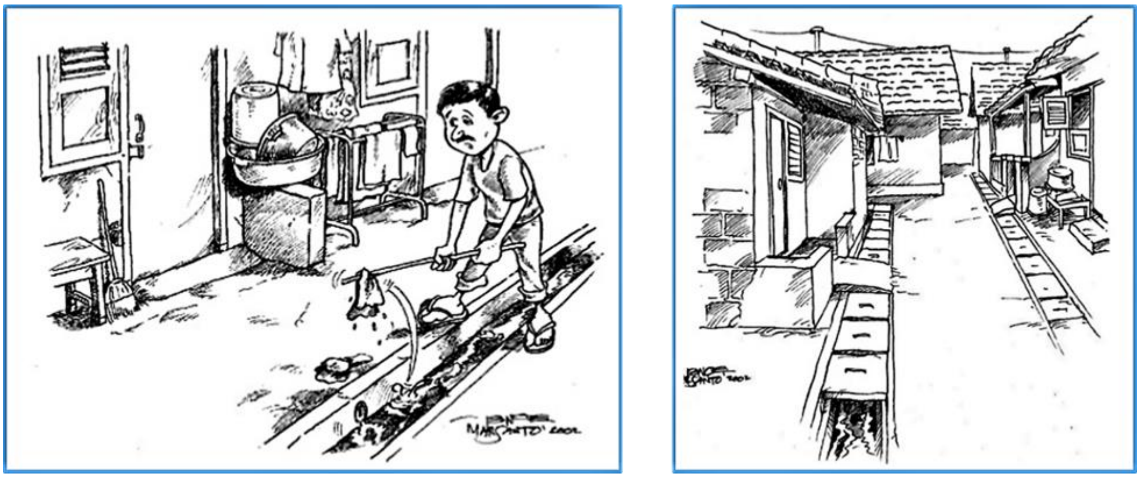

Figure 1.4 Open channel drainage system (Source: SANIMAS 2005)

Pluvial flooding can occur during periods of moderate rainfall and even during dry weather. This kind of flooding is very difficult to predict due to the numerous possible causes. These causes can be related to operational deficiencies such as pipe blockages and gully pot obstruction especially in open channel drain or negligent behavior e.g. The discharge of fat and grease from restaurants, and waste from construction sites (Cherqui et al, 2015). The urban flood problem is intensified further by the natural sloping pattern of the cities. In addition to these, clogging of storm drainage, siltation of the existing canals and shrinkage of the wetlands and natural detention ponds in the city which act as the repository of cities of developing countries' storm and sewage water have worsened the scenario (Akukwe 2014). The hydraulic performance of urban drainage systems can be dramatically affected by the operational condition of its components as in the case of gully pot blockage, sewer pipe blockage and inlets, through which surface storm-water runoff enters the underground storm water drainage (Despotovic et al.,2005, ten Veldhuis and Clemens,2011)

1.2 Previous studies

Numerous hydrodynamic models have been established for determining the flood conditions through diverse methods. Their applications have also been conducted through commercial and open-source simulation tools depending on different uses (Henonin et al. 2013; Jiang et al. 2015). From application points of views, different applications require various information and accuracy levels. As an example, flood risk assessments in urban areas rely on the accuracies of critical flow representations. The flow velocity should be sensibly modeled for flood damage assessment, while the maximum water depth and extent of inundation could be adequate for hazard mapping creation, water resource planning and environmental flow assessment. Flood modeling provides the distribution and extent of flood conditions its dynamics. Besides, real-time flood simulations can provide emergency operations (Jiang et al., 2015; Gharbi et al., 2016). Flood inundation model has also been considered as an effective tool to plan, design and analyze for the urban drainage system and flood events in cities (Fan et al., 2017; Teng et al., 2017; Ahamed and Agarwal 2019; Laouacheria et al., 2019). It is useful to assess the performances of stormwater sewer networks under extreme events by using climate models and urbanization scenarios as well as to check the operational and structural solutions. Although its benefits, reliable flood inundation modeling is not as simple as it sounds, due to the confused and complex phenomena of flooding (Basnayaka and Sarukkalige 2011; Fan et al., 2017). There are many uncertainties to input data, model parameters and so on in urban flood modellings. So, calibration and verification procedures need before applying the model results for decision making processes. A well calibrated model can provide the assurance that, at least for a range of tested conditions, the model behaves like the real system, and the results may be used for different purposes (Mark, 2014).

Regarding urban drainage networks, flood protection measures are often considered using modelling software to identify flood prone areas, or pipes and channels with inadequate hydraulic capacities for draining stormwater during heavy rains (Jin et al., 2015). However, pluvial flooding simulations remain very complex, and are difficult to reflect practical inundations, affected not only by the various possible factors such as inlet or sewer blockages, hydraulic overloading, breaks or detriorations of storm drains due to their super annuations and wastes discharged from construction sites, but also by the various overflowing locations (manholes, retention tanks, etc.) in the system (Aronica and Lanza, 2005; Palla et al., 2018). In order to tackle to this issues, it can be mainly used other data related to the system limitations such as observed flooding records, complaints from inhabitants, operational problems, etc. (Marlow et al. 2011; Rodríguez et al. 2012). Few studies have been done using pluvial flooding databases and causal analyses in order to improve urban flood management (e.g. ten Veldhuis et al., 2009). ten Veldhuis (2009) assessed pluvial flood events by using complaint registers data, which might give a better understanding of the mechanisms in Haarlem, the Netherlands and the main causes was due to gully pot blockages (79% of reported complaints), while the effects of rainfall intensities were much smaller (5%). Pluvial floods in the cities are mainly caused by the blockage problems not only in the developing countries such as South Asian, South East Asian and African countries, but also in the developed countries (Gupta and Nair, 2011). Ramachandra (2011) investigated most vulnerable flood prone locations in Bangalore, India by using survey data such as interview with residents, direct observation post flood event and found that there were many blockings due to solid wastes in open channels. So, data are very important to clarify the causes of flooding, obtained from on-site interventions following flood reports or routine inspections.

Data availability of pluvial flood is limited not only in developing countries, but also in developed countries because time and place of pluvial flood events are difficult to predict. Some of the developing countries still use conventional methods to get pluvial flood data. They are direct observation during floods with chalk gauges and resident gauges (Kolsky, 1999). Chalk gauge consist of meter rulers coated with chalk, built into a small protective structure into which floodwaters are free to enter it, and resident gauge is simple ruler on telephone pole or walls which are marked in 0.2 m to 1m. Nowadays, some of the developed countries use crowdsource data for flood data collection like GPS in mobile phones and social media including Facebook, Twitter and You Tube (Starkey et al., 2017; Li et al., 2017). These sorts of data (text, pictures and videos) were mostly collected through social media services and public image sources. Gathering data from such sources requires mining of the relevant materials, extracting specific data from a dataset, like estimating flood depth with comparing reference object's height. It also needs dealing with uncertainties in the spatiotemporal characterization of the data of interest because some of these photos and videos taken during flood occurrences do not include time records (Kutija et al., 2014; Assumpção et al., 2018). So, crowd source data are difficult to apply model calibration, verification and to compare directly with simulation results. Besides, in Sweden flood insurance data from insurance company and water utility company are used to investigate the mechanisms and characteristics led urban flooding impacted with rainfalls, types of drainage systems and tidal level variations (Sörensen and Mobini, 2017). Most of the developing countries do not widely use insurance data for inquiring pluvial flooding situations. However, water depth logger can fill the data gaps in spatiotemporal variations of the water level fluctuation for tree filter performance and open channel drain (Ertezaei et al., 2018; Hiroi et al., 2019).

Flood hazard maps provide one way to visualize flood risks, and are generally created with future projections based on geographic information system (GIS) and hydrodynamic model (Russo, 2012; Martínez-Gomariz et al., 2019). Previous researchers analyzed the pluvial flood risks to track the flood prone locations in the study area by applying integrated models and different future scenarios related to climate changes and urbanizations, however they did not track the real flood events because of the data scarcities. Although flood hazard maps are beneficial for promoting a public awareness of flood risks, they usually do not show the variations in inundation severities impacted by sediment depositions in the drainage system. Visualization of sediment effects will help the residents and policy makers to understand flood risk and further contribute to make better plans for its maintenance. Also, research studies that simultaneously assess the impacts of these two driving factors such as rainfall intensity and sediment depth are lacking. In this study, I develop an estimation method for pluvial flooding in urban areas using water depth loggers and digital elevation models that fill the data gaps to track their processes. Besides, I evaluate the pluvial flood severities due to combined effects of rainfall intensities and sediment depositions in drainage channels.

1.3 Research aim and objectives

The aim of this study is to assess the causes and severities of pluvial flooding in the cities of developed and developing countries with the old drainage systems. In this study, I chose two study areas Tsushima, Japan and Yangon, Myanmar because of these cities' drainage basin characteristics, drainage type characteristics and pluvial flood frequency are nearly similar. The following factors are same characteristics in these two cities

- Old drainage system
- Open channel storm drain
- Lowland areas
- Large number of flood frequency

This thesis is organized with the following concrete objectives:

Objective 1: To track pluvial flood events by using logger data and high resolution altitude distributions,

Objective 2. To introduce the collection schemes of effective data which apply for evaluating the pluvial flood events with simulation results,

Objective 3. To analyze flood inundation processes under different scenarios via the incorporation of rainfall intensities and sediment depositions in the drainage channels, and

Objective 4. To quantify and visualize the sediment effects on inundation under rainfall intensity variations.

1.4 Study area

1.4.1 Yangon

Yangon, the largest industrial and commercial city in Myanmar that is situated at the Yangon river bank and Irrawaddy delta. Yangon city is facing pluvial flood frequently than the previous situation because of city expansion was arisen within 12 years from 133 sq. miles to 260 sq. miles that causing reduction of pervious area and natural flood retention storage (Win and Win 2010). Yangon is facing sometimes unexpected rainfall like maximum 24-hour rainfall observed during the past 35 years was 343 mm, or 13.54 inches in 2007. Besides, the increase urbanization effects and rainfall, pluvial flood in Yangon city has occurred due to the inadequate size, lack of proper maintenance and tidal effect (Kyi et al., 2018a). (Kyi et al., 2018b) analyzed the performance of the existing drainage capacity by using Modified rational method and EPA SWMM, then proposed new drain size capacity for future development effects. (Kyi et al.,2018b) applied conventional way by using modified rational method and EPA SWMM that can analyze only 1 D situation and to meet more accurate results for this area integrated 1D 2D approach need to be considered. However, there is lack of detailed analyzed for pluvial flood events in Yangon city and lack of flood data. Yangon situated on Irrawaddy delta region and that suffer extreme weather events, such as typhoons, and sea level rise (Chan et al., 2012). For example, close area of Yangon city, Myanmar was hit by cyclone Nargis in 2008 that caused inundations to 75 km inland area and caused more than 140,000 casualties and US$17 billion economic losses (Terry et al., 2012). During Nargis cyclone approach, some part of urban drainage system fails to convey storm water into the receiving water bodies because of inadequate drainage capacity and high river water level (Lwin, 2009).

1.4.1.1 Topography

Existing land is basically flat and nearly 100 percent urbanized with highest ground elevation of 16.5m above mean sea level (MSL) at the Northwest border of Latha Township. Fairly rolling terrain exists only in the part of Latha Township. Rest of the CBD area is basically flat and all below the level of 5.0 metres, with some areas at the marina border as low as 1.0 metre above MSL. Prevailing land slopes in the CBD area vary from 1.75 percent at the higher strips in CBD to 0.10 percent for the areas next to the Yangon River. In summary, in the CBD area the maximum level is approximately 15 m above MSL, with lowest areas lower than 1 m above MSL (Figure 1.5).

Figure 1.5 Elevation of Yangon downtown study area

1.4.1.2 Rainfall

The climate of Myanmar follows a typical monsoon pattern. Historically, the average annual mean rainfall for Yangon is 2,681 mm with the annual average rainy days of 129.3 days. (Fig 1.6) shows annual rainfall for Yangon from 1989 to 2017. The month with the most precipitation was in July. The relative humidity was generally higher from May to October. The dry season occurs from November to April. Based on the historical weather for the last twelve months in Yangon, no precipitation was observed in December 2012, February 2013 and March 2013. Mean annual rainfall is 2757 mm (1967-2016). Maximum on day rain observed in 2007 was 343 mm.

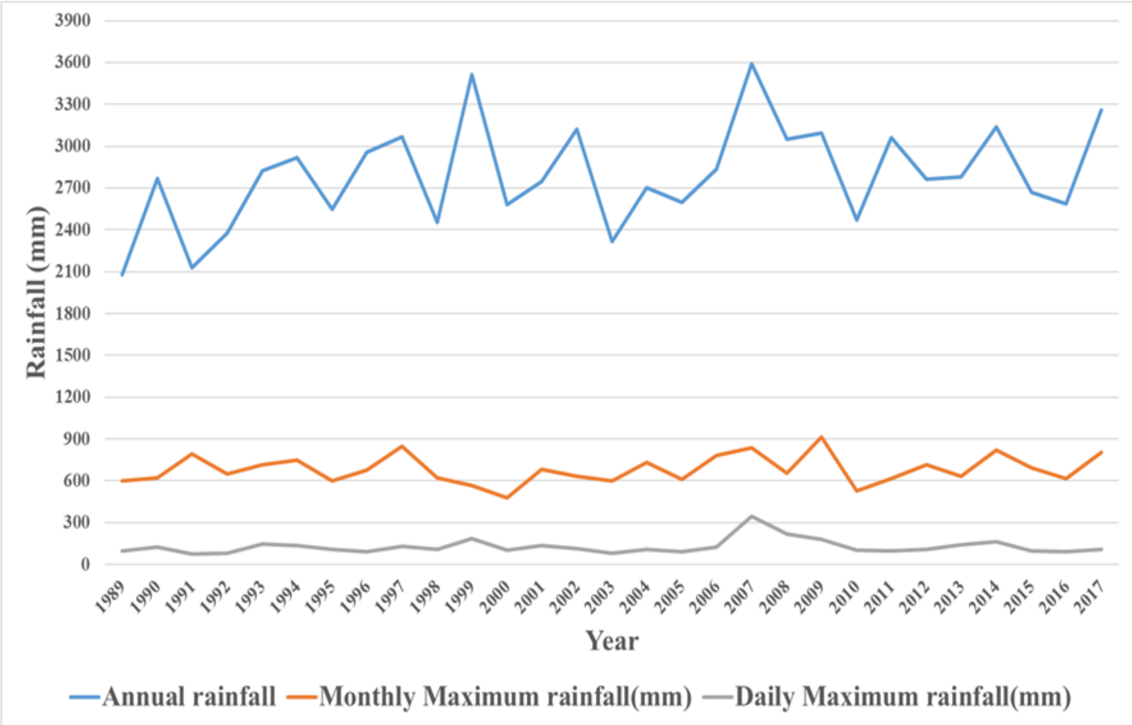

Figure 1.6 Rainfall data in Yangon (1989-2017)

1.4.1.3 Drainage system

The drainage system of Yangon was built nearly 100 years ago both open channel storm drain and separate sewer system. The system has, more or less, not been developed since it was built until last several years ago. Some parts of drainage system were rebuilt or retrofit, but most of the drainage system are deteriorated until now. The storm drainage consists of 73 km of open channel length, 609 nodes and 16 outfalls are shown in (Figure 1.5)

1.4.2 Tsushima

Tsushima city is suffering pluvial flood frequently during the typhoon season. It is also situated in lowland areas, that is one of the reason to flood prone area in Aichi prefecture. Besides, land use change rate is increasing e.g. urbanized land increased from 30% in 1976 to 51% of total area in 2009, whereas the extent of crop fields decreased from 65% in 1976 to 42% in 2009 (Min., 2015). The drainage system of this area is constructed more than 50 years ago, current drainage capacity cannot handle the increase storm water runoff due to climate change and urbanization effects. The type of urban drainage system consists of combined and open channel system, so pluvial flood management to different types of drainage system need to evaluate in this area. Figure 1.7 shows the flood area and damage cost of Tsushima city's recent flood events. Most of the flood events are pluvial flood events.

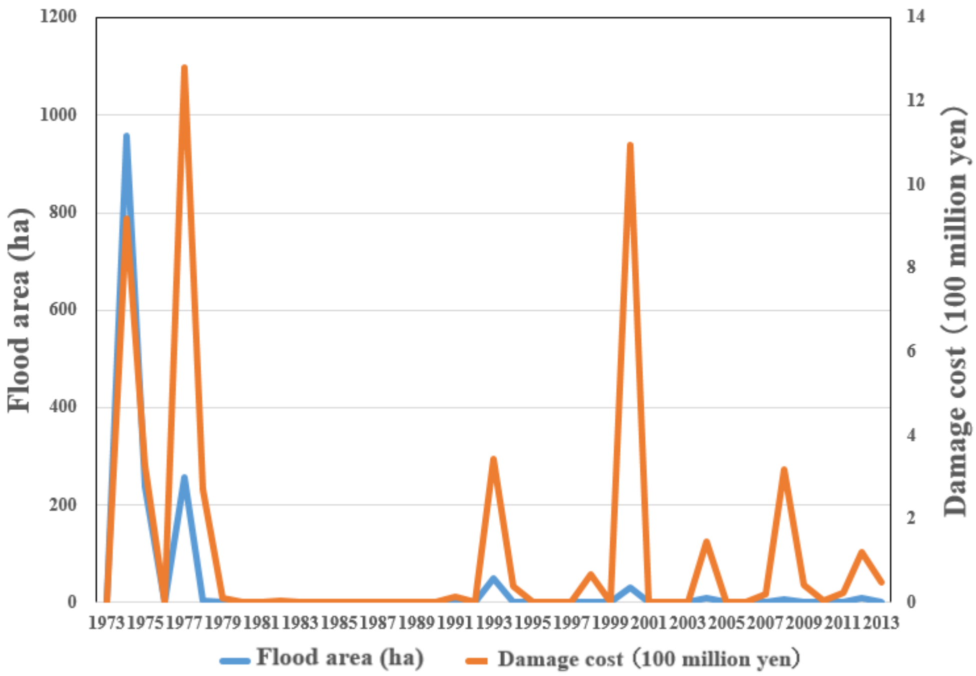

Figure 1.7 Historical damage cost and flood area in Tsushima for the period 1973-2013 (Source-Tsushima city website)

1.4.2.1Topography

Topographically, Tsushima city is a low-lying area at an elevation of 3.6 m below to 8.2 m above mean sea level. The elevation of the study area is 3.m below to 3.6m above mean sea level (Figure 1.8).

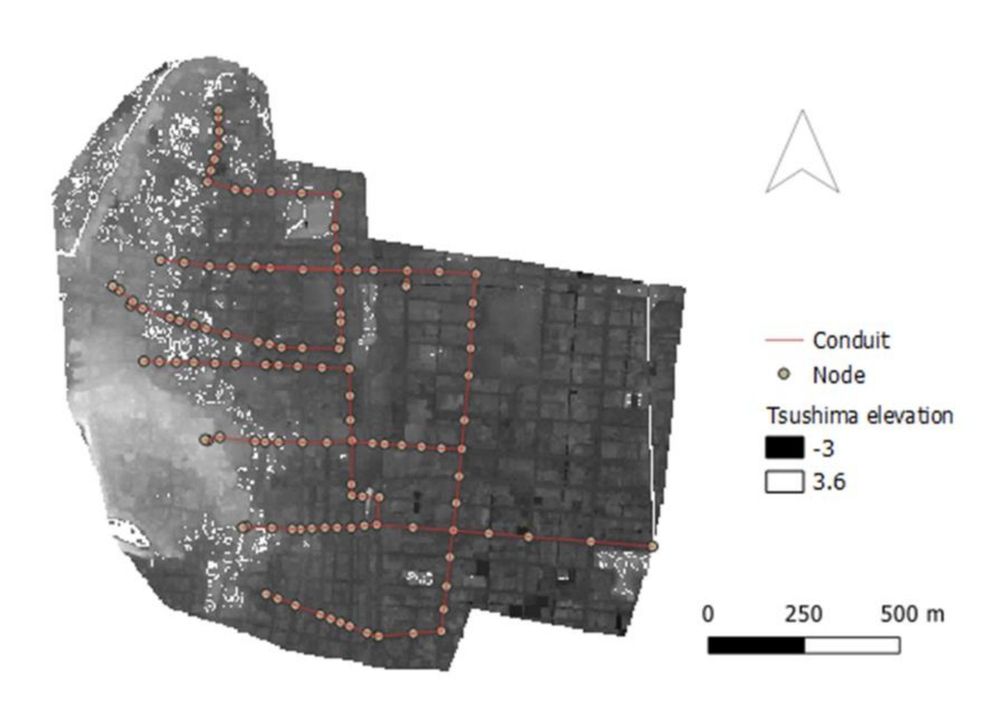

Figure 1.8 Elevation of Tsushima study area

1.4.2.2 Rainfall

Owing to its location in the East Asian monsoon region, the city experiences a rainy season in June; annual precipitation is approximately 1,500 mm. Figure shows annual rainfall from 1979 to 2013 for Tsushima city. The annual rainfall does not change prominently, but Tsushima city meet frequently pluvial flood until now. (Hashimoto et al., 2014) clarified rainfall pattern in Japan changed like heavy rainfall over 50mm/h and heavy rainfall concentrated into short time span on the order of 10 min have occurred more frequently. This is one of the reason for increase Tsushima pluvial flood events. Figure 1.9 shows annual rainfall in Tsushima city from 1979 to 2013.

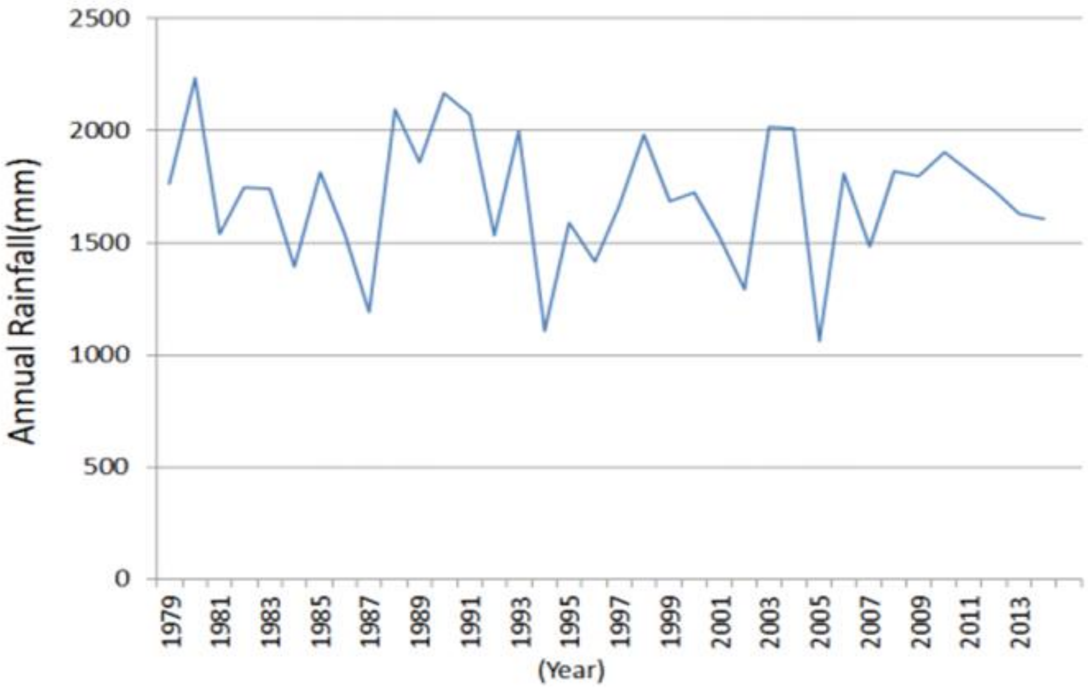

Figure 1.9 Annual Rainfall of Tsushima city (1979-2013)

1.4.2.3 Drainage system

The drainage system of Tsushima city was built more than 60 years ago. The drainage system consists of open channel storm drain and combined sewer system (Figure 1.8). Drainage infrastructure of the sewer system encompasses 122 manholes, 3159 flow regulators and 6.6 km of combined sewer pipes (larger than 0.6 m in width), and 115 open channels (larger than 1.2 m in width) with a total of 6.2 km length. The open channel drainage system is open channel without covers, trash screens were installed to reduce garbage clogging at the entrance of culvert or open channels with cover. There are two open channel outfalls in the study area, and flood gates did not install at the outfalls to prevent back water effects from Zenta river. Sometimes, storm water cannot discharge properly into the river because of water level variation in Zenta river.

1.5 Outline of the thesis

This dissertation consists of eight chapters, which will cover the following:

Chapter One "Introduction" consists of research review about pluvial flooding, urban drainage system, urban flood modelling, and monitoring. It also provides a brief overview of the background, study area, outline of the study and it discussed specific objectives of the study.

Chapter Two "Assessment of pluvial flood event applying monitoring, and modelling" includes monitoring for water depth variation in the open channel and pluvial flood analysis with simulation model.

Chapter Three "Factors controlling the pluvial flooding in the downtown area of Yangon, Myanmar with the old storm drainage system" discusses details about the effects of sediment depth in the drain and increase rainfall intensity on pluvial flood severity.

Chapter Four "Effective sensing and computing inland flooding processes in a lowland urban area with sewer and drainage systems" introduce effective sensing method for pluvial flood and evaluate the effects of open channel drainage of pluvial flood severity by using New Integrated Lowland Inundation Model.

Chapter Five "Identifying the pluvial flood occurrence using monitoring and modelling (InfoWork ICM)" analyze the logger data and monitoring data, suggest the possible solutions for this gap.

Chapter Six "Influence of sediment depth and rainfall intensity on pluvial flood severity" shows the sediment depth and rainfall intensity has severe effects on pluvial flood analysis using InfoWorks ICM.

Chapter Seven "A comparative study between Tsushima and Yangon for flood mitigation measures" discusses current and future pluvial flood mitigation measures in Tsushima and Yangon based on simulation results and field visits.

Chapter Eight "Conclusion and Recommendations" draws the final conclusion of this research and some recommendations for future research.

The framework of the research phases presented in the dissertation with the relationship between them is delineated with a (Figure 1.10)

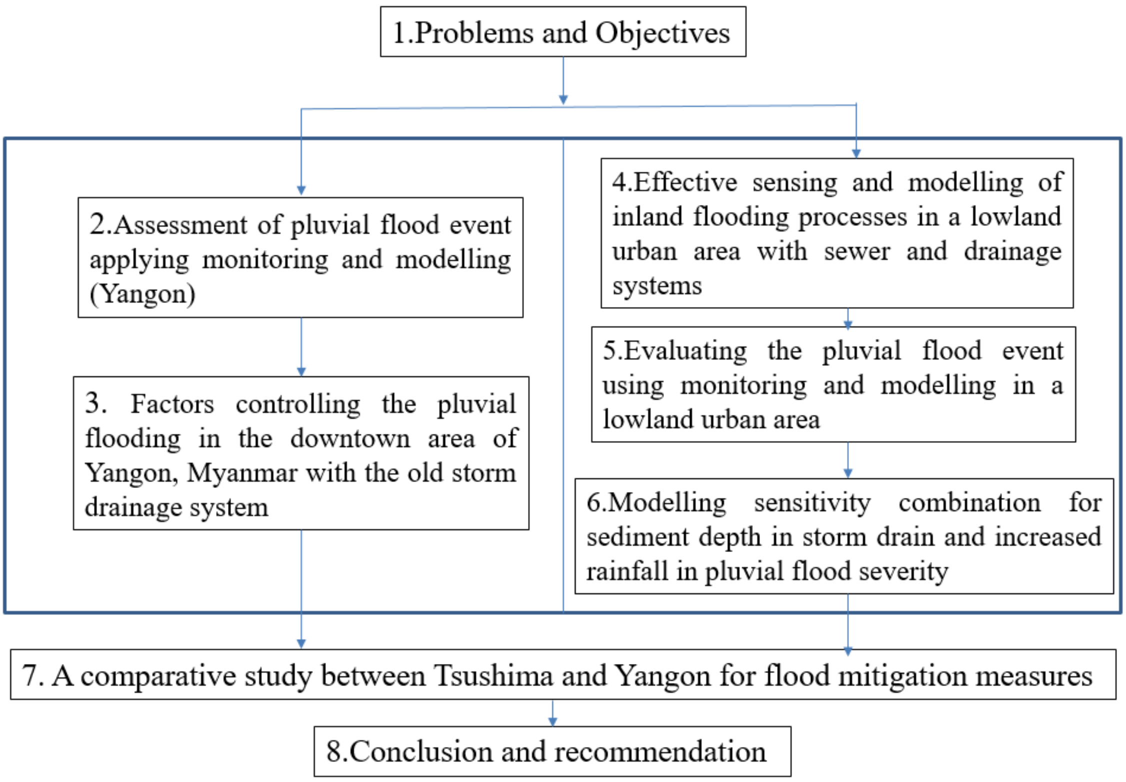

Figure 1.10 Graphical representation of the dissertation framework

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Chapter 2

Assessment of pluvial flood events applying monitoring and modelling

2.1 Introduction

Pluvial flooding is one of the most frequent disasters, causing contaminant and pathogen exposure, significant property damage, traffic congestion problems, and damages to urban critical systems in many cities worldwide (Hammond et al., 2015). Pluvial flooding occurs when the natural or engineered drainage capacity exceeds the design limit due to intense or prolonged rainfall (Dawson et al., 2008; Falconer et al., 2009). Most cities, particularly low-lying areas near the coast and along tidal river banks, witness pluvial flooding not only because of the large amount of storm water received by the inadequate drainage system but also because of the direct or indirect effects of tidal waves on receiving water bodies (Chan et al., 2018; Pervin et al., 2019).

Developing countries are particularly susceptible to urban pluvial flooding because their drainage systems are inadequate, mismanaged, and often congested for a variety of reasons, including the disposal of solid waste into drains and canals (Zurbrugg, 2003). The clogging of waste is seen not only in the drainage channels but also at the inlets and drainage throats. Therefore, when flood severity increases due to this clogging effect, water from the drainage cannot escape through the drain throat, and surface water cannot enter the drain even if the drain has enough capacity to carry the surface water (Despotovic et al., 2005; Guo, 2017; Palla et al., 2018). During extreme flooding, drainage throat blockage and sediment existence in the drain channel are more frequent under low-intensity rainfall. The drainage throats and channels in most open-channel drains are not sanitized and are only periodically cleaned. The deposition of soil, sand, and waste reduces the drainage capacity. This is a recurring problem in the big cities of developing countries because of the lack of an effective waste management system and the unacceptable behavior of residents (Ishigaki, 2018). The sources of sediment and waste in the drainage system are irregular street sweeping, solid waste disposal, and poor coordination between different institutions (Parkinson, 2005). Moreover, leaves and small litter can block the grates; this issue can be resolved by good design considerations as seen in Japanese cities such as Kitakyushu. It has been estimated that half of the grate area is blocked by leaves and small litters, and the other half area can be used for connecting water through this area between the ground and underground drainage system (Kitakyushu, 2017). In addition to waste issues, the urban drainage system in developing countries is deposited with sediments, which reduce the carrying capacity of the drain, resulting in floods of varying magnitude (Kolsky et al., 1996; Nyameche, 2007). Construction materials, such as sand, gravel, and wood, and demolition wastes, have been found in the drainage, further aggravating the blockage problem (Cherqui et al., 2015).

Pluvial flooding in developing countries is rarely studied because of the lack of quantitative flood data, input data scarcity, and uncertainties in flood modeling. Nowadays, high-resolution elevation data can be easily assessed from websites. Researchers have widely used water depth loggers to evaluate the overflow of basins, compare a traditional storm pipe trench with an infiltration trench and to check the performance of tree filter (Toran, 2016; Ertezaei et al., 2018). In addition, detailed rainfall data are important for simulation and can help roughly check the relationship between rainfall and pluvial flood events (Schellart et al., 2011; Bruni et al., 2015; Ochoa-Rodriguez et al., 2015).

A flood inundation model has also been considered effective for planning, designing, and analyzing urban drainage and flood events in cities (Fan et al. 2017; Teng et al., 2017; Bulti et al., 2020; Nkwunonwo et al., 2020). Conventional modeling approaches (1D and 1D–1D) cannot provide accurate results when flood water overtops the curbs in urban areas (Mark et al., 2004). Currently, the 1D–2D coupled model represents a powerful tool to simulate the hydraulic behavior of flooded urban areas due to excess runoff not conveyed by the drainage networks (Chang et al., 2015). The most well-known models are the storm water management model (SWMM), which is an open-source model with complete functions (Rossman, 2015), and commercial packages such as XP-SWMM (XP Solutions, 2013). Other software packages with hydraulic solvers, such as MIKE MOUSE (DHI Software, 2014) and InfoWorks ICM (Innovyze, 2019), are also popular in industrial practices. The InfoWorks ICM model is widely used for many purposes such as risk assessment (Cheng et al., 2017) and pre- and post-analysis of earthquake effects on sewer networks (Biswas, 2017). Most studies identified pluvial flood occurrence due to gully pot blockage and waste blockage by conducting interviews and evaluating complaint data (Ten Veldhuis et al., 2009; Akukwe, 2014; Peter et al., 2015). Sörensen (2017) clarified the mechanism and characteristics of pluvial flood occurrence in Malmo, Sweden, using insurance data. However, insurance data are rarely available to identify the causes of pluvial events in developing countries, where the insurance system is not widely used. The conventional approach to identify pluvial flood events is to apply simulation models to check the impact of climate changes and the drainage capacity (Semadeni-Davies et al., 2008; Salike & Pokharel, 2017; Russo et al., 2020). Identifying pluvial flood occurrence is a complex problem, and this is an essential step in devising flood mitigation measures. Previous studies did not assess pluvial flood occurrence in developing countries using systematic approaches such as monitoring methods with water depth loggers, simulation models, and information from drainage departments.

In this study, we applied a monitoring and modeling method to assess the occurrence of pluvial flood events in Yangon City, Myanmar. We introduce an effective monitoring system and demonstrate the application of the obtained data to evaluate the mechanism of pluvial flood occurrence. Level gauges are inexpensive and can be used in data collection systems for onsite flood monitoring. InfoWorks ICM was also applied to analyze flood events in the study area. The objective of this study was to understand and identify pluvial flood occurrence in the downtown areas of Yangon, where pluvial floods have frequently occurred in the rainy season with high rainfall intensity and even low rainfall intensity. The drainage system of this study area is composed of an old open-channel storm drainage system.

2.2 Study site and data

Yangon (16°48'19.01"N, 96°9'22"E) is the largest industrial and commercial city in Myanmar and is situated along the Yangon river bank and Irrawaddy delta (Figure 2.1). It has an average annual rainfall of 2700 mm during the monsoon period from mid-May to October. The maximum 24 h rainfall observed during the past 35 years was 343 mm or 13.54 inches in 2007. The city is facing pluvial floods more frequently than in previous years because of city expansion in the past 12 years, from 133 sq. miles to 260 sq. miles, causing a reduction in pervious area and natural flood retention storage (Win and Win, 2010). Currently, the central business district (CBD) in Yangon has seen severe flooding in most of the main roads under intensive rainfall events of 50 mm or more (EDRB 2018). The study area is located in the city's CBD of Yangon, and severe floods occur frequently in the monsoon season. The total area is approximately 2.62 km^2, the land is flat, nearly 100% urbanized, and the elevation of the river border is less than 1.0 m. Sluice gates are installed at each outfall to prevent the backwater effects of the Yangon River, and all the gates are controlled manually. The Yangon River water level is directly related to astronomical tide conditions, and the tidal gate is closed for certain hours during high tides, and the closing duration is approximately 4 or 5 h.

In the following section, we describe the data and current problems in Yangon associated with urban pluvial flooding, such as meteorological, hydrological, and other factors related to the drainage system.

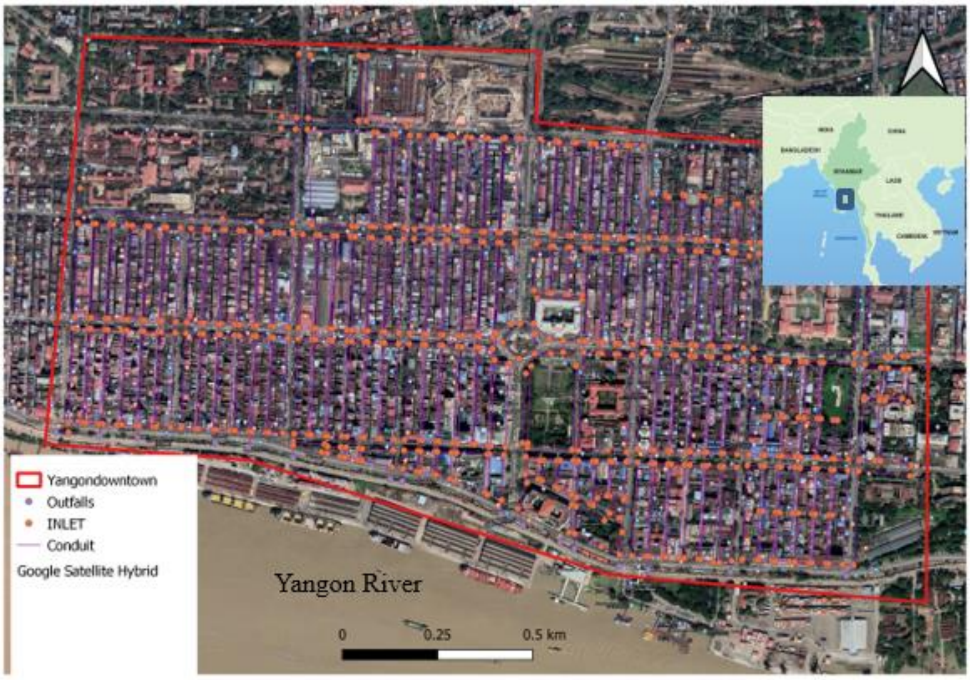

Figure 2.1 Yangon downtown area. The blue square marks where Yangon is situated in Myanmar (small map) (Source: Google map)

2.2.1 Land use pattern in downtown area

The study area is situated in the downtown area of Yangon, where there are many commercial, cultural, and government buildings such as government offices, religious structures, historic buildings, shopping areas, and hospitals. This area is nearly 100% urbanized, and most of the surfaces consist of impervious surfaces such as concrete and asphalt. Therefore, heavy rainfall can lead to runoff because the impervious surface does not allow water to seep in, and water runs over faster, with little absorption.

2.2.2 Topography

The existing land is flat and nearly 100% urbanized with the highest ground elevation of 16.5 m above the mean sea level (MSL) at the northwest border of Latha Township. Fairly rolling terrain exists only in parts of Latha Township. The rest of the CBD area is flat and below the level of 5.0 m, with some areas at the marina border being as low as 1.0 m above the MSL. Prevailing land slopes in the CBD area vary from 1.75% at the higher strips to 0.10% in the areas next to the Yangon River. In summary, in the CBD area, the maximum level is approximately 15 m above the MSL, with the lowest areas being lower than 1 m above the MSL (Figure 2.2).

Figure 2.2 Elevation of Yangon downtown study area

2.2.3 Climate and precipitation

Myanmar has three different seasons because of its location within the tropical monsoon climate region, characterized by the northeast and southwest monsoon wind systems. The annual total rainfall in Yangon is between 2500 and 3000 mm, with annual average rainy days of 129.3. Early monsoon and late monsoon rainfalls have decreased, whereas peak-monsoon rainfall has slightly increased (Khaing, 2012). The month with the most precipitation is July.

2.2.4 Drainage

The drainage system of Yangon is an open-channel type, constructed more than 80 years ago, and some parts have now deteriorated (Figure 2.3). The system has no pump and relies on a gravity drainage system. The recent decade has witnessed a remarkable increase in flooding events due to rapid urban development in the CBD. Periodical inundation worsens when heavy rainfall coincides with the spring tide, since the existing drainage system relies exclusively on gravitational flow. Due to such frequent severe flooding, with up to 0.50 m depth in the most populated and largest business centers of Myanmar, there has been significant economic, social, and environmental despair. As such, the responsible government organization, namely the Drainage and Wastewater Management Authority (DWMA) of the Yangon City Development Committee (YCDC), is preparing a program to mitigate and ultimately provide full protection against flooding events in these priority areas with immediate effect.

Figure 2.3 Structural deterioration of storm drainage in Yangon (Source-DWMA Latha)

2.2.5 Urban drainage problem in Yangon downtown

Figure 2.4 show the type of problems faced by the DWMA every day in maintaining the drainage system in the downtown areas of Yangon. Solid waste dumping in the drainage routes reduces the carrying capacity of the drainage system, resulting in undesirable waterlogging in the event of a heavy rainfall. Waste collection coverage in Yangon is approximately 53% due to limited public awareness of cleanliness, inadequately organized street cleaning as pushcart operators act both as street sweepers and waste collectors, and income from solid waste management services is insufficient to cover the costs of solid waste collection and disposal. In Myanmar, illegal waste disposal into the water bodies remains an unsolved problem. Approximately 40%, 30%, and 15% of the total waste products are disposed into water bodies in the nearby villages, towns, and cities, respectively (Premakumara, 2017; Fuhr, 2020). Consequently, a substantial quantity of waste is illegally dumped, resulting in blocked drainage systems; this adds to the workload on the Pollution Control and Cleansing Department (PCCD) in cleaning the drainage systems (World Bank, 2019). While dredging, workers often find many types of solids, such as solid waste, food waste, sediments, and water bottles, and sometimes construction materials such as sand and gravel. Sediment dredging is vital for reducing flood severity in Yangon downtown areas, and drainage departments conduct sediment dredging before and during the rainy season (Figure 2.5). However, the sediment deposition rate is difficult to predict, and some areas have higher pluvial flood severity due to sediment and waste blockage. In addition, some utilities exist in the drainage that increase garbage clogging and the chance of flood severity (Figure 2.6). In Yangon city, there is significant drain-throat clogging during the rainy season. Therefore, surface water on the roads cannot flow into the open-channel drain through the drain throat because of drain-throat clogging. The drain even accepts inflow discharge (Figure 2.7). The downtown areas of Yangon have also seen illegal construction material and demolition waste disposal due to lack of enforcement in preventing the entry of illegal construction and demolition waste disposal into the drain (Figure 2.8). If the flood situation is severe, local residents call the DWMA office to clean the clogged garbage in the drain throat and drain channels.

Figure 2.4 Waste blocking the drain in Yangon (Source-DWMA Latha office)

Figure 2.5 Sediments in the drain and sediment dredging work

Figure 2.6 Water pipe (Left) and communication cable in the drain (Right)

Figure 2.7 Cleaning at the drain throat clogged during flooding events

Figure 2.8 Sediment blockage due to construction materials in the drain

2.3 Pluvial flood monitoring

In this study, we applied water depth loggers to measure the water-level variations in the drain and river. In addition, we installed a tipping bucket rain gauge to obtain input rainfall data for modeling.

2.3.1 Materials and methods

We deployed water-level loggers (Onset, HOBO U20L-01) at eight locations in the storm drainage system of the study area and at the bank of Yangon River one location (Figure 2.9). The parameters of the channels, such as the height, width, and location of each station, were measured (Table 2.1).

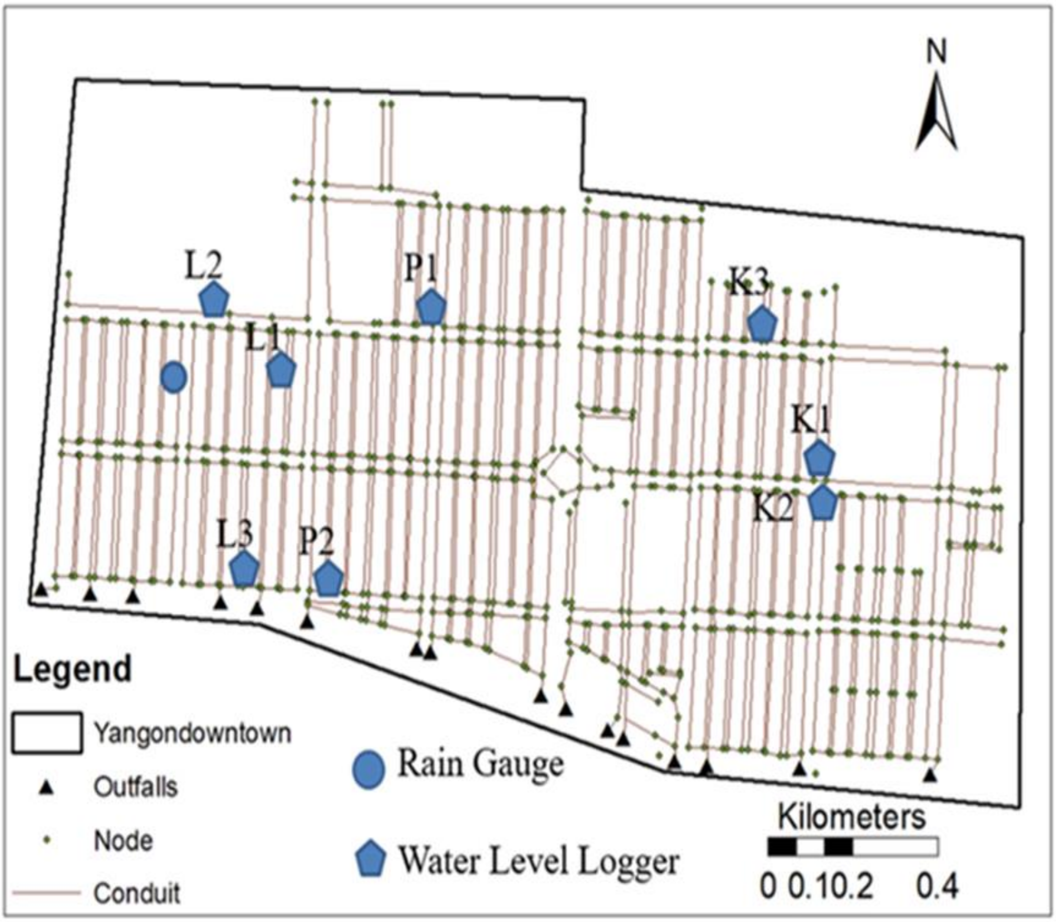

Figure 2.9 Storm drainage system and monitoring device locations in Yangon

Conventional flood monitoring methods, such as resident and chalk gauges, cannot accurately determine the inland flood frequency and duration. Monitoring systems with sensors are more practical than manual measurements because they can obtain continuous water fluctuation, flood duration, and flood frequency more accurately (Tashrio and Min, 2020). Water-depth data were collected from June to December, and the total monitoring period was approximately 200 days during the monsoon season of 2019. We designated a flood event as such when the water overflow was at the rim level of the storm drainage channel in this case study.

Table 2.1 Main characteristics of observed drainage channels and their locations

Township	Logger ID	Width(m)	Height(m)	Location	Coordinate (Latitude, Longitude)
Latha	**L1**	**0.914**	**0.61**	**Latha road, between Anawratha & Bandola road**	**16.775519, 96.150510**
	L2	**0.635**	**0.838**	**Anawratha road, between latha & 19th road**	**16.777267, 96.149943**
	L3	**0.381**	**0.914**	**Corner of 23th and strand road**	**16.772208, 96.152076**
Pabedan	**P1**	**1.578**	**0.863**	**Corner of Anawratha and Shwebonethar road**	**16.774333, 96.155758**
	P2	**0.8382**	**1.5**	**Corner of Shwedagon road and Strand road**	**16.772134, 96.153156**
Kyauktada	**K1**	**2.1336**	**1.626**	**Corner of Bandola and Boaungkyaw road**	**16.774279, 96.164251**
	K2	**1.23**	**1.14**	**Corner of Bandola and Boaungkyaw road**	**16.774081, 96.164262**
	K3	**0.381**	**0.61**	**Bogyoke road, between 35th&36th**	**16.776830, 96.161012**

The loggers have a variety of characteristics, including simple and quick deployment, low cost, reusability, and durability in harsh environments. Installation requires a non-stretch wire for mounting in the channel. These sensors can measure water-level data in an operation range of approximately 0–9 m (up to 30 ft) of fresh water. The atmospheric temperature and pressure were measured using HOBO water depth logger devices. The level loggers recorded the absolute pressure, which was later converted to water-level readings using the provided HOBO software.

This software was used to launch the logger and to export data into Excel (HOBO U20L water-level logger manual)

In addition to the water depth loggers, a one-tipping bucket-type rain gauge with a 0.5 mm resolution (Climatec, Inc., CTFK-1) was connected to a pendant data logger (Onset, HOBO CO-UA-003-64). Rainfall data were also collected from June to December, and the total monitoring period was approximately 200 days during the monsoon season of 2019. During this gauging period, nearly 1920 mm of rain was recorded. The heaviest one-hour rainfall record was 41.5 mm/h on October 10, 2019.

2.3.2 Results and discussions

The logger results show 12 flood events in the 2019 rainy season in Yangon. Some of the events are related to high rainfall intensity, whereas some are not directly related to the rainfall intensity, and some severe floods occurred under low rainfall intensity and high tide conditions.

2.4Pluvial flood analysis with simulation model

2.4.1 ICM model building methodology

The following sections provide an outline of the methodology adopted for constructing an ICM model for Yangon study area including information related to the model input data, approach, and software used. The storm drainage has an open-channel length of 73 km, with 609 nodes and 16 outfalls, as shown in (Figure 2.9). Figure 2.10 shows the 1D–2D ICM computation model.

Figure 2.10 Storm drainage ICM model for Yangon downtown area

2.4.2 Software and approach

a) Computational domain

The model was built and run using InfoWorks ICM version 11 modeling software (Innovyze, 2019). An existing InfoWorks ICM 1D drainage model was available for the study area. It represents the 2D model surface using irregular triangles (of varying size, which make up individual elements within the mesh).

b) Computational condition

According to the logger results, 12 flood events occurred during the rainy season of 2019 in Yangon. First, we checked the rainfall data of the tipping bucket with the logger results. We found no strong correlation between rainfall intensity and flood events recorded by each logger. Therefore, the 12 selected flood events were evaluated using Infoworks ICM models. The input rainfall data of each simulation were based on a tipping bucket rain gauge. Table 2 compares the logger and model results for the 2019 rainy season.

Table 2.2 Flooding simulation results between logger and modeling for validation

		Logger
		Flood
Model	Flood	3 (Close Gate)
	No flood	9 (Open Gate)

2.4.3 Results and discussions

The 1D–2D coupled model represents an innovative technique to analyze the overflowing process and performance of existing drainage networks. There is some unmatched condition between the loggers and simulation results when the flood gate is open. Table 2 shows the flood and no-flood events in the study area. Among them, we chose three flood events (one flood event where the simulation and logger results coincide under the closed flood gate condition, and two other flood events for which the logger and simulation results do not coincide) to analyze this problem. First, we chose the flood event on 2 August, 2019, for the simulation approach. A comparison of the flood situation as obtained from the logger data, an image of the DWMA office, and simulation results showed that the flood events occurred at the same time and place when the flood gates were closed (Figures 2.11 and 2.12). The other flood event was chosen to be evaluated again using logger data, DWMA office image, and simulation results. These events did not match the simulation results and logger data with the DWMA office image when the flood gate was opened on 7 August, 2019. (Figure 2.13) shows a comparison between the simulation and logger results with the flood image. Similarly, the other events that occurred on 14 October, 2019, were under the open flood gate condition (Figure 2.14) shows a comparison between the simulation and logger results with the flood image. According to the reports of the DWMA office, workers cleaned the waste blockage at the drain throat and drain during the flood events on 7 August, 2019, and 14 October, 2019. An analysis of the pluvial flood events shows some uncertainties related to the capacity and condition of the system, such as sediment, tree roots, and blockage of gully pots in the drain (Veldhuis and Clemens, 2009; Djordjevic, 2014). Therefore, the difference seen between the simulation and logger results may have been due to the blockage and sediment impact at the drain throat and drain according to the DWMA report reference, even though the simulation results showed no flood conditions for these days. This finding is valuable information and effective when we identify the difference between the observation data and simulation results. However, the simulation results and logger results coincided under the closed condition of the flood gate when the river water level was rising. This phenomenon showed that the pluvial flood problem in Yangon is related to the fluctuation in the receiving water level. Some flood events occurred because of the low rainfall intensity when comparing rainfall data of our rain gauge and logger results. This is an interesting problem in Yangon, and we identified the possible cause of flood events by checking with the simulation, monitoring data, and information from the local engineering department.

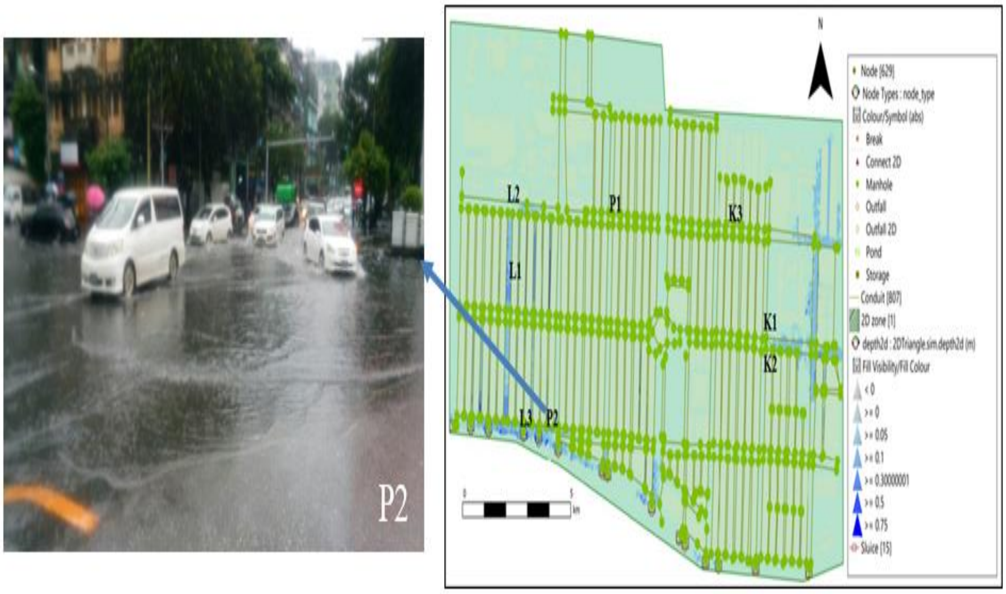

Figure 2.11 Flood condition near Logger ID-P2: A comparison between the inundation map provided by ICM software and image taken during the event on 2 August 2019

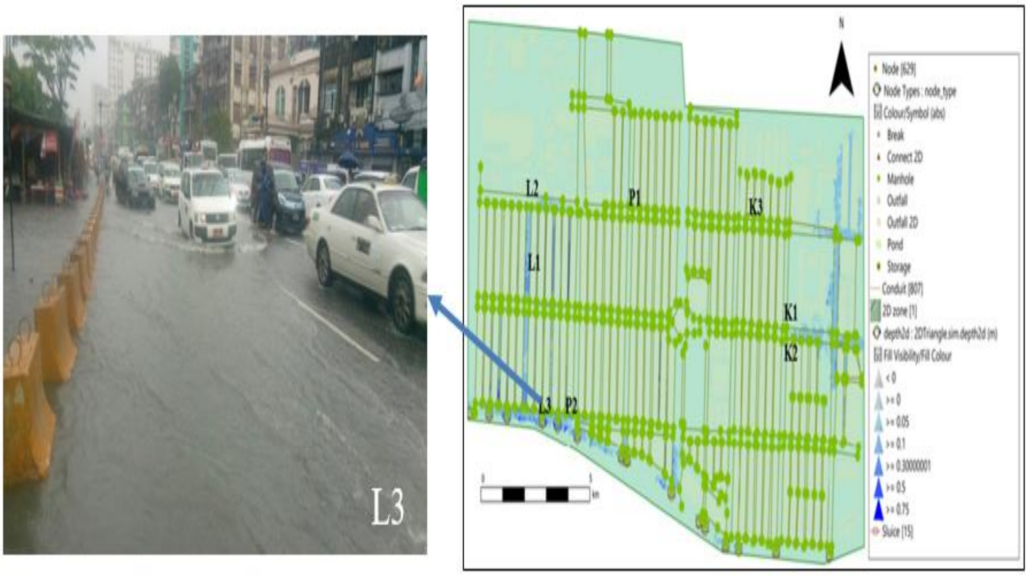

Figure 2.12 Flood condition near Logger ID-L3: A comparison between the inundation map provided by ICM software and an image taken during the event on 2 August 2019

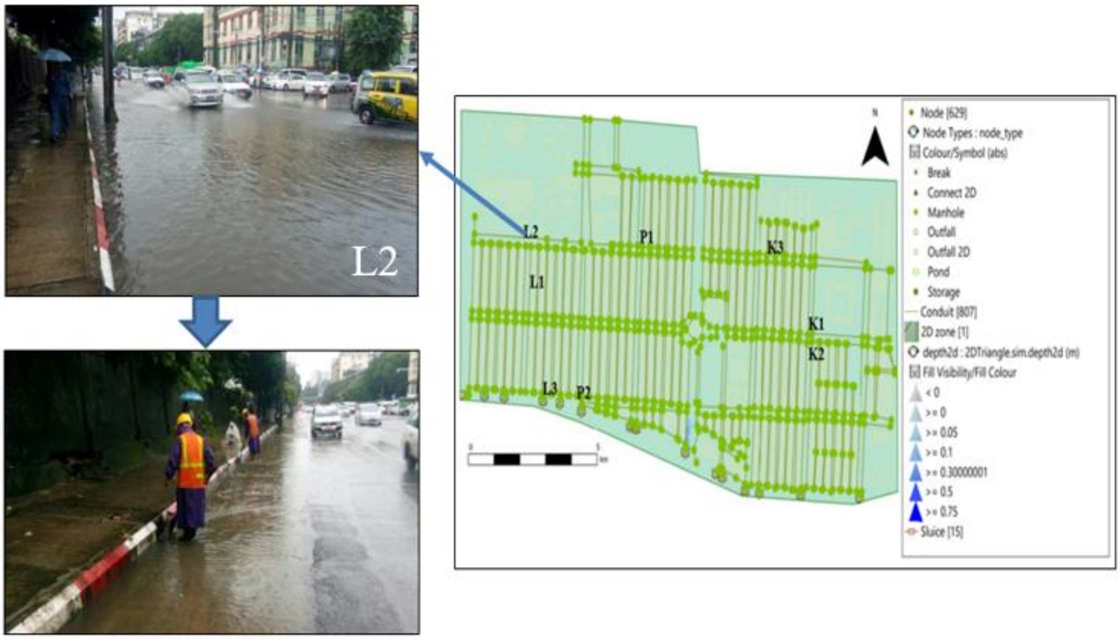

Figure 2.13 Flood condition near Logger ID-L3: A comparison between the inundation map provided by ICM software and an image taken during the event on 7 August 2019

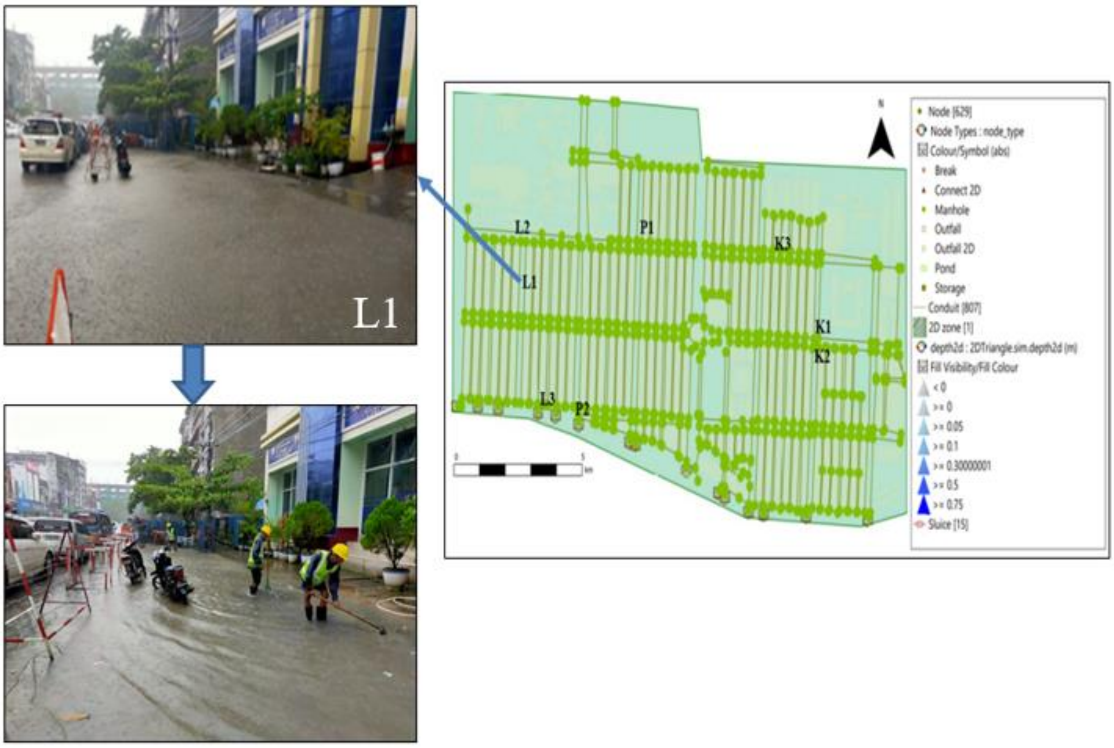

Figure 2.14 Flood condition near Logger ID-L3: A comparison between the inundation map provided by ICM software and an image taken during the event on 14 October 2019

2.5 Conclusions

In this study, we introduced a process for investigating local pluvial flooding events in the downtown area of Yangon using water-depth loggers and a simulation model. The simulation approach cannot clearly identify the occurrence of pluvial flooding in urban cities of developing countries because of the different design and actual capacities of the drainage system. In addition, we identified a gap between the simulation results and logger data for the downtown areas of Yangon using water depth loggers, a simulation model, and a report from the local drainage office DWMA. Based on a comparison of the results and information of drainage department, sediment blockage in the drain and garbage blockage at the drain throat were cause of pluvial flooding. Therefore, we need to evaluate the sediment blockage effects on pluvial flooding in storm water drainage in advance. One of the prominent factors is the water-level variation in the receiving water bodies that affects pluvial flood severity based on a comparison between logger and simulation results given that the results coincided with the flood gate closed situation. We believe preventing solid waste and sediments from entering the drain throat and open-channel drain is important for reducing pluvial flood severity in developing countries. A certain level of education in waste management is necessary in schools, universities, public, and private sectors in Yangon downtown area, and the municipality officers should clearly explain the consequences of illegal waste disposal that can increase flood problems in their environment. In addition, the authorities should construct a flood water detention pond to reduce pluvial flood severity under heavy rain and river water level rising conditions. Well-planned scheduled for dredging sediment and ad-hoc cleaning events is an essential procedure; moreover, some sediment trap installation and a cover for the open channel can help reduce flood severity in the city.

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Chapter 3

Factors controlling the pluvial flooding in the downtown area of Yangon, Myanmar with the old storm drainage system

3.1 Introduction

Urban pluvial flooding is an inevitable problem for many cities around the world. The increasing urban growth rate combined with insufficient drainage systems (Wongsa, 2019) and climate change (Huong, 2013) aggravate the problem. Most large cities in the developing world are belong the humid tropical climates, including Myanmar, where there are large in the numbers of rain days, rainfall volumes and intensities than those of the other developed countries with temperate climates (Silveira, 2001). The characteristics of developing countries facing more frequent urban flood than in developed countries are a scarcer resource for management of drainage systems, such as drainage construction, maintenance, less capable of solid waste and sediment deposition management. The sources of the sediment and waste in the drainage system are irregular street sweeping and solid waste disposal and poor coordination between the different institutions (Parkinson 2005). The primary maintenance requirements for storm drains within developing countries are the removal of sediment and solid waste. Conventional estimation described how effects of sediment depth on the sewer discharge capacity by using experiment, which indicated a considerable increase in the depth (from 2% to 10%) resulted in a 10% to 20% reduction of the full capacity compared to its clean sewer condition (Banasiak, 2008). It also highlights regular maintenance works to remove sediments, and waste are important because sediment deposition in the drainage system will still impact the performance of drainage and urban flood problem in developing countries (Heywood, 1997). Conventional design and analysis neglect the effects of sediment deposition in the drain, because it is assumed that the fine sediment can flow smoothly whereas coarse materials can hardly enter in the drain owing to well-designed inlets gully traps (Ashley,2004). However, in the developing countries, there have been a few studies for sediment management in the drain, most notably from India and Malaysia (Kolsky, 2000; Bong 2014), where the particle sizes of sediments are much larger than those reported in developed countries. Hence, the sediment in urban drainage of developing countries comes from different sources such as the building construction materials and road material, which can quickly enter the storm drain.

The pluvial flood occurs in the downtown area of Yangon at least 6 to 10 times per year; the water level reaches up to a depth of 0.5 meters and lasting from 3 to 5 hours. Traffic congestions due to flood are significant economic consequences in this area, and roads are damaged due to periodic submergence over time flood water. Flood water is polluted by domestic sewage pipe leakage and increases the incidence of water-borne diseases. These floods occur when heavy monsoon rainfall coincides with high tide. Especially, extreme rain events, combined with insufficient drainage capacity, can cause temporary local inundation with suffering economic damages. In recent Yangon, blockages have been caused by solid waste illegally dumped, and sedimentation in the storm drain channel is a significant problem. Consequently, flooding can also occur even in the low tide condition and small rainfall intensity at some specific locations. Hence, the sensitivity of drainage performance due to the sediment deposition is concerned and it is needed to identify how the effects on the severity of flood situations.

Modeling is a powerful tool to analyze the drainage system's response with different conditions such as the current situations, and the future scenarios with different climates or land uses. There are many modeling packages available free or commercial software such as EPA SWMM, XPSWMM, InfoWorks, which enable to check the performance of drainage system and to support its designing (Butler,2018). The purpose of this study is to evaluate the effects of rainfall intensity and drain channel sediment on the flood situations and the drainage responses in urban Yangon, by using the numerical analyses with InfoWorks Integrated Catchment Modelling (ICM). These series of simulations are effective and efficient for preparing some mitigation measures in the study area and can support decision making for the YCDC.

3.2. Materials and methods

3.2.1 Study area

Yangon lies along the Yangon River between around 17°06' and 16°35' N latitude and between 95°58' and 96°24' E longitude, east of the Ayeyarwaddy River delta. Yangon city, the largest economic center of Myanmar, has about 5.14 million populations. The city has expanded rapidly from 133 sq. miles to 260 sq. miles within 12 years causing reduction of pervious area and natural flood retention storage. It has an average annual rainfall of 107 inches (2,711 mm) during the monsoon period of May through October (Win and Win, 2010). The study area is organized by three townships Latha, Pabedan, and Kyauktada, located in the city's central business district of Yangon (Figure 3.1). The total area is about 2.66 km^2, the land is flat, nearly 100% urbanized, and the elevation next to the Yangon river is less than 1.0 meter. The population of this area is about 105,000, and there are many historical buildings, hospitals, big markets, religious buildings, universities, and schools.

Figure 3.1 Location of study area and sediment dredging from storm drain in Yangon (map source: Open Street Map)

The present storm drainage system of the city was constructed at the beginning of the 20th century. This drainage system is one of the oldest infrastructures in Yangon, and some parts are deteriorated. The data of storm drainage system include connections, dimensions and locations of the rectangular channels with surficial elevation and land use distribution which are provided in the shape file format for GIS software by the Drainage and Wastewater Management Authority (DWMA) of the Yangon City Development Committee (YCDC). The storm drainage network consists of about 73 km of channel length and 15 downstream outfalls. The drain system works with gravity flow, with no pumping stations to speed up the drainage. Yangon river water level is normally depending on astronomical tide conditions, and the tidal gates at the downstream ends of drainage network are closed for certain hours during the high tides to prevent the backwater effects. The DWMA of YCDC is responsible for urban flood management in the Yangon downtown area (YCDC, 2018). They dredge the sediment and waste before and during the rainy season. They also work sedimentation dredging work according to the complaints of local residents. Sediment deposition rate is difficult to estimate and the main cause of sedimentation is confused due to improper sweeping on the road and other factors. The sediment depth of the drain sometimes reaches up to half of the drain height (Figure 3.2). One rain gauge was installed by YCDC in the study area for recording hourly rainfall data, and this data are applied roughly to check the relationship between the maximum hourly rainfall and the flood occurrence in the 2019 rainy season. According to the flood report of YCDC in 2019, the authority and its engineers keen to know why small rainfall intensity causes severe urban flood problems in this study area. That's why, first, we check the present drainage capacity with different design storm, and then examine the sensitivity of sediment depth in the drainage system.

Figure 3.2 Sediment in the drain (source-DWMA Latha)

3.2.2 Design of rain events

Design storms, along with intensity–duration–frequency (IDF) curves, are utterly useful tools internationally and widely applied in urban drainage system (UDS) projects and studies. They are used to evaluate the effects of intense rainfall events over a given urban basin or, most generally, as a tool for urban drainage infrastructure design (Wang et al., 2018). The alternating block method is a method to create the temporal rainfall distribution (design hyetograph) using based on the rainfall IDF curve (Balbastre, 2019). Time of concentration is beneficial to evaluate the duration of the storm, and it is the fundamental requirement in the determination of the time step for modeling a catchment for various rainfall intensities. For natural and landscaped catchments and mixed flow paths, the time of concentration (Tc) can be found by the use of Bransby-William's Equation (Abustan, 2008).

$$T_c[\text{min}] = \frac{F_c L}{A^{1/10} \quad S^{1/5}} \qquad (1)$$

where F_c is the conversion factor (58.5), A is the catchment area [km^2], L is the stream length [m], and S is the slope of stream flow path [m/km].

3.2.3 Computational model and setup

InfoWorks ICM has been one of the most powerful tools from Innovyze, which are applied for fluvial and pluvial flood simulation works reflecting practical situations such as sedimentation in the drainage system and controlled weirs and pumps (Wallingford, 2019).

The study area needs to be divided into sub-catchments for hydrological modeling. Thiessen polygon method was applied for totally creating 599 sub-catchments. The 2D meshes were created on the ground surface area using the Shew-chuk meshing algorithm (Wallingford, 2019), which covered the whole computational domain with 10801 triangles. The ground level for a mesh element was calculated by sampling the ground model within the 2D triangles in the element, and then taking the average of these sampled point levels. In this model, the fixed percentage runoff volume model and the Wallingford standard routing model were applied (Wallingford, 2019).

The coupled model simulates the water exchange between surface and subsurface according to this phenomenon. Some researchers applied ICM to evaluate existing the drainage system, and show the benefits of the drainage transformation and sustainable urban drainage system. They used the calibrated model to assess the outlet drainage and pipe loads for storm scenario existing or possibly occurring in the future scenarios (Peng, 2015). Some parameters such as infiltration rate, roughness coefficient and drain channel distributions are applied for calibration and verification purposes. In the developing countries, only these parameters described above are not enough for calibration and verification purpose, because sediment and waste blockage are serious problems. Besides, applying model simulation without considering the effects of sedimentation can cause over-estimating of drainage system performance and under-estimating of urban flood risk. Our study highlights the effect of sediment deposition on pluvial flooding using Infowork ICM. It could consider the thickness for permanent and consolidated sediment deposits. Besides, these options can apply up to the 80% sediment of drainage channel’s cross sectional area, but this model assumes the sediment as a fixed bed which obstructs the flow by reducing hydraulic radius used in the Colebrook-White equation (Wallingford, 2019). Therefore, we use this setting to evaluate the effects of drain channel sediment on pluvial flood situations, by assuming that the hydraulic properties of urban drainage channels with uniform sediment depth. There are three scenarios about sediment deposition in the drainage system: no depth, 20% and 50% depth. These scenarios are unrealistic in developed countries' situations for combined, separated sewer or urban drainage systems. However, the sediment depositions in developing countries are possible to reach a high percentage of conduit capacity. In India, the sediment depth reached as high as 85% of drainage height in 1994 (Kolsky,1996). The authors also found that the sediment depth reached up to 70% in the height of drainage system partially in the study area, during 2019 December that is the end of the rainy season.

In order to discuss the sensitivities to flood severities, we adopt not only the distribution of inundation depth (m) in “depth 2d” but also channel and node conditions as follows: “surcharge state” shows the hydraulic state that the drain channel is not filled with water (< 1), filled with the water under open-channel flow (1) or pipe flow (2) conditions, whereas “flooding node” means the overflowed node describing with its flood discharge (m^3/s).

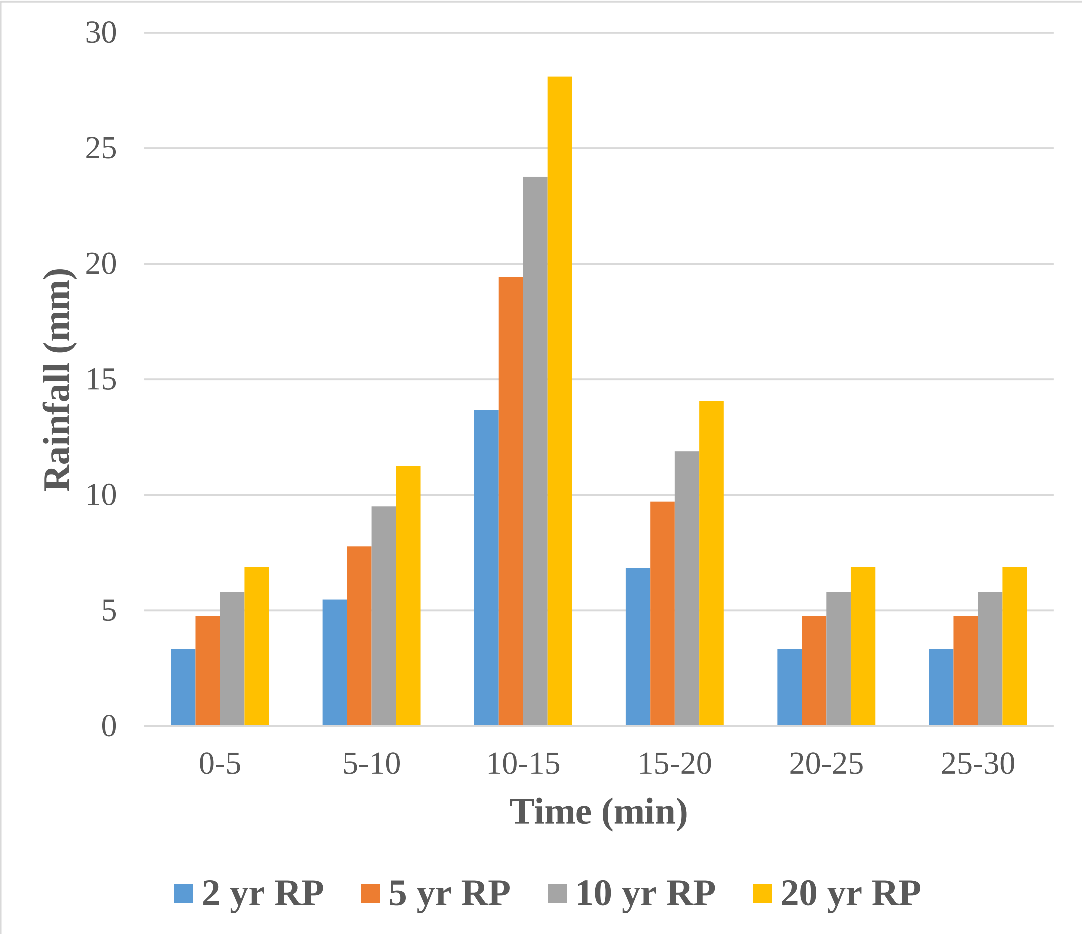

Figure 3.3 Hyetographs during the design events for 30 minute durations with 2,5,10 and 20 year of return periods

3.3. Results and discussions

Considering the concentration time of study area (Eq. (1)), 30 minute durations were chosen to draw design hyetographs by using the alternative block method. Figure 3.3 shows the hyetograph variations treated with different return periods 2, 5, 10, and 20 years, which was made to evaluate the capacity of the urban drainage system and the flood situations in the study area.

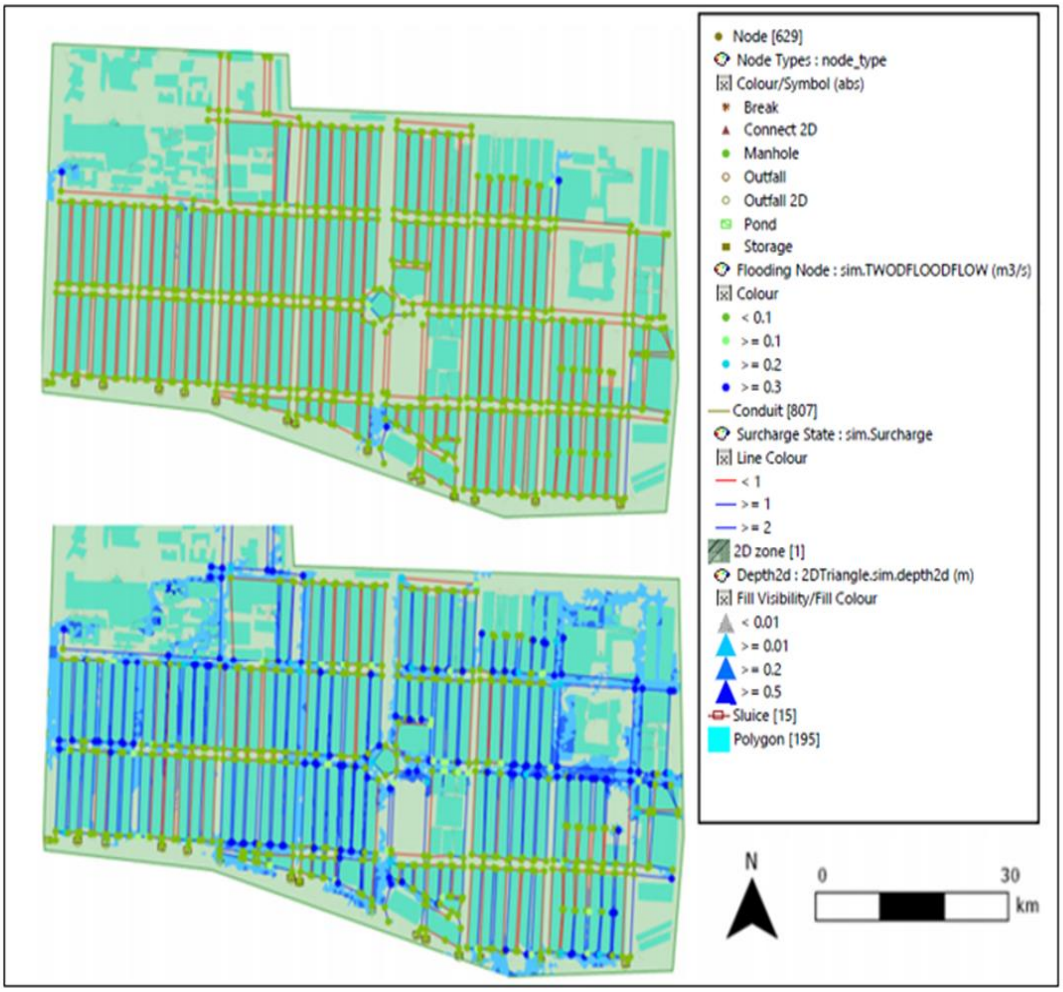

Figure 3.4 Inundation maps for the severest time under 2 year return period without sediment depth condition (upper) and 20year return period with 50% sediment depth condition in the drains (lower)

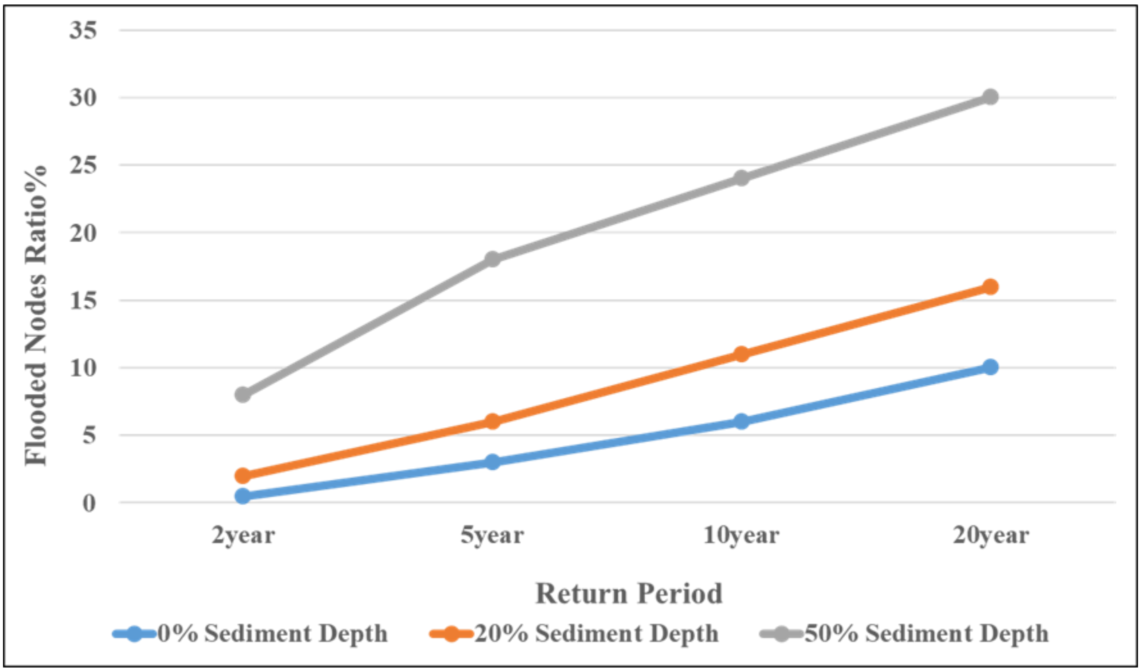

Figure 3.5 Percentage of flooding nodes related to different return period rainfalls and channel sediment depth

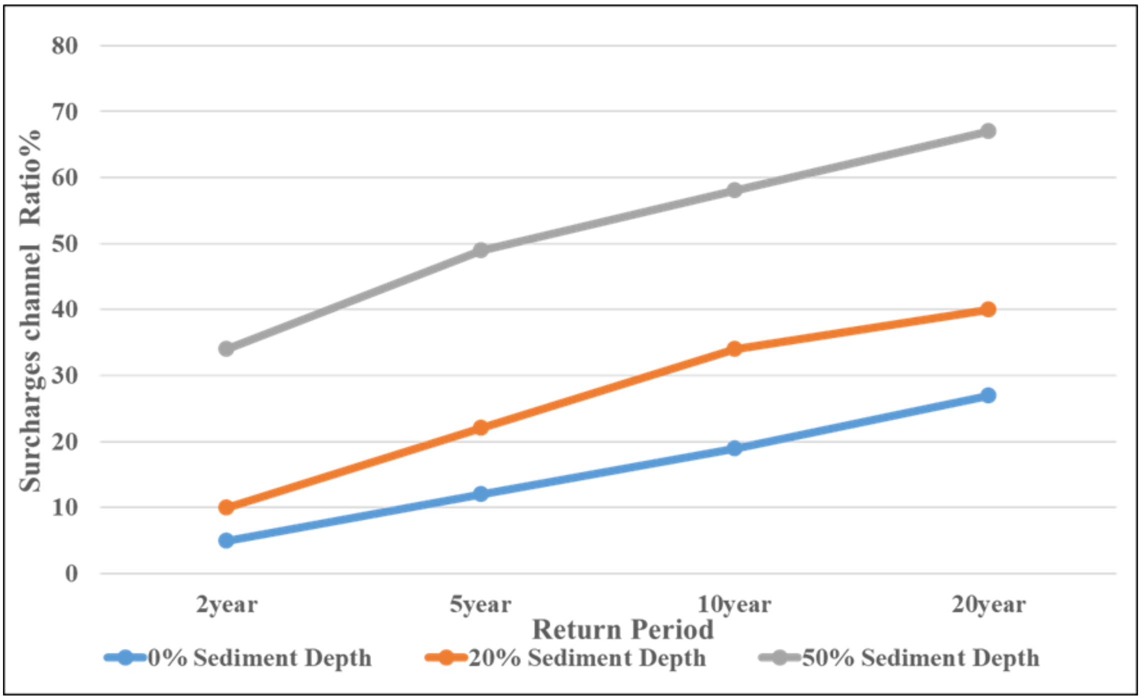

Figure 3.6 Percentages of surcharge state related to different return period rainfalls and channel sediment depth

3.3.1 Analyses of channel surcharges and flooded nodes

By comparing the different simulation results, we can identify the increased severity due to increase the year of design storm return period and the sediment deposition in the urban drainage channel. Surcharging of the drain channel causes overflowing from the node. Figure 3.4 shows the flood map of the 2 and 20 year return period rainfalls without sediment deposition and with 50% sediment deposition in the channels. It was clarified that there were big differences in flood situations between the base scenario under the 2 year return period rainfall without sediment deposition and the most serious scenario under the 20 year return period rainfall with 50% sediment deposition. The upper figure indicates that the present drainage system is unable to meet the possible design standard for the 2year flood, and the lower figures shows the severity of 20 year return period with 50% sediment deposition.

Flooded nodes ratio under the 2year rainfall with 50% sediment deposition is nearly the same of the 20year rainfall with no sediment condition. It shows that if the drainage system keeps clean conditions, the capacity of drainage system can mostly accept the 20year rainfall without sediment deposition (Figure 3.5). Similarly, surcharges channel ratio under the 2year rainfall with 50% sediment deposition is nearly the same of the 20year rainfall with 0% sediment conditions (Figure 3.6). It shows that the severity of surcharge channels could directly related to the sediment deposition in the drainage channels.

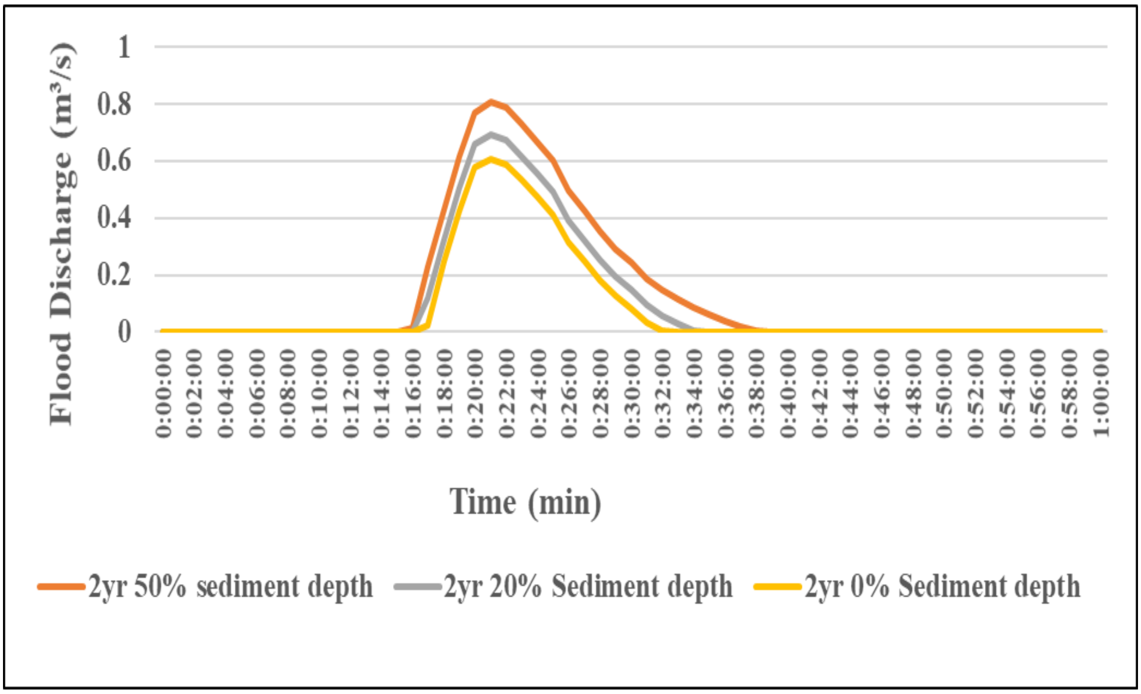

Figure 3.7 Flood discharge variations at the L2ai node under 2 year return period with varied channel sediment depth

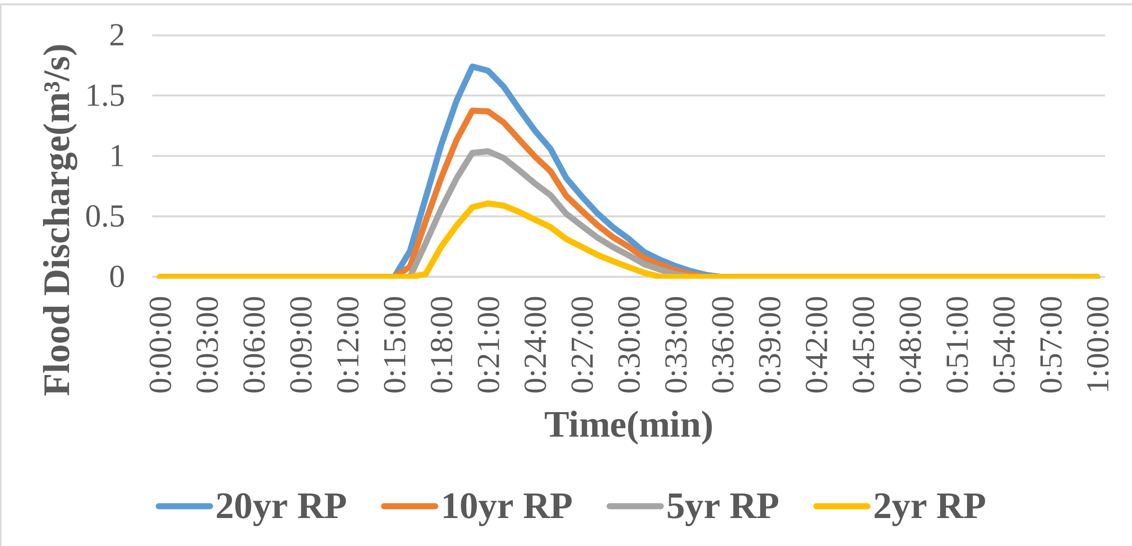

Figure 3.8 Flood discharge variation at the L2ai node under the varied return period rainfalls with no sediment conditions

3.3.2 The effects of sediment depth on pluvial flooding

Figure 3.7 shows flooding discharge variations under the 2year rainfall with the varied sediment depth at the node L2ai which is the most vulnerable flood node in the drainage system. The maximum variation in flood discharges between the drain channels with 0 and 50 percent sediment depth reaches about 0.2 m^3/s. In this case, the clean channel causes the flood for 15 minutes, whereas the channel with 50 percent sediment depth causes that for 22 minutes. When a node is filled with flood water, overflowing water enters to the nearest node which can receive the water for draining, before moving to the surrounding area. Because the deposited sediments in drain channels reduce not only carrying capacities of the channels but also the receiving capacities of their connected nodes, they make the overflowing water difficult to be drained and can increase the flood duration. That's why, it suggests that sediment deposition in drain channel especially aggravates the flood duration.

3.3.3 The effects of different return period on pluvial flooding

Figure 3.8 shows the flood discharge variations at the L2ai node under the varied return period rainfalls with clear channel conditions. The maximum variation in flood discharges between the rainfall conditions of 2 year return period and 20 year return period reaches about 1.0 m^3/s. In this case, the 2year rainfall causes the flood for only 15 minutes, whereas the 20year rainfall causes that for 19 minutes. The difference in these flood durations is only 4 minutes. Consequently, it could suggest that the rainfall intensity mainly effects on the peak discharge of flood under the clean channel conditions.

3.3.4. The effects of sediment and garbage blockage

We evaluated the pluvial flood events 2019 rainy season in Yangon with real rain fall data for simulation process and monitoring. When we identifying these floods, some flood events that occurred during flood gate closed conditions are coincide with logger data, but some flood events that occurred during flood gate opened conditions are not coincided with logger data. InfoWorks ICM can provide accurate results based on terrain, drainage and rainfall input data. However, when the simulation results of ICM showed non-flood condition, logger showed flood condition at the same time. One of the possible causes of pluvial flood events will be sediment existence in the drain channels according to the simulation results with different sediment sensitivities analysis of this chapter. When we check the flood severity with same return period and different sediment depth in the drain, the results show the severity of low rainfall intensity with sediment in the drain can be serious like high rainfall intensity clean condition. One of the uncertainties when checking the logger results is water level inaccuracies at the logger station. This inaccuracy will be usually associated with unstable water surface (ripples and or waves) due to the blockage or clogging in the drain and drain throat (Mark, 2014) even the logger itself is well calibrated. So, we need to consider not only uncertainties of model results but also water level measurement inaccuracies when we identify the pluvial flood causes and severity.

3.4. CONCLUSION

Based on the existing drainage system in the study area, we applied the InfoWorks ICM for modeling the drainage systems which have varied sediment depositions in their drain channels, and for evaluating their functions and limitations under the design rainfalls with varied return periods. As a result, we roughly checked the flood sensitivities related to the effects of channel sediment depositions in the urban drainage system and rainfall intensities in the design storms. The model simulation results reflected the drain channel sediment depositions made more severe for the pluvial urban floods due to the increases of flood discharges and durations. Therefore, these findings suggested the importance of maintenance works such as preventing solids and wastes that potentially clog the drainage system, in order to reduce the number of overload channels and flood nodes and shorten the duration of surface waterlogging. Besides, sediment depth in the drain can cause inaccuracies of water level measurements and it will be a big problem for calibration and verification procedure in modelling approach. Furthermore, by applying the procedures for monitoring continuous rainfalls and channel water depths, it could be identified these relationships and might be solved their problems, which will the drainage managers help to make flood mitigation measures in this study area.

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Chapter 4

EFFECTIVE SENSING AND MODELLING OF INLAND FLOODING PROCESSES IN A LOWLAND URBAN AREA WITH SEWER AND DRAINAGE SYSTEMS

4.1 Introduction

Inland flooding is one of the most frequent disasters in urban area with tropical or monsoon climates, and it can cause significant damage in developing countries because of insufficient infrastructures preventing inundation (Kundzewicz and Takeuchi, 1999; Balk et al., 2013). There are a few conventional studies that visualize and observe the inland flooding processes. It is necessary to monitor these practical scenarios to collect data related to inland flooding, and reliable computational methods needs to be employed to analyze the causes and effects of the storm water drainage system in urban areas during heavy rainfall events in order to mitigate inundations to minimize damage. This study proposes an effective data collection system and its application to a conventional open source model for identifying inland flooding processes.

Few studies focus on inland flooding processes, based on quantitative records. Although inland flooding frequently leads to large economical costs in urban areas, such as caused by the Tokai Flood (Sato, 2006), these phenomena or processes have not been sufficiently described. Currently, high-resolution elevation data can be easily collected via remote sensing using satellite images, and water depth collection can be obtained using pressure sensors, on a global scale. Thus, one of the objectives in the present study is to propose a cost effective and reliable sensing system for inland flooding by employing conventional data and devices. This may help develop and spread onsite monitoring systems using recently developed communication techniques such as Internet of Things (IOT) (Hiroi and Kawaguchi, 2016).

Modelling inland flooding processes is a popular research topic not only in the hydraulic or hydrology fields, but also in other fields such as electrical engineering and informatics. There are various approaches based on their different specialization. Although some new methods such as Artificial Intelligence (AI) and machine learning techniques have been recently applied (Wada and Kojirim 2010), some hydraulic researchers have managed to develop a real-time predicting system for urban inland flooding (Sekine, 2018). However, in order to analyze urban inland floods on a global scale, most studies recommend the use of commercial software such as InfoWorks, MOUSE, XP-SWMM and so on; however, these soft wares have not been sufficiently applied due to their high expense, especially to developing countries that suffer from severe inland flooding (Balk. 2013).

Thus, owing to these issues and concerns, the current employ the New Integrated Lowland Inundation Model (NILIM 2.0), which is a conventional free and open source model (National Institute for Land and Infrastructure Management, Japan, (Nakamura, 2004) for inland flooding simulations. Conventionally, only a few researchers have applied the NILIM 2.0 model (Sunaguchi and Tsuchiya, 2008) and (Tashiro and Min, 2017), and thus, the software developers have not updated their content for recent years. Hence, we also attempt to discuss the advantages and disadvantages of the application of NILIM 2.0 by verifying its performance using originally collected data in order to develop an effective modeling of inland flooding. Furthermore, to better understand inland flooding and discuss the effective sensing and modeling, we introduce a case study conducted in the downtown area of the Tsushima City, located in the Noubi plain, which is the western lowland area of Aichi prefecture. The study area features a storm drain function composed of a small combined sewer system and drainage channel networks.

4.2. Sensing Inland Flooding

In this study, we present the estimating procedures of local inland flooding processes in the downtown area of Tsushima City using water depth loggers and a digital elevation model, which may not require the latest technology and significant expenses.

4.2.1 Materials and methods

Tsushima City (35º 10' 37’ N and 136º 44' 29’ E) has a total area of 25.09 km². In 2012 the total population was 65,118, i.e. a population density of 2,596 inhabitants per 1 km² (Tsushima city guide.2013). Topographically, this is a low-lying area at an elevation of 3.6 m below to 8.2 m above mean sea level. Owing to its location in the east Asian monsoon region, the city experiences a rainy season in June; annual precipitation is approximately 1,500 mm.

The typical forms of land cover have under-gone rapid change; e.g. urbanized land increased from 30% in 1976 to 51% of total area in 2009, whereas the extent of crop fields decreased from 65% in 1976 to 42% in 2009 (Min, 2015). Most inundation is in the form of inland flooding; river flooding has hardly been observed in this area since the Isewan Typhoon of 1959.

Table 4.1 Main characteristics of observed drainage channels

	Width (m)	Height (m)	Bed elevation (m)	Remarks
St. 1-1	2.00	1.25	-2.15	open straight type
St. 1-2	2.00	1.18	-2.08	-1: upper, -2: middle, -
St. 1-3	2.00	0.99	-2.09	3: lower part
St. 2	2.15	1.14	-2.44	open straight type
St. 3	1.20	0.65	-2.35	junction of open / closed channels
St. 4	5.00	1.28	-2.68	effluent stream

We conducted a survey with four survey stations, including a total of six observation points that are set up at the two main stem drain channels (A: Sts. 1 & 2 and B: Sts. 3 & 4 in totally six main stems), which flows into the same effluent stream. The specification of channels such as heights and widths of each of the stations were measured (Table 4.1). Self-recording depth loggers (HOBO U20L-01, Onset Computer Corporation) were simultaneously installed at these observation points in storm water drainage channels. The time series data of water level elevations were obtained by adding the measured water depth to the altitude value around each of the stations in the GSI map based on the digital elevation model acquired by airborne laser surveying with a 0.3 m resolution level (Geospatial Information Authority of Japan, https://maps.gsi.go.jp/).

The survey period is about 450 days October 2017 to January 2019; however, the water level is not measured in some non-flooded seasons. The overflow of water channels at the survey sites are recorded using loggers, and these results are used to describe the inundation area from the altitude distribution of the area surrounded by these sites. The hourly rainfall data were available at the nearest local rain gauge station “Aisai” about 6 km away from our study site, in the website of Japan Meteorological Agency (http://www.jma.go.jp/jma/index.html) during the survey period, and the rainfall intensity in ten minutes were also collected in Tsushima City by River Division of Aichi Prefecture.

4.2.2 Results and discussions

Figure 4.1 shows the water level fluctuations at each station along with the rainfall distribution. The heaviest rainfall was recorded as 32 mm/hr (23:00 on October 23) when Typhoon No. 21 (LAN) was approaching in October 2017 (Figure 4.2), and the second heaviest one was 30.5 mm / hr (21:00 on July 7) at the time of the heavy rain event in July 2018, which caused water level promotions at the observation stations. By comparing each of these water levels and channel specifications such as heights and bed elevations (Table 4.1), the overflow from the drainage channels could be monitored if the water levels exceeded the height of the channel wall as follows: -0.9 m, -0.9 m, -1.1 m, -1.3 m, -1.7 m, and -1.4 m in Sts. 1-1, 1-2, 1-3, 2, 3, and 4, respectively. According to this survey, overflow was observed in Sts. 1 and 2 for a total of 8 and 10 hours respectively, for both these events. However, the overflow occurrence was observed 11 events for a total of 34 hours at St. 3 where drainages merge from three directions, and those were observed 3 events for a total of a 12 hours period at St. 4 where drainages poured.

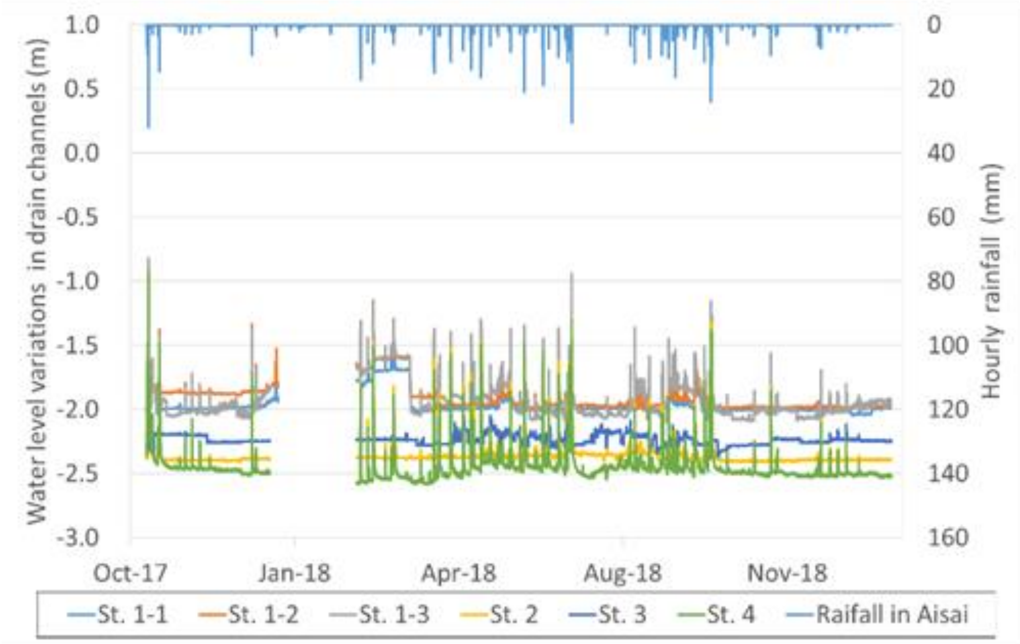

Figure 4.1 Water level variations in the drainage channels and rainfall distributions in the target area during the survey period (rainfall data source: Japan Meteorological Agency)

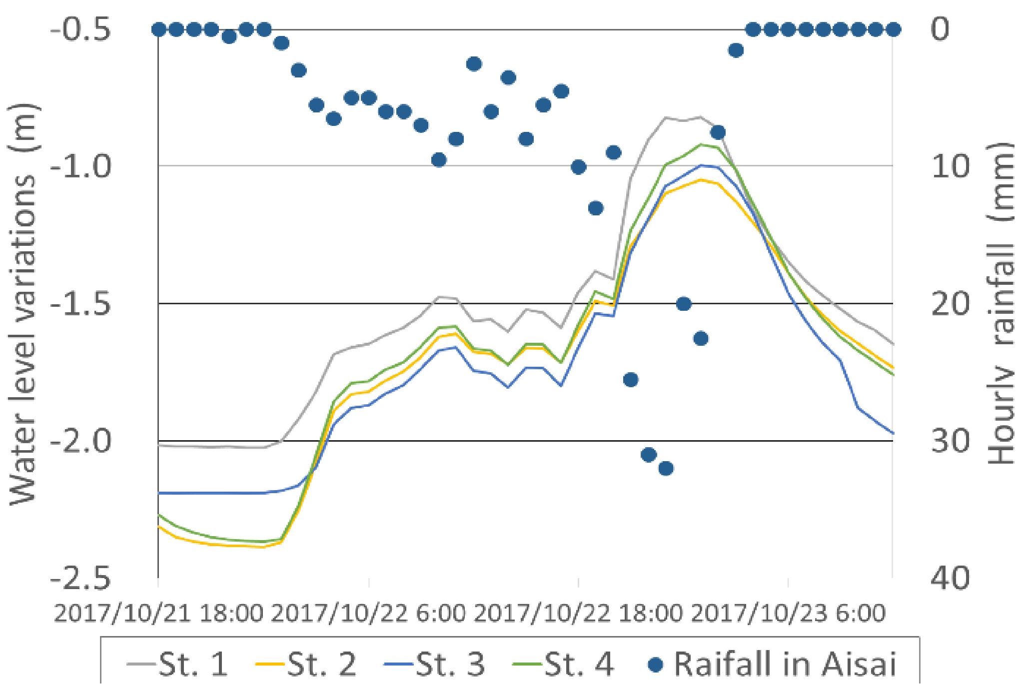

Figure 4.2 Water level variations in the drainage channels and rainfall distributions in the target area at the time of the Typhoon No.21 (LAN) approaching on October 2017 (Rainfall data source: River Division of Aichi Prefecture)

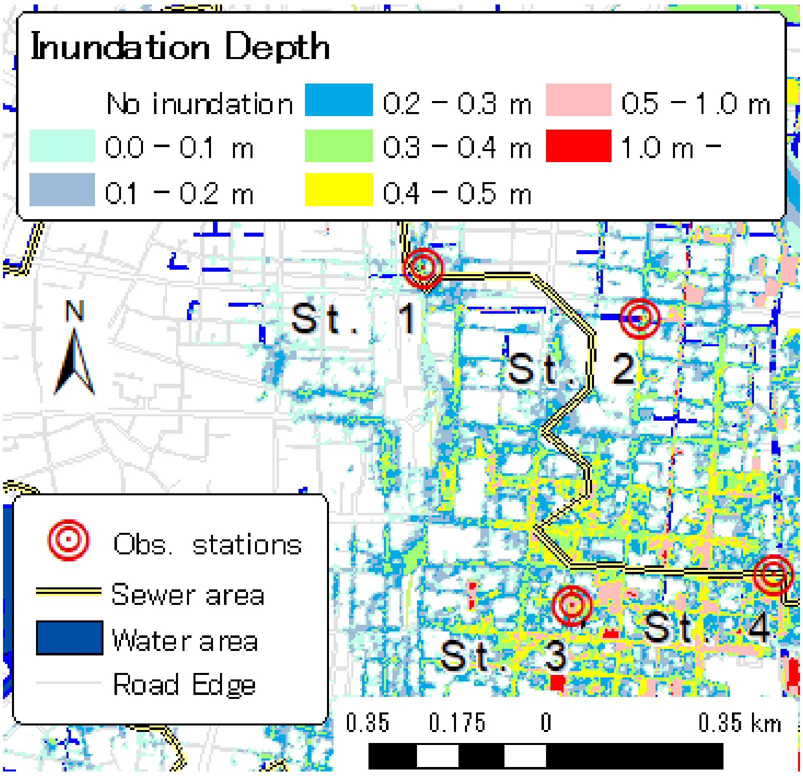

Figure 4.3 Severest inundation map on networks of roads (gray lines), drainage channels (blue lines) with observation stations (Sts. 1-4) in Tsushima city downtown area, drawn by ESRI Arc GIS 10.2 with collected water level variations and digital terrain model during the Typhoon LAN approaching, October 2017

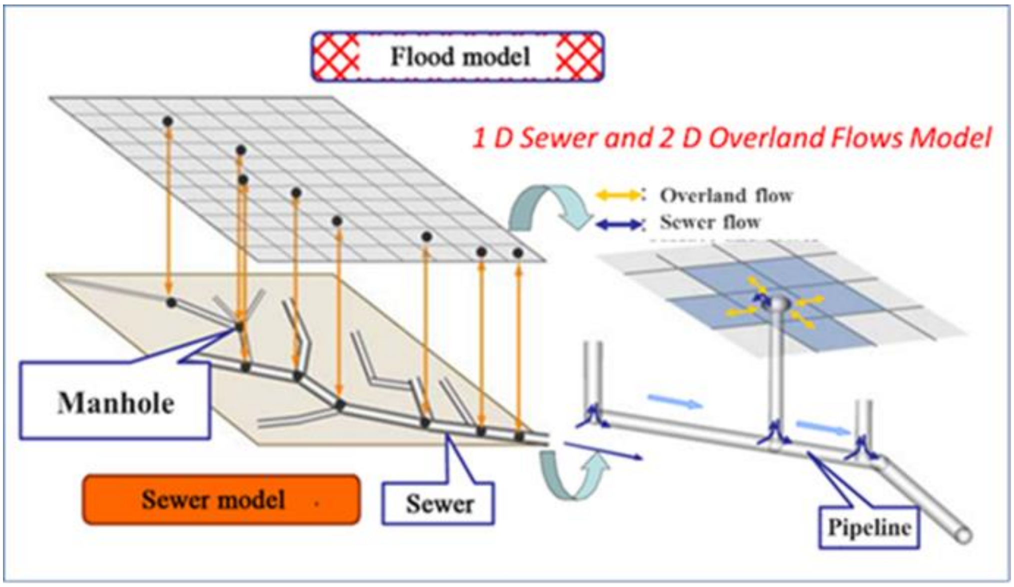

Figure 4.4 Structure of the adopted NILIM model with one dimensional sewers and two dimensional overland flows

Figure 4.3 shows the inundation area at the peak of flooding when the water levels reach -0.9 m in altitude, estimated with the water level at each of the points at the time when the 2017 Typhoon No.21 was approaching (Figure 4.2) and the terrain altitude distribution of the surrounding area. It was clarified that the inundation expanded along drainage channels and roads at relatively lower area in eastern areas (Figure 4.3). Because Typhon No 21 caused inland flooding in this area at midnight 21:00 to 5:00, it could not seriously damage public/private properties. These figures and processes might be important, be-cause thus far, the inland drainage process during heavy rainfall in urban areas has hardly been analyzed empirically.

4.3 Modelling of inland flooding

To cover the entire process of inland flooding with free and open source conditions, we selected the NILIM 2.0 model (Nakamura, 2004). In Tsushima City, the combined type of sewer system has been used in the downtown area since 1964 (Tushima city guide.2013). This system comprises sewer pipes, manholes, regulators and pumping stations, and the drainage channel networks help drain storm water. The data on the position of each component, including the slope, shape, and diameter of pipes, were obtained from Tsushima City authorities.

Drainage infrastructure of the sewer system encompasses 796 manholes, 28 km of sewer pipes, and 3,159 flow regulators.

4.3.1 Simulation model

The NILIM 2.0 (Nakamura.2004) model was used in this study. This is an integrated flood model that combines three separate modules: a one-dimensional un-steady river flow model, a sewerage network model, and an urban floodplain overland flow mesh model. An overview of the NILIM model is shown in Figure 4.4. The model can analyze complex hydraulic interactions between the surcharging flow from sewer pipes and the flow of overland surface flooding by considering the detailed conditions of surface topography and the features of the underground sewer network. In the sewer system, two flow conditions are considered: open channel state and pressure state. The open channel state is considered when the water level is lower than the pipe crown and the pressure state is considered when the water level is higher than the pipe crown. The selection of basic equations for the simulations depends on this situation. For floodplain surface conditions, a variety of structures and drainage facilities can be specified on the mesh and regarded as the roughness or boundaries of the surface water calculation.

4.3.2 Setup for the computation environment

a) Computational domain

The computational domain was selected considering the distribution of the combined sewer system and the drain channel networks by reviewing flood data from the Tsushima City authorities to cover the areas that frequently experience inland flooding. This domain includes the Tsushima station and some parts of the core downtown areas, which is a total area of 202.59 ha. A two-dimensional surface model (30 m × 30 m) was established using the digital elevation model (DEM) of LiDAR data (5 m resolutions) with a vertical resolution of 0.1 m, and the actual building distribution in the period 2014–2015. Both datasets were part of the basic geographic data for Japan provided by the website of the MLIT's Geospatial Information Authority (http://www.gsi.go.jp/kiban/).

Figure. 4.5 shows the computational domain with modeled sewer systems and drainage channel networks. We described 122 manholes and 6.6 km of pipes (larger than 0.6 m in width) in total for the modeled sewer system, and 115 channels (larger than 1.2 m in width) with a total of 7.2 km length in the computational domain. These settings were given based on the information provided by the water and sewage department of Tsushima City.

In this computational domain, each manhole was modeled to be combined with its drainage area, and it was to be treated as interfaces of the 2D surface and 1D sewer flow (Nakamura, 2004; NILIM 2.0, 2012). An infiltration rate of 10 mm/hr was selected as the condition for the area without buildings according to the manual (NILIM 2.0 Manual).

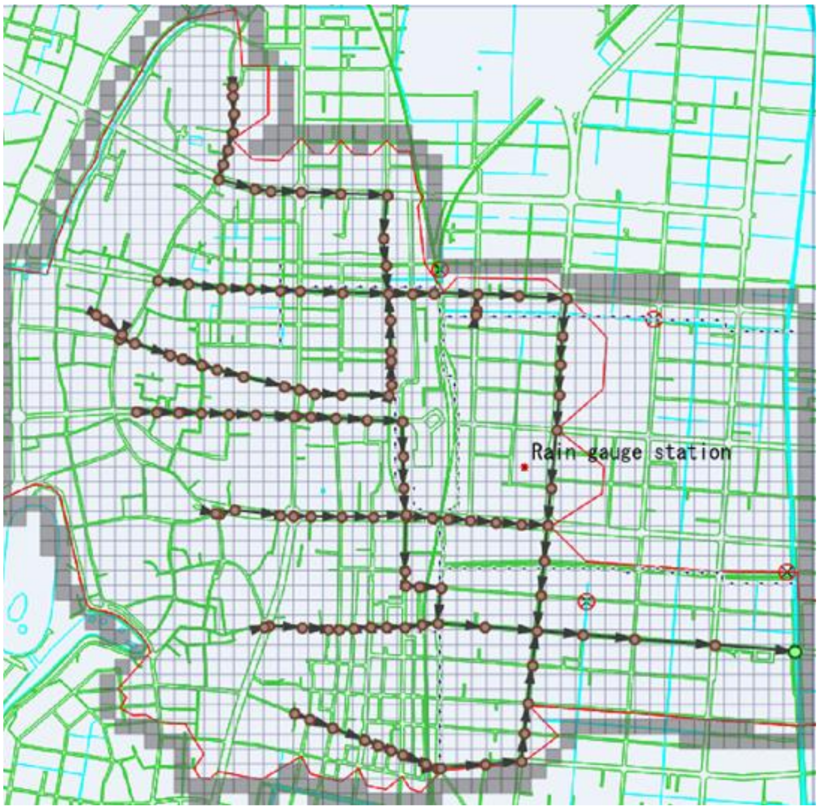

Figure 4.5 Computational domain and observation stations (Sts.1-4 and rain gauge) in the map of railway, road and water location (green and light-blue) with 30m square mesh configuration, including modeled sewer manholes and pipes (arrows and plots) and drainage channels (broken lines)

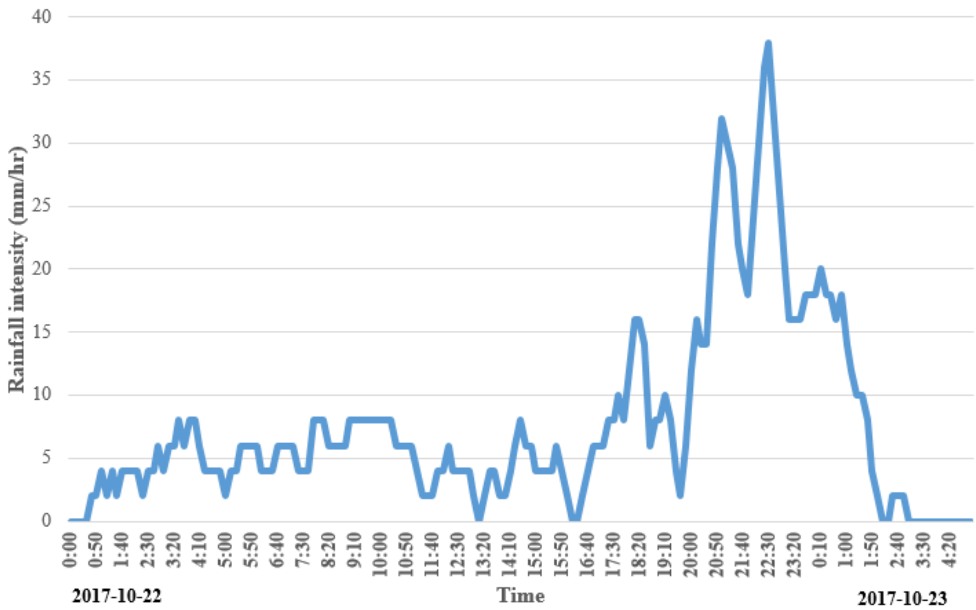

Figure 4.6 Hyetograph used for the inland flooding computation, made from the rainfall data in every ten minutes (Data source: River Division of Aichi Prefecture)

b) Computational condition

The rainfall event to be considered in this simulation is the 29-hour rainfall from 00:00 on October 22 to 05:00 on October 23 when the 2017 Typhoon No.21 was approaching. This is the period when the study area was most recently inundated by severe inland flooding (Figures 4.1-4.3). A hyetograph was plotted from the data recorded at the regional prefectural office near the study location (Figure 4.6). These data were collected in the location "Rain gauge station" as shown in Figure. 4.5 and it was provided by the River Division of Aichi Prefecture.

For the roughness condition (given as the Manning's n values) in the domain, the building occupation ratio in each of the meshes were reflected for the 2D overland flow calculation, whereas common values such as 0.015 were used for sewer pipes and 0.013 for drainage channels for the 1D sewer and drainage flow calculations. As the boundary conditions, the base flow discharges were provided based on estimation using the water-shed area and the specific discharge (0.015 $m^3/s/m^2$) for each of the manholes, whereas the water level data monitored in St. 4 were at the downstream end of pipe. These default values are inputted as per the NILIM manual).

Moreover, because the NILIM model can reflect the phenomenon with drainage culver networks as its optional function, both cases with and without these channel networks were simulated.

4.3.3 Results and discussions

The simulations provided information on the overland flooding processes and the performance of the existing drainage network. We identified that inland flooding was firstly occurred around at 21:00 October 22 when we had heavy rains with its intensity more than 30 mm/hr (Figure 4.6) and they were continued to the end of simulation duration in both cases. They were caused by overflowing from the manholes due to the sewer system saturations, and the total volumes of inundated water reached around 29,000 m^3 and 65,000 m^3 in the case with/without drainage channels at 3:00 October 23, respectively. Figure 4.7 shows the two cases of computed inundations with the drainage channel network (left) and without those (right) at 03:00 on October 23, 2017 when Typhoon No.21 was approaching. We identified that the storm water is collected by the sewer network, which leads to inundations in the south or east flatland at lower elevations in the study area. Furthermore, these figures clarified that the channel networks practically drained the storm water to decrease not only the area, but also the depth of inundation, although the computed inundation distribution without drainage channels is more similar to the observed one (Figure 4.3).

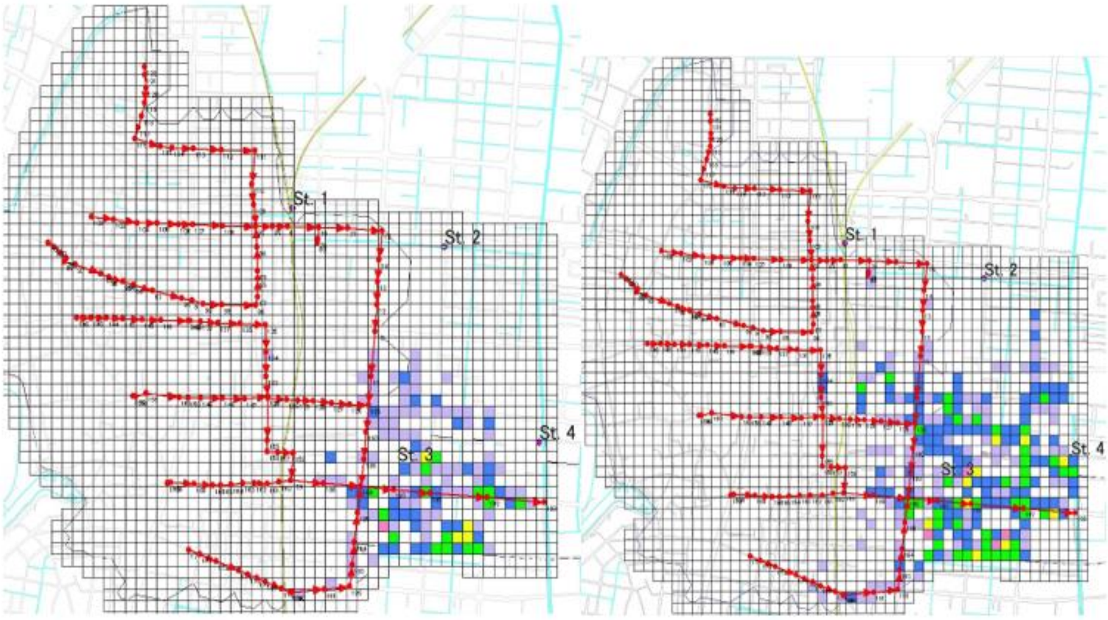

Figure 4.7 Computed inundation depth distributions with (left) and without (right) drainage channel network on the map with sewer system network (red arrows and plots), at 3am October23,2017 in the severest situation

We could simulate and describe the spatio-temporal processes of detailed inundations (in 30 m meshes with 10 min intervals) in the case of urban flooding due to heavy rainfall. However, by comparing the temporal processes, although both of the starting times of inundations are equally around at 21:00 October 22, the severest times were quite different, such as practically occurred around at 01:00 (Figure 4.2) and computationally described around at 03:00 October 23 (Figure 4.7). Moreover, these depths and locations of computed inundations (Figure. 4.7) were under-estimated in both of the computational cases in compared to the real situation (Figure 4.3). The computed results could be improved by tuning (but would be not so meaningful under the strange conditions), if we change the setting of the pipe and channel conditions such as roughness coefficient and so on. However, we consider that the drainage functions might be degenerated due to clogging with sediments or garbage from up-stream drainage areas, according to the conventional report (Lamond, 2012) and our field observation. There are few studies which focused on these clogging effects on drainage capacities, although there have been several studies that reported on enlarging sewer pipes (Sunaguchi, and Tsuchiya.2008) or raising the infiltration rate of the surficial area (Tashiro and Min.2017) to mitigate inland flooding by using the conventional soft wares. Solid wastes and sediments would be more crucial issues for effective maintenance or development of drain-age systems not only on the sanitation improvements but also on the flood mitigations in (sub)urban areas.

4.4 Conclusions

In this study, we presented a procedure to estimate the local inland flooding processes in urban areas using water depth loggers and digital elevation model, which may not require latest technology and considerable expense. The logged observation data in storm water drainage systems could be applied to track the inland drainage process by combining it with the high-resolution altitude distribution.

Further, we examined that the NILIM model could describe the spatiotemporal processes of detailed inundations and could identify the effect of drainage channel networks on mitigating inundation depth and area in our study area. However, there are some gaps between observed and computed processes of the inundations. We hence suggest the clogging of drainage system due to solid wastes and garbage as a future work for the flood mitigations in urban areas.

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Chapter 5

Evaluating the pluvial flood event using monitoring and modelling in a lowland urban area

5.1 Introduction

Pluvial flooding is an inevitable problem for many cities in developing and developed countries. Global climate change and population growth are increasingly concentrated in cities, and hence there is a need for a better understanding of urban flood risk and their impacts (Hammond et al. 2015). Pluvial flooding occurs as a result of high rainfall intensity when surface runoff cannot be efficiently discharged into an underground storm water drainage or sewer system (Rosenzweig et al., 2018). In addition, the underground storm water drainage system itself overflows due to drainage system failure or inadequate capacity (Ball and Alexander, 2006).

Pluvial flooding is often considered to be nuisance flooding with minimal impacts. However, there are many instances where it caused different types of damage, such as loss of life, significant property damage, and traffic disruption or other critical infrastructures in the UK and many European cities (Falconer et al., 2009; Douglas et al., 2010; Spekkers et al., 2013). According to reports by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan, 86% of the total economic flood damage in the Tokyo metropolitan area during 1998–2007 was due to pluvial floods alone (MLIT, 2008). In addition, large cities experience pluvial flood damage;

smaller cities and towns are also typically more severely affected by pluvial floods, possibly due to less-established flood defences, as the pluvial flood damage per capita in these areas has been reported to be higher than in larger cities (Bhattarai et al., 2015).

Numerical models have become a widely used tool for flood risk analysis to evaluate the performance of drainage networks and flood severity during heavy rainfall events. EPA SWMM is a popular open-source model with complete functions (Rossman, 2015); other commercial packages such as XP-SWMM (XP Solutions, 2013), MIKE MOUSE (DHI Software, 2014), and InfoWorks Integrated Catchment Modelling (ICM) (Innovyze, 2020) are also used for integrated surface and sub-surface simulation purposes. Modelling is an effective method for well-structured analysis and management of urban drainage systems and flooding. The results obtained from models are used to simulate the behaviour of the real system with reasonable accuracy. To obtain more reliable results and accurate representation of reality using a model, calibration or comparison of the results of the model with other monitoring data such as the water depth or flow is an important procedure (Mark et al., 2014; Nkwunonwo et al., 2020). One of the main barriers to assessing pluvial flood events is the scarcity of observed flood data in urban areas because of the limitations of the historic record of pluvial flood occurrence in the municipality and social media reports (Wang et al., 2018). Leandro et al. (2011) investigated the calibration of a 1D1D model with a 1D2D model when there is no field data. However, major differences were observed between the 1D1D and 1D2D results, such as instantaneous flow propagation and overestimation of the flood-depths. Nowadays, some researchers use water depth loggers for different applications such as to measure the capacity of infiltration trenches, collect data for model calibration purposes, and create inundation maps according to logger data (Toran, 2016; Ertezaei, 2018; Tashiro and Min, 2020).

In this study, we selected the InfoWorks ICM model for pluvial flooding simulations and to assess pluvial flood occurrence. The InfoWorks ICM model is widely used for many applications such as risk assessment (Cheng et al., 2017), and pre-and post-analysis of earthquake effects on a sewer network (Biswas, 2017). To explore pluvial flooding and identify its severity based on effective monitoring and modelling, we conducted a case study in the downtown area of Tsushima City located in the Noubi Plain, which is in the western lowland of Aichi Prefecture. The drainage system in this study area consists of a combined sewer system and open channel drainage networks. The purpose of this study is to investigate the pluvial flood event during the Typhoon Lan approach and evaluate the difference between simulation results and logger results at the stations. In addition, the results of the open source model (NILIM) and commercial model (InfoWorks ICM) were compared and analysed with an inundation map prepared using the logger data and terrain data.

5.2 Sensing pluvial flooding

In this study, we present the estimation procedures of pluvial flooding processes performed in the downtown area of Tsushima City using inexpensive water depth loggers that are easily deployed.

5.2.1 Materials and methods

Tsushima City (35º ° 10' 37’ N and 136º ° 44' 29’ E) has a total area of 25.09 km^2. In 2012, the total population was 65,118, indicating a population density of 2,596 inhabitants per 1 km^2 (Tsushima city guide, 2013). Topographically, it is a low-lying area at an elevation of 3.6 m below to 8.2 m above the mean sea level. Because of its location in the east Asian monsoon region, the city experiences rainy season in June with an annual precipitation of approximately 1,500 mm.

The typical forms of land cover have undergone rapid changes; for instance, urbanised land increased from 30% in 1976 to 51% of the total area in 2009, whereas the area of crop fields decreased from 65% in 1976 to 42% in 2009 (Min.2015). Most inundation is in the form of inland flooding; river flooding has hardly been observed in this area since the Isewan Typhoon of 1959.

Table 5.1 Main characteristics of observed drainage channels

	Width (m)	Height (m)	Bed elevation (m)	Remarks
St. 1-1	2.00	1.25	-2.15	open straight type
St. 1-2	2.00	1.18	-2.08	-1: upper, -2: middle, -
St. 1-3	2.00	0.99	-2.09	3: lower part
St. 2	2.15	1.14	-2.44	open straight type
St. 3	1.20	0.65	-2.35	junction of open / closed channels
St. 4	5.00	1.28	-2.68	effluent stream

We conducted a survey with four survey stations, including a total of six observation points that were set up at the two main stem drain channels (A: Sts. 1 & 2 and B: Sts. 3 & 4 in six main stems), which flow into the same effluent stream. The dimensions of the channels such as the height and width of each of the stations were measured (Table 5.1). Self-recording depth loggers (HOBO U20L-01, Onset Computer Corporation) were simultaneously installed at these observation points in the storm water drainage channels. The time series data of water level elevations were obtained by adding the measured water depth to the altitude value around each of the stations in the GSI map based on the digital elevation model acquired by airborne laser surveying with a 0.3 m resolution level (Geospatial Information Authority of Japan, https://maps.gsi.go.jp/).

The survey period was approximately 450 days from October 2017 to January 2019; however, the water level was not measured in some non-flooded seasons. The overflow of water channels at the survey sites was recorded using loggers, and these results were used to represent the inundation area from the altitude distribution of the area surrounded by these sites. The hourly rainfall data were collected during the survey period at the nearest local rain gauge station "Aisai", approximately 6 km away from our study site, and available at the website of the Japan Meteorological Agency (http://www.jma.go.jp/jma/index.html), whereas the rainfall intensity was also collected every 10 min in Tsushima City by the River Division of Aichi Prefecture.

5.2.2 Results and discussions

Figure 5.1 shows the water level fluctuations at each station along with the rainfall distribution. The heaviest rainfall recorded was 32 mm/h (23:00 on 23 October) at the time Typhoon No. 21 (LAN) was approaching in October 2017 (Figure 5.2), and the second heaviest rainfall was 30.5 mm/h (21:00 on 7 July) at the time of the heavy rain event in July 2018, which caused water level increase at the observation stations. By comparing each of these water levels and the channel parameters such as the height and bed elevation (Table 5.1), the overflow from the drainage channels can be monitored if the water levels exceeded the height of the channel wall as follows: -0.9 m, -0.9 m, -1.1 m, -1.3 m, -1.7 m, and -1.4 m in Sts. 1-1, 1-2, 1-3, 2, 3, and 4, respectively. According to this survey, an overflow was observed in Sts. 1 and 2 for a total of 8 and 10 h, respectively for both events. However, overflow occurrence was observed at 11 events for a total of 34 h at St. 3, where the drainages merge from three directions, and three overflow events were observed at St. 4 for a total of 12 h, where drainages poured.

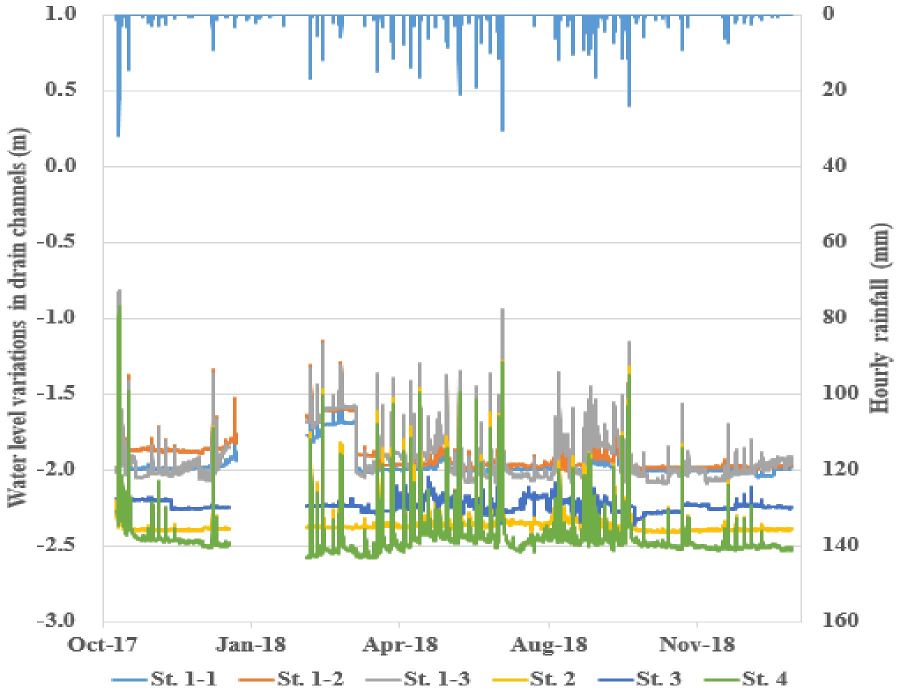

Figure 5.1 Water level variations in the drainage channels and rainfalls distributions in the target are during the survey period (rainfall data source: Japan Meteorological Agency)

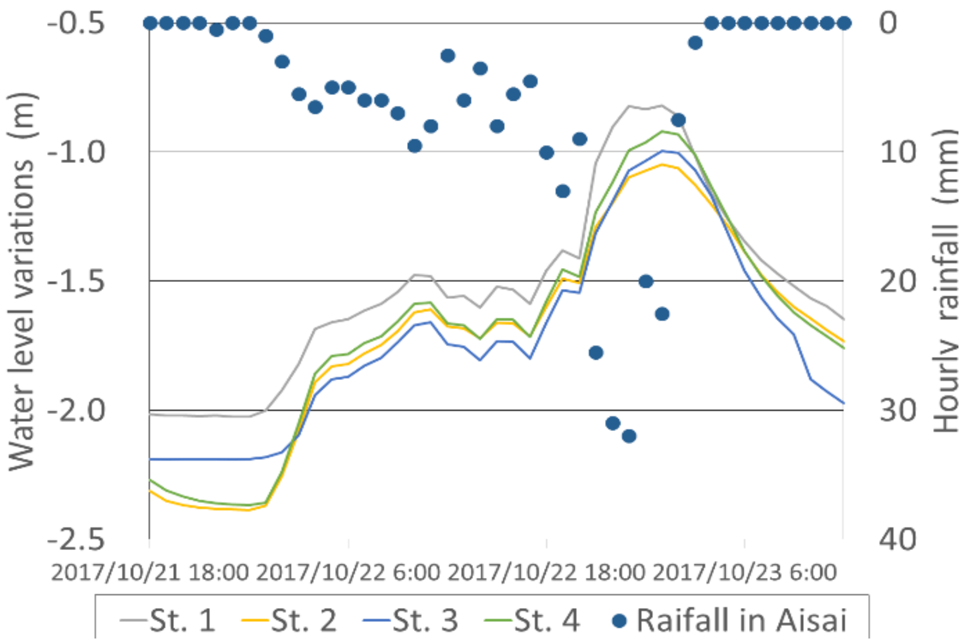

Figure 5.2 Water level variation in the drainage channels and rainfall distributions in the target are at the time of the Typhoon No.21(LAN) approaching on October 2017 (rainfall data source: River Division of Aichi Prefecture)

5.3 Modelling of Pluvial Flooding

We selected Infoworks ICM to identify the flooding process in the study area. In Tsushima City, a combined type of sewer system has been used in the downtown area since 1964 (Tsushima City Guide, 2013). This system comprises sewer pipes, manholes, regulators, and pumping stations, and the drainage channel networks help drain storm water. Data on the position of each component, including the slope, shape, and diameter of the pipes, were obtained from Tsushima City authorities. The drainage infrastructure of the sewer system consists of 796 manholes, 28 km of sewer pipes, and 3,159 flow regulators.

5.3.1 Simulation model

Infoworks ICM is a modelling tool from Innovyze and one of the modules from the InfoWorks product series. Infoworks ICM can be employed for studies with sub-surface and surface drainage systems for short and long study periods. It can perform hydrological and hydraulic modelling of floods to study sedimentation in pipes, and also ensures that model structures such as bridges, weirs, and pumps can be included to create an accurate model that is close to reality.

According to ICM help 11.0, the total study area is divided into non-overlapping sub-catchments to complete the calculation in InfoWorks ICM. The tool can assign six different system types for sub-catchments that are displayed as a separate layer on the GeoPlan of the InfoWorks Window (see Figure 5.5). Each sub-catchment represents an area from which water is collected. Urban area catchments include urban sewerage systems. An urban sewerage network can be built comprising conduits, manholes, and other drainage facilities such as inlets. Moreover, an urban sewerage network can be designated as a storm, foul, and a combination of different types depending on the city sewerage systems.

Several parameters need to be defined to describe the sub-catchment area (drain area), namely the system type, land use, soil type, contributing area, etc. and these need to be defined directly in the sub-catchment window. The runoff surface reflects the runoff characteristic of a specific surface type. Each runoff surface can generally be defined as an impervious or pervious type and can require its own assigned parameters.

Different input databases are needed to build a model in InfoWorks ICM. A specific number of database items is necessary for running the model. Moreover, a given number of parameters is needed for each database item to use the item in modelling.

Two main processes are performed during rainfall-runoff modelling in InfoWorks ICM: the initial and continuous losses and overland flow routing. The runoff volume model is used in to calculate the amount of rainfall after reducing any initial losses that run off the catchment into the drainage system. Several runoff volume models have been included in Infoworks ICM: Constant Infiltration, Fixed Percentage Runoff, Deficit and Constant Loss Model, New UK, Wallingford, Horner, PDM, USA SCS Method, SRM, Green-Ampt, ReFN, Horton, Horton SWMM, and UKWIR. Each of the runoff volume model processes rainfall in different ways, and the runoff volume model used in the model depends on the sub-catchment surface type and aims of the model. The runoff overland flow is calculated using a routing model built to calculate how quickly the rainfall enters the drainage system (InfoWorks ICM Help, 11). There are 13 types of routing models in InfoWorks ICM, such as SWMM, USA SCS, Rational, RAFTS, and Wallingford. This study used the Wallingford model for both the runoff volume model and runoff routing model.

5.3.2 Setup for the computation environment

a) Computational domain

The computational domain was selected considering the distribution of the combined sewer system and the drain channel networks by reviewing flood data from the Tsushima City authorities to cover the areas that frequently experience inland flooding. This domain includes the Tsushima station and some parts of the main downtown area, which is a total area of 202.59 ha. Figure 5.3 shows the computational domain with the modelled sewer systems and drainage channel networks. We represented a total of 122 manholes and 6.6 km of pipes (larger than 0.6 m in width) for the modelled sewer system, and 115 channels (larger than 1.2 m in width) with a total of 6.2 km length in the computational domain. These settings were based on the information provided by the water and sewage department of Tsushima City. Two D meshes were created for the two-dimensional surface model; the maximum triangle area was approximately 200 m2 and a minimum element area of approximately 100 m2 was established using the digital elevation model (DEM) of LiDAR data (5 m resolutions) with a vertical resolution of 0.1 m and the actual building distribution in the period 2014–2015 (see Figure 5.4). There are 168 sub-catchments for the rainfall runoff process (Figure 5.5). First, the DEM data was changed to ASCII data and a ground model was created for the terrain input data of ICM. Both datasets were part of the basic geographic data for Japan obtained from the website of the MLIT's Geospatial Information Authority(http://www.gsi.go.jp/kiban/).

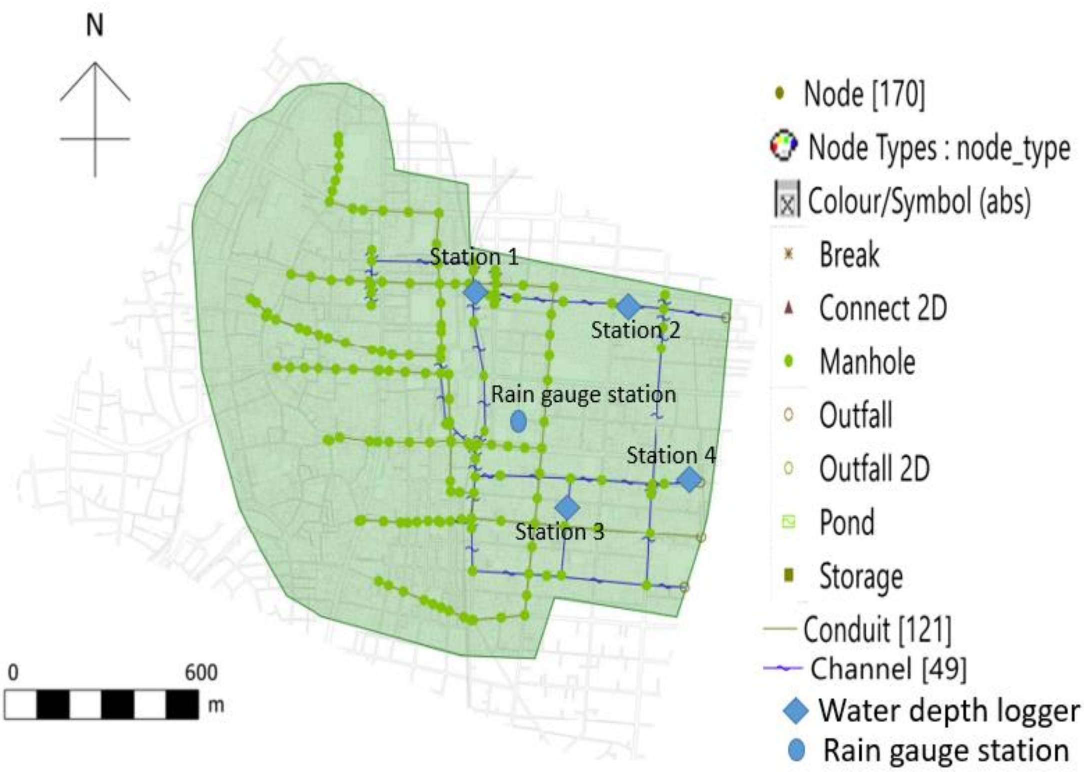

Figure 5.3 Computational domain and observation stations (Sts. 1to 4 and rain gauge) in the map including modeled sewer manholes and pipes and drainage channels

Figure 5.4 Flexible unstructured mesh with triangular cells representing the streets and pervious areas (shown with shadows) of the city. Building areas are excluded by 2D domain

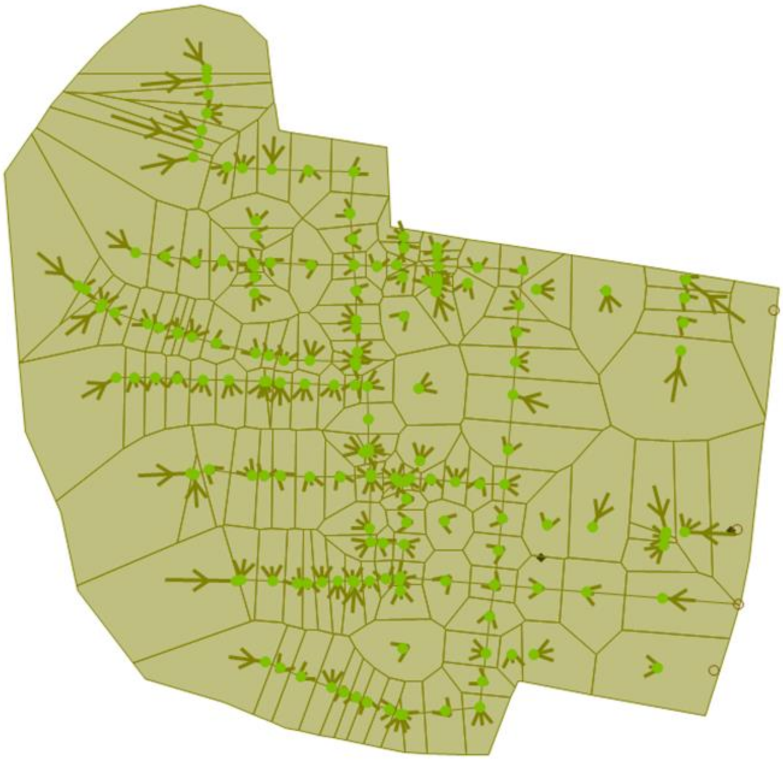

Figure 5.5 Sub catchment in the Tsushima city

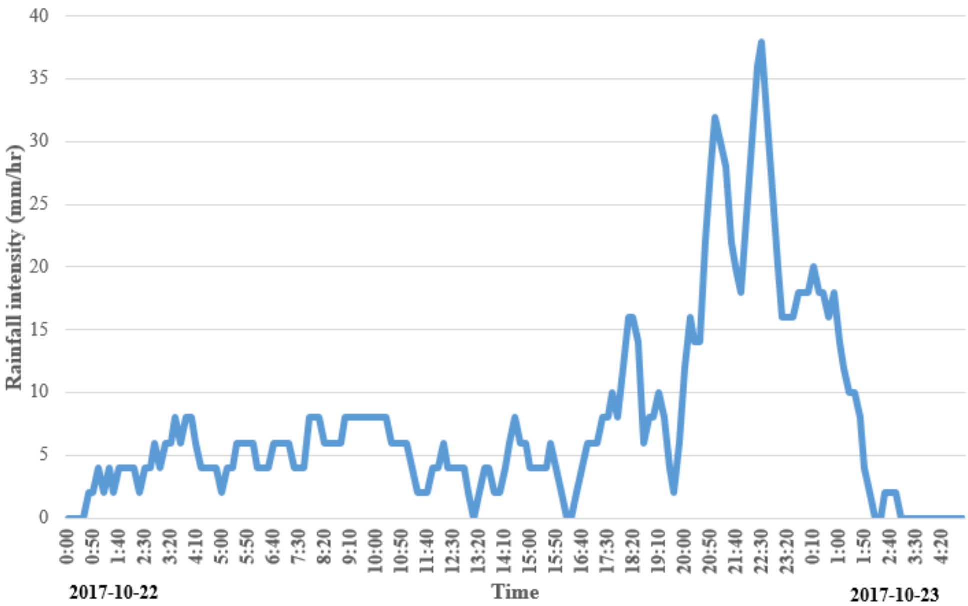

Figure 5.6 Hyetograph used for the pluvial flooding computation, made from the rainfall data in every ten minutes (data source: River Division of Aichi Prefecture)

b) Computational condition

The rainfall event to be considered in this simulation is the 29-h rainfall from 00:00 on 22 October to 05:00 on 23 October at the time the 2017 Typhoon No. 21 was approaching. This is the period in which the study area was most recently inundated by severe inland flooding (Figures 5.1–5.2). A hyetograph was plotted using the data recorded at the regional prefectural office near the study location (Figure 5.6). These data were collected at the "Rain gauge station", as shown in Figure 5.5, and were provided by the River Division of Aichi Prefecture.

5.3.3 Results and discussions

The simulations provided information on the overland flooding processes and the performance of the existing drainage network. We found that pluvial flooding first occurred around 21:00 on 22 October when heavy rain was observed with an intensity of more than 30 mm/h (Figure 5.2), and it continued till the end of the simulation. This is caused by overflow from the manholes owing to saturation of the sewer system, and the total volume of the inundated water reached approximately 30,000 m3 with drainage channels at nearly 1:00 on 23 October. Figure 7 shows the computed inundations with the drainage channel network at the maximum flooded time of approximately 01:00 on 23 October 2017 at the time Typhoon No. 21 was approaching. We found that storm water was collected by the sewer network, inundating the south or east flatland at lower elevations in the study area. A comparison of the simulation and logger results at each station in the study area is shown in Figures 5.9–5.12. The figures show the occurrence of floods at each station.

There are many possible reasons for the difference between the simulation and logger results. Flood gates were not installed at all the open channel outfalls to prevent backwater effects from the Zenta River in Tsushima City. Otherwise, blockage will occur at the trash screen during the Typhon Lan approach. In addition, garbage clogging occurred during the Typhoon Lan approach because clogging is an important driver for pluvial flood occurrence (Ishigaki and Kawai, 2015). This is also one of the possible causes of pluvial flood events in the study area. We set up an interval recorder camera (KING JIM) to monitor the flood situation near station 4 set time intervals. Figure 5.13 shows the flood situation before and after Typhoon Lan approach; some garbage is observed at the bank of the open channel at station 4 after Typhoon Lan approach. The main aim of installing the trash screen is to transfer the risk of blockage from inside a culvert to outside where removal of the blockage can be easily performed (Wallerstein and Arthur, 2012). Sometimes the trash screen itself constitutes a problem for urban flooding when routine cleaning is not performed (Ray, et al., 2019). When we visited the study area, we found that some of the trash screens were blocked with small litter and other organic debris (Figure 5.8). Therefore, one of the possible causes of pluvial flooding is related to garbage blockage at the trash screen. The typhoon approaching time and flooding time were night time, and there were some difficulties in cleaning the trash screen blockage. Therefore, the logger near the trash screen will provide water level inaccuracies and, consequently, there is a difference between the logger and simulation results. Uncertainties in the calibration process can occur because of inaccuracies in the simulation results as well as those of the observed data (Mark, 2014; Beven, 2014). Taking the water level variations into consideration is particularly important during the simulation process. If water level variations in the Zenta River were not considered, the simulation and logger results would be entirely different, even if the logger reflects the flood situations, whereas the simulation results do not.

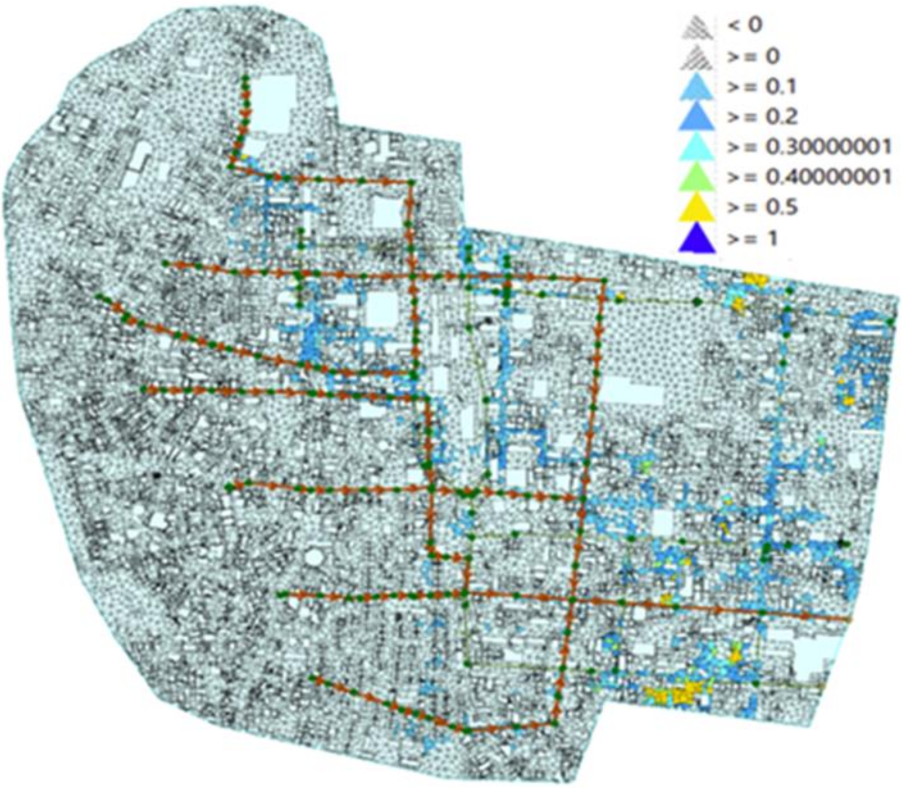

Figure 5.7 Computed inundation depth distributions on the map with sewer system network, at 1 am October,2017 in the severest situation

Figure 5.8 Garbage and organic debris at the trash screen

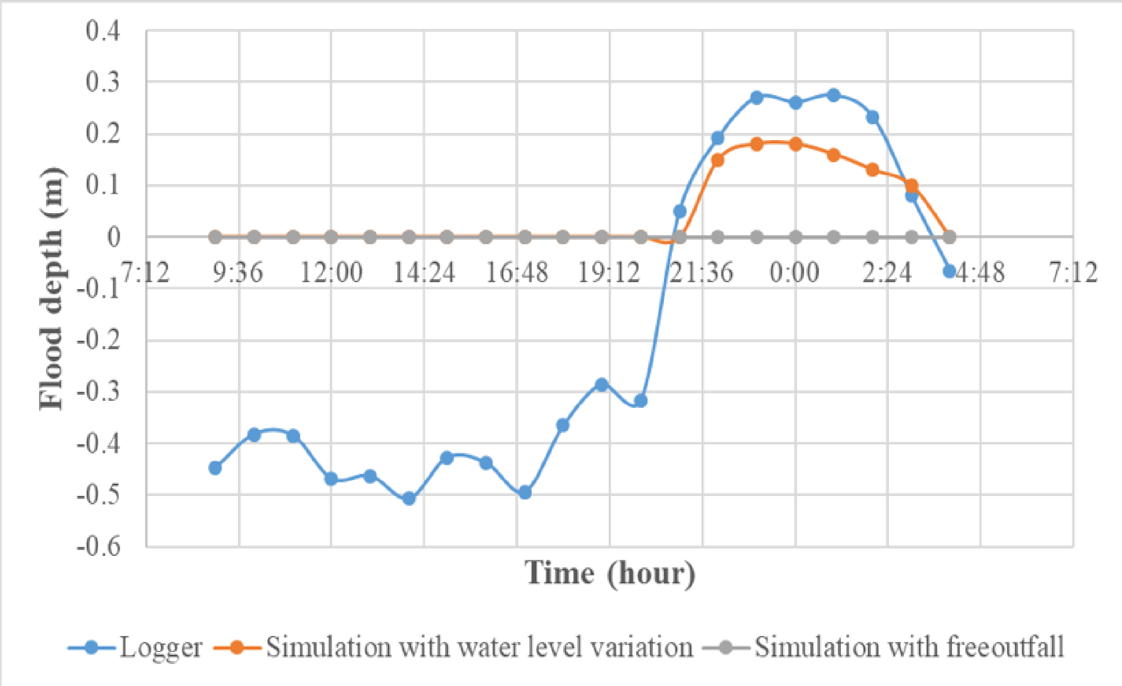

Figure 5.9 Observed vs simulated flow depth during Typhoon Lan approach at Station 1

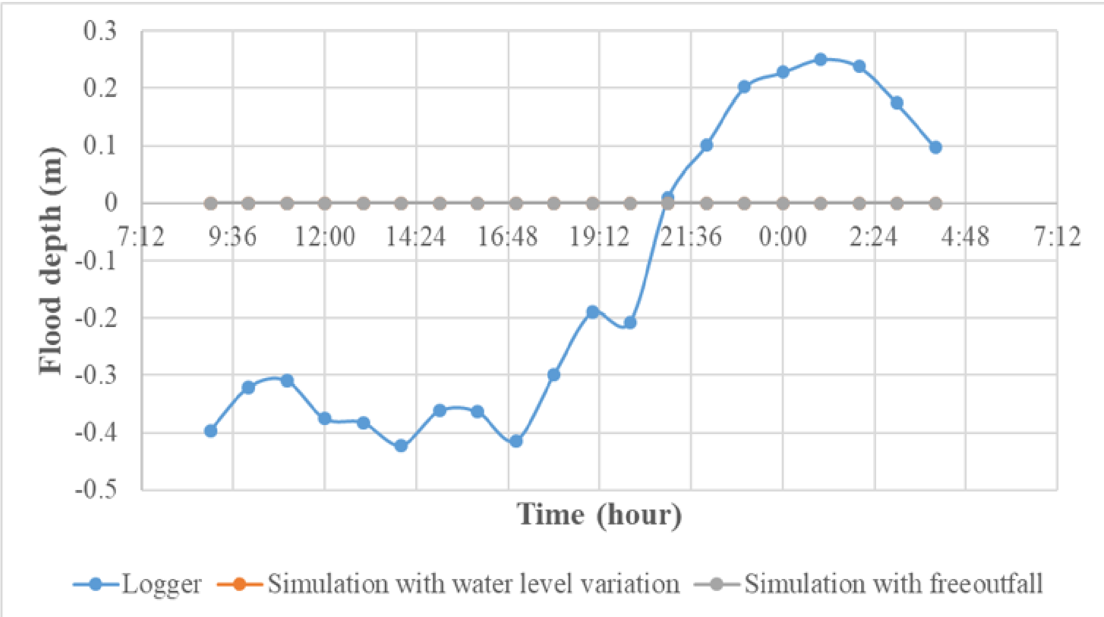

Figure 5.10 Observed vs simulated depth during Typhoon Lan approach at Station 2

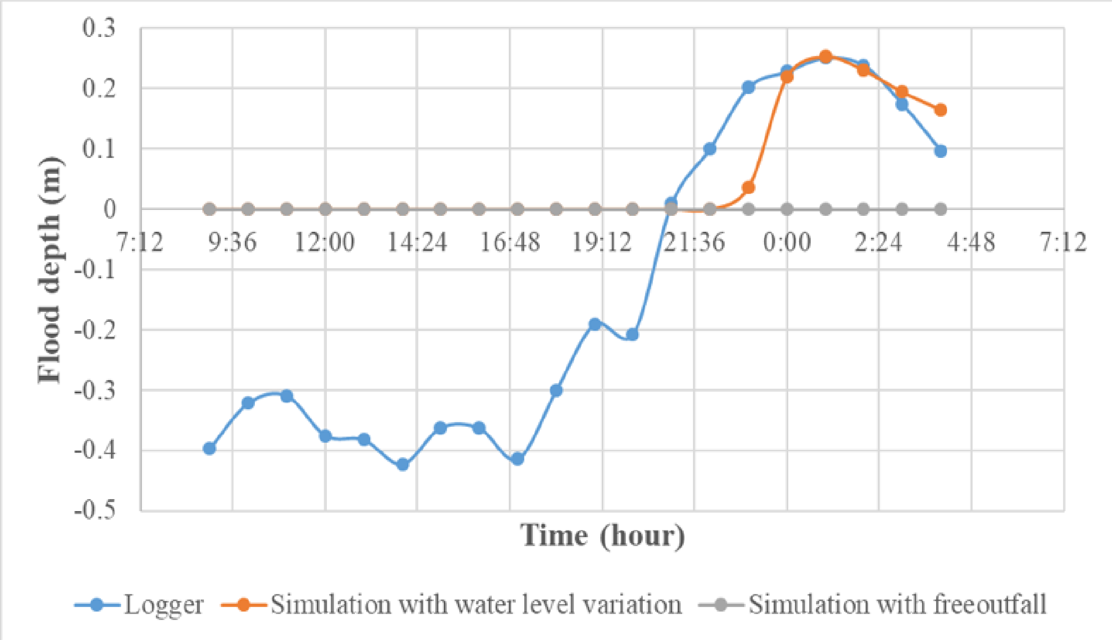

Figure 5.11 Observed vs simulated depth during Typhoon Lan approach at Station 3

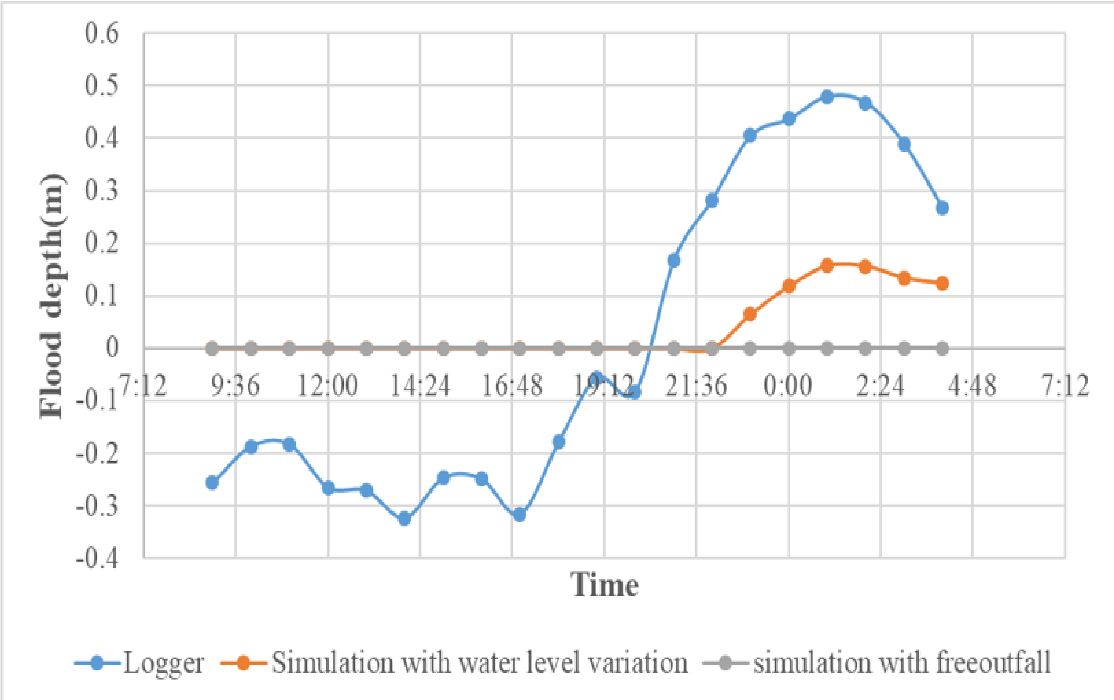

Figure 5.12 Observed vs simulated depth during Typhoon Lan approach at Station 4

Figure 5.13 Garbage situation near station 4 before and after Typhoon Lan approach

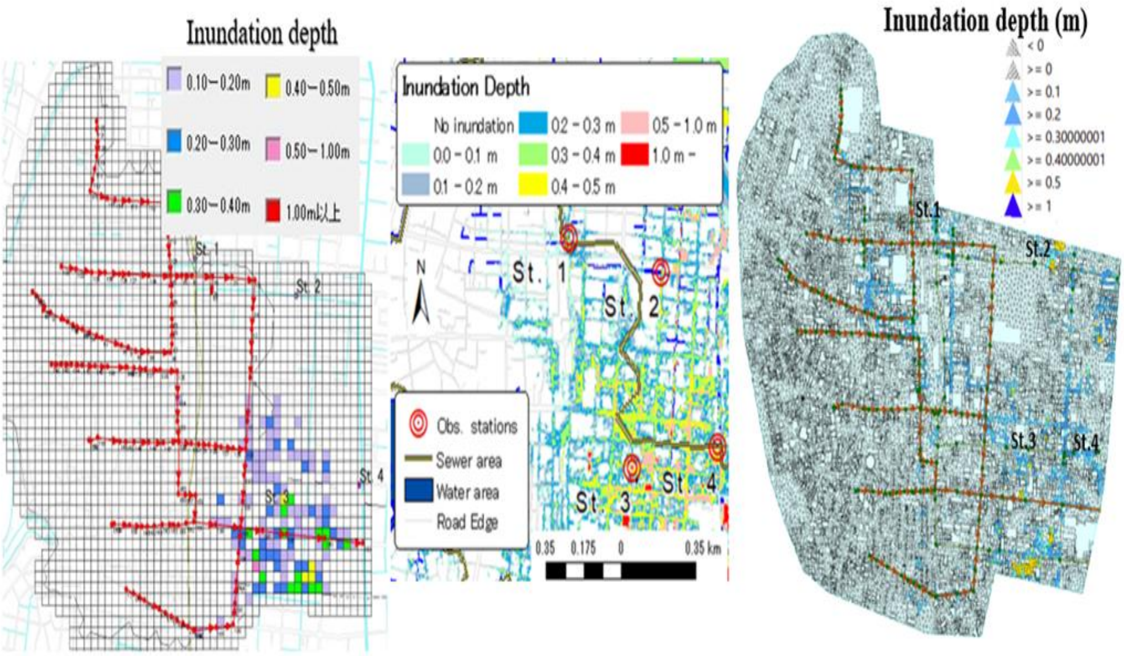

Figure 5.14 Depth of water on domain determined by NILIM model (left), Inundation map creation based on logger results (middle) and InfoWorks ICM model(right)

5.3.4 Comparison of two models

In this section, we compared the results of the New Integrated Lowland Inundation Model (open source), inundation map (Tashiro and Min, 2020), and Infoworks ICM (commercial) model for this case study. All the modelling techniques predicted some flood characteristics, including the depth of inundation, volume of inundation, flood extent, and peak time (Figure 5.14).

In general, the modelling techniques showed flooding at the same locations, although there are some differences for specific locations, particularly at some logger installation points. A comparison of the results of each model with an actual inundation map created based on logger results and high-resolution elevation data shows that the results of the Infoworks ICM model closely resemble inundation maps. The Infoworks ICM model predicted flooding of location such as stations 1, 3, and 4, whereas the NILIM simulation model predicted only station 3 flooded conditions. The results of the loggers indicate that the ICM simulation models take more physical processes into account compared with NILIM models and, hence, are expected to provide the most accurate results. In addition, ICM uses a flexible mesh for 2D calculation, and the NILIM model uses a structured mesh (rectangular grids) for model simulations because a flexible mesh can support more accurate results than a structured mesh (Neelz and Pender, 2013; Teng et al. 2017). However, one of the uncertainties of the simulation approach is that the inlet is not considered for the 1D2D simulation process. Most of the models considered only the 1D 2D connection through the manhole and neglected the inlets. The actual connection between the 1D2D process comprises both manholes and inlets; hence, there are some differences in the results because the inlets were not considered for the simulation process (Jang et al., 2018).

Factors such as the balancing accuracy, computation time, data requirements, and communication possibilities should be considered before choosing the appropriate models. This study showed that the results of Infoworks ICM models are similar to logger results and, hence, their accuracy is sufficient to perform quick scans for urban pluvial flooding in most situations. Furthermore, the computation time of these models is significantly less than those of the NILIM simulation model, and they offer extensive communication possibilities. The simulation time of the Infoworks ICM model was approximately 10 min for the complete Tsushima case study; however, the same simulation lasted more than 5 h when the NILIM simulation model was used because Infowork ICM 3.0 uses the CA cellular automata, which can be eight times faster than the traditional model, as noted by Guidolin et al. (2016). InfoWorks ICM can provide more accurate results than NILIM; however, the disadvantages of the former is that it is very expensive compared with the open source model (NILIM).

5.4 Conclusions

In this study, we performed flood assessment during Typhoon Lan using monitoring and modelling methods. Further, we examined whether the Infoworks ICM model can reflect the detailed spatiotemporal processes of inundations in our study area. We also analysed the differences between the NILIM and InfoWorks ICM models for this case study. We highlighted that the water level of receiving water bodies is an essential factor in the simulation process and described one of the possible causes of pluvial flood events, namely blockage effects at the trash screen in the study area, based on field observations and literature review. We found that there are some differences between the monitoring and simulation results. Therefore, the effects of solid blockage such as garbage and sediment, which increases the severity of pluvial flood events, should be considered.

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Chapter 6

Modelling sensitivity combination for sediment depth in storm drain and increased rainfall in pluvial flood severity

6.1 Introduction

In recent years, storm water models have been applied for design, optimization, and evaluation purposes and they play a critical role in the management of urban storm water drainage and flood risk, respectively (Beck et al., 2017; Massoudieh et al., 2017). Accordingly, several researchers have adopted comprehensive urban stormwater simulation models. A storm water management model (SWMM) is an open-source model with complete functions (Rossman, 2015) and commercial packages such as XP-SWMM (XP Solutions, 2013). Additionally, in industrial practices, other software packages with different hydraulic solvers, such as MIKE MOUSE (DHI Software, 2014) and InfoWorks ICM (Innovyze, 2019), are also popular. However, owing to various reasons, model predictions are subject to uncertainty, and the total elimination of uncertainty cannot be realized (Walker et al., 2003). The general uncertainties of model prediction are owing to model input data, parameter selection, and calibrations based on limited rainfall events, model structure, and approximation of natural processes for a particular model (Freni et al., 2009). Several researchers have identified the need for assessing the influence of model parameters on simulation results before simulation results are employed in the decision-making process (Stephenson, 1989; Hasan et al, 2019). For runoff modeling in hydrology, model structural deficits result primarily from process misspecifications, unsatisfactory spatial resolutions, oversimplified empirical equations, and numerical errors. The model structure for hydrological models depends on the selection of the perceptual and conceptual/physical models. Butts et al. (2004) examined the influence of the model structure on the model performance for catchment runoff, as well as high- and low-flow conditions, by combining two hydrological models (MIKE 11 and MIKE SHE) with different spatial resolutions and process descriptions. Liu et al. (2020) also evaluated the influence parameter of model outputs by adopting a combination of experiments and modeling. However, researchers rarely evaluate the uncertainty inherent in pipe diameters and their drainage capacities, either owing to incomplete or inaccurate databases, or because the effective pipe diameters are reduced owing to sedimentation. This uncertainty can be minimized if CCTV inspections are conducted regularly and siltation is considered (Beven, 2014).

Sewer asset management systems are limited in their implementation owing to budget limitations and technological barriers in the cities of developed and developing countries. Therefore, the prediction of sediment effects on drainage capacity should be evaluated in advance. Gong et al. (2018) systematically analyzed the influence of rainfall, model parameters, and catchment routing methods on outflow prediction using InfoWorks ICM. InfoWork ICM is a powerful tool with several routing methods for calculating rainfall runoff processes. With InfoWork ICM, the user specifies the depths of solids at each section of the channel, and the hydraulic computations of the model reflect both the reduced hydraulic cross-section and increased hydraulic roughness owing to sedimentation (Innovyze, 2019). Sedimentation in the drain, which is an inevitable challenge that limits the hydraulic capacity of the drain, has been identified as one of the factors that trigger pluvial flooding in urban areas, especially the open channel drainage system (Kolsky et al., 1996; Ghani et al., 2008; Rodríguez et al., 2012). Fortunato et al. (2014) evaluated the system's performance when faced with extreme climate-driven events, and inferred on the need to consider different return periods. Currently, the literature exploring the impacts of climate change on urban flooding focuses on single storm events of a particular return period, or rainfall events generated by downscaling global circulation models (Prudhomme et al., 2002; Arnbjerg-Nielsen et al., 2013). Although each of these two aspects can worsen flooding in low-lying areas of urban cities, presently, there are no attempts to simultaneously model the effects of these factors. The aim of this study was to assess the effects of sediment depth in the drain consisting of combined and open channels with different rainfall intensities for pluvial flood severity using InfoWorks ICM.

6.2 Modelling of Pluvial flooding

6.2.1 Material and Methods

Tsushima City (35° 10' 37' N and 136° 44' 29' E) spans a total area of 25.09 km². In 2012, its total population was 65 118, i.e., a population density of 2 596 inhabitants per 1 km² (Tsushima City Guide, 2013). Topographically, this city covers a low-lying area at an elevation of approximately 3.6–8.2 m above mean sea level. Owing to its location in the east Asian monsoon region, the city experiences a rainy season in June with an annual precipitation of approximately 1500 mm.

The typical forms of its land cover have undergone rapid changes; for example, between 1976 and 2009, urbanized land increased from 30% to 51% of the total area, whereas the area of crop fields decreased from 65% to 42% in in the same time period (Min, 2015). Because river flooding has been rarely observed in this area since the Isewan Typhoon of 1959, most inundations occur in the form of inland flooding.

6.2.2 Simulation model

a) Computational domain

Considering the distribution of the combined sewer systems and drain channel networks, the computational domain was selected by reviewing flood data obtained from the Tsushima City authorities to appropriately cover the areas that frequently experience inland flooding. This domain includes the Tsushima station and some parts of the core downtown area, which covers a total area of 202.59 ha. This drainage network consists of two types of drainage systems: combined and open channel drainage systems (Figure 6.1). Table 6.1 presents the input data requirements for the ICM model.

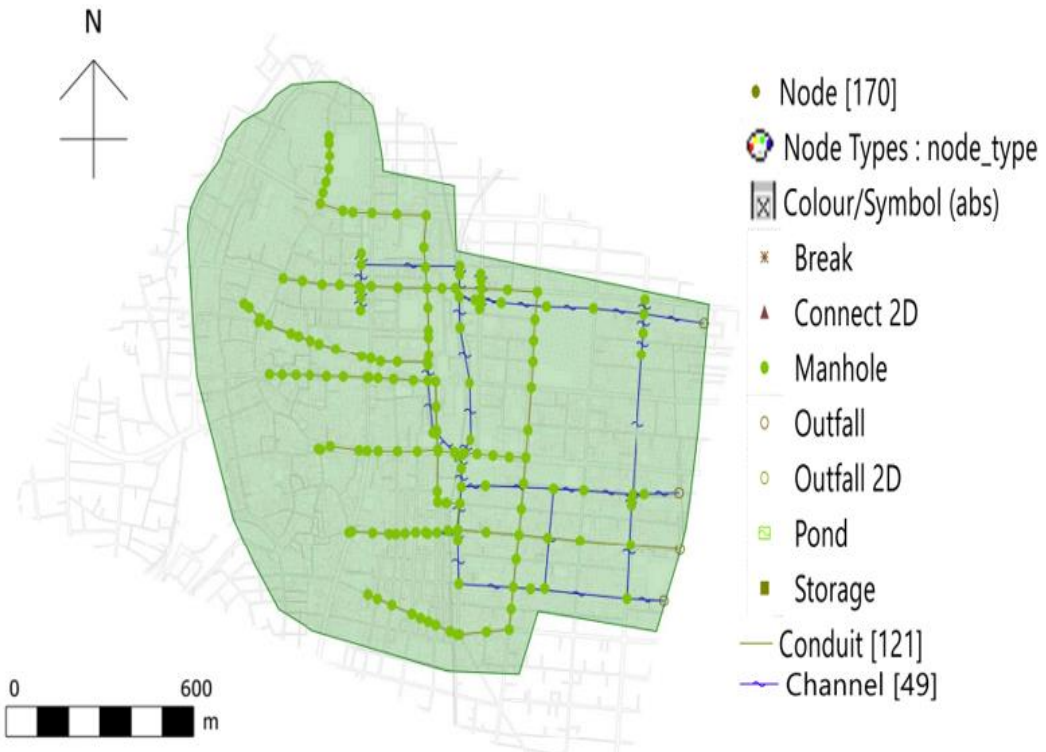

Figure 6.1 Computational domain in the map including modeled sewer manholes, pipes and drainage channels

Table 6.1 Input data for ICM Model

Input Description	Model
Ground Level	Extracted Obtained from the digital elevation model (DEM) of LiDAR data (5 m resolutions) with a vertical resolution of 0.1 m (http://www.gsi.go.jp/kiban/)
Network Data	A total of 121 combined sewer systems with 6.6-km pipes (larger than 0.6 m in width) 49 open channels with 6.2-km channels (larger than 1.2 m in width)168 manholes, 4 outfalls, and 168 sub catchments
Sediment in pipe	At 0%, 20% and 50% of open channel depth
Runoff volume model	Wallingford
Routing model	Wallingford

6.2.3 Design of rain events

Design storms, together with intensity–duration–frequency (IDF) curves, are useful tools that are internationally and widely applied in urban drainage system (UDS) projects and studies. They are used to evaluate the effects of intense rainfall events over a given urban basin, or more conventionally, as a tool for designing urban drainage infrastructure (Wang et al., 2018). The alternating block method is a method for determining the temporal rainfall distribution (design hyetograph) based on the rainfall IDF curve (Balbastre-Soldevila et al., 2019). The time of concentration (Tc) is beneficial for evaluating the duration of a storm, and it is a fundamental requirement in determining the time step required to model a catchment for various rainfall intensities. For natural and landscaped catchments, as well as mixed flow paths, Tc can be determined using the Bransby-William's Equation (Abustan, 2008).

$$T_c[\min] = \frac{F_c L}{A^{1/10} \quad S^{1/5}} \qquad (1)$$

where F_c is the conversion factor (58.5), A is the catchment area [km^2], L is the stream length [m], and S is the slope of stream flow path [m/km].

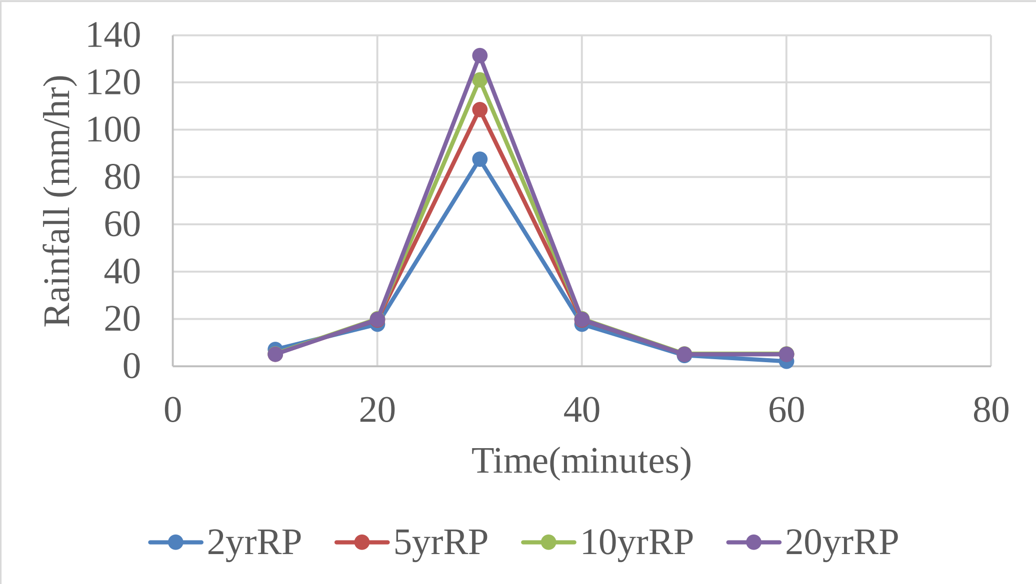

Figure 6.2 Hyetograph created by the alternating block method for return periods of 2,5,10 and 20 years

To discuss the sensitivities to flood severities, we adopt both the distribution of inundation depth (m) in "depth 2d," as well as in the flooded area and node conditions, which is expressed as follows: when the flooded area of each simulation results regardless of "flooding node," this indicates the overflowed node described with its flood discharge (m^3/s).

6.2.4 Sensitivity to Sediment Depth in drain

Regardless of the solid waste management system adopted, sediment deposition is an inevitable challenge in urban areas. Sediments enter the drain from different sources, such as road surfacing and road works, construction works, wind-blown sand/soil, and litters (Ashley and Hvitved-Jacobsen, 2003). Sediment depth was specified for an open channel drain as fixed percentages of channel depth, and the model was then used to predict the flood severity. The sediment yield of the urban catchment was between 7 and 1700 t/km2/yr. (Russell et al., 2017). Flood severity was examined with sediment depths set at 0%, 20%, and 50% of channel depth, respectively. In this study, the watershed area of the open channel and sediment yield of the catchment were approximately 0.58 km2 and 986 tons, respectively. Therefore, 20 % of the open channel storage volume was approximately 890 tons, which is approximately similar to the annual sediment yield in the study area. According to the site inspection, although the current sediment depth in the drain is not too high, we should examine the severity of pluvial flood events owing to the sediment depth in the drain. Sediment depositions frequently occur at the open channel with a mild slope because the drainage system is in the lowland area (Ghani et al., 1999).

6.3. Results and discussions

Considering the T_c of the study area (Eq. (1)), 60-min durations were selected to develop design hyetographs using the alternative block method. Figure 6.2 presents the hyetograph variations treated with different return periods of 2, 5, 10, and 20 years, which were used to evaluate the capacity of the urban drainage system, as well as flood situations in the study area. Rainfall return periods were assessed using data obtained from the Japan Meteorology Agency about the Aichi Prefecture.

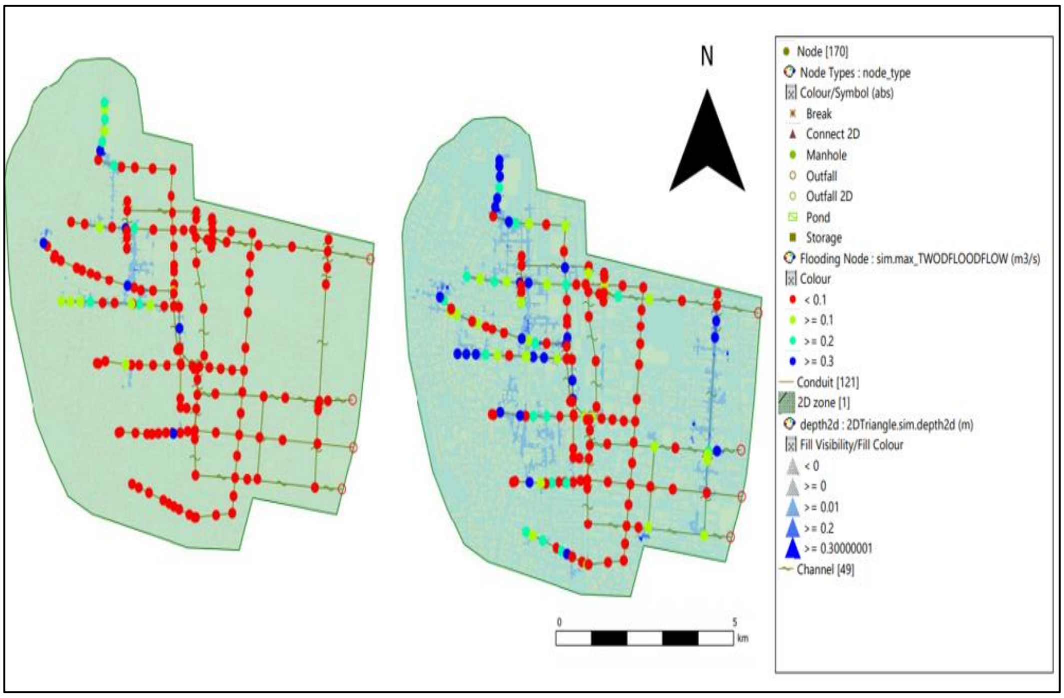

Figure 6.3 Inundation maps for the severest time under 2 year return period without sediment depth (left) and 20year return period with 50% sediment depth (right) in the study area

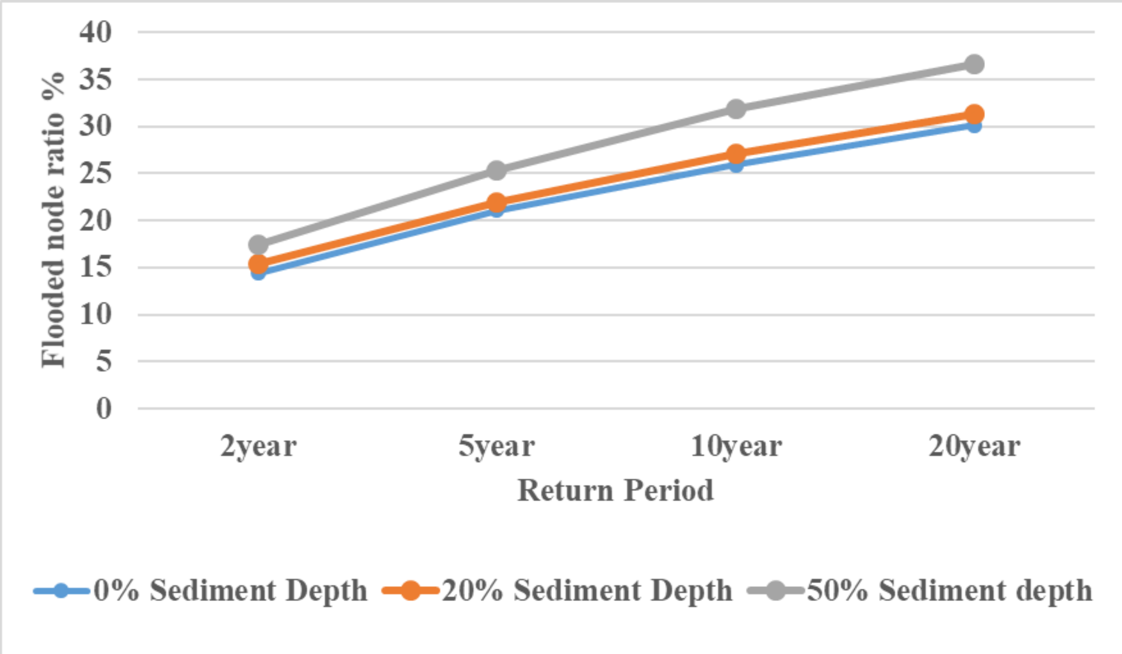

Figure 6.4 Percentage of flooded nodes related to different return period and channel sediment depth

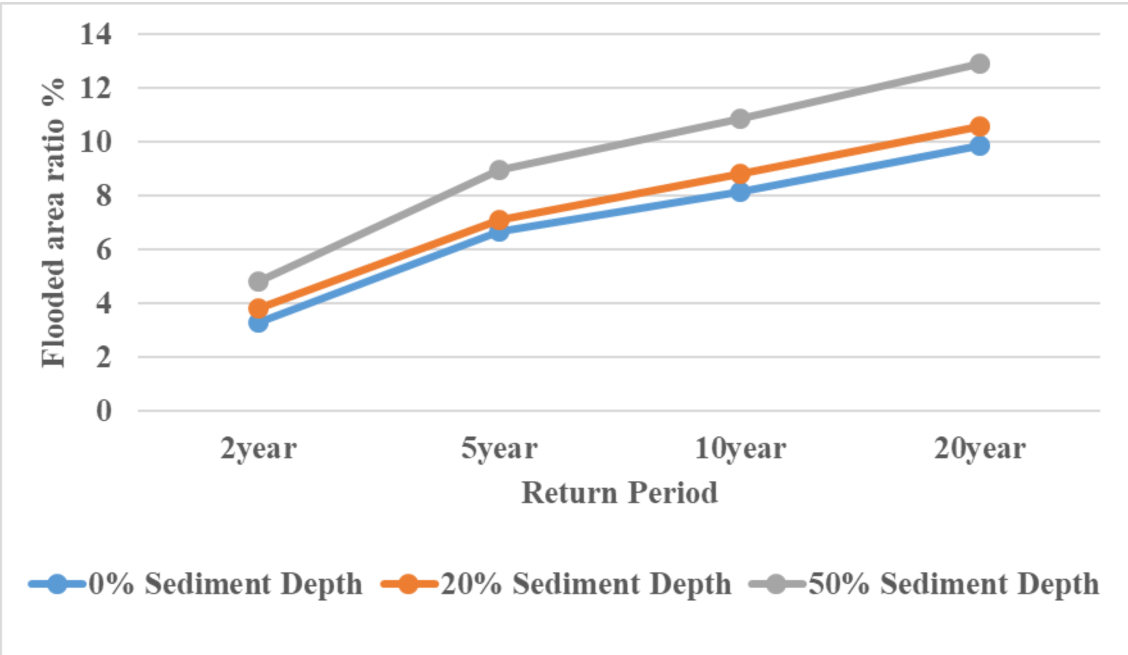

Figure 6.5 Percentages of flooded area ratio related to different return period and channel sediment depth

6.3.1 Analyses of flooded nodes and flooded area

By comparing the different simulation results obtained, we can identify the increased severity owing to an increase in the year of the design storm return-period, including the sediment depth in the urban drainage channel. Figure 6.3 shows the flood map of the 2-year return period of rainfall without sediment depth and the 20-year return period of rainfall with a 50% sediment depth condition in the channels. It was clarified that there were significant differences in flood situations between the 2-year return period of rainfall without sediment depth and the most severe cases under the 20-year return period of rainfall with 50% sediment depth. The figure on the left (Figure 6.3) shows that the flood severity of the 2-year return period under the clean channel condition is low; however, the figure on the right indicates that the flood severity of the 20-year return period with 50% sediment depth is high.

The ratio of the flooded nodes under the 2-year rainfall with 50% sediment depth condition is nearly 15% lower than that of the 20-year rainfall with no sediment condition. This indicates that the clean drainage conditions of the 20-year rainfall with no sediment condition and that of the 2-year rainfall with 50% sediment condition system exhibit a significant difference in severity if both sediment depth and designed rain are increased. Consequently, the differences between the 2-year rainfall with 50% sediment depth and the 20-year rainfall with no sediment condition can be approximately two times the severe flood conditions (Figure 6.4). Moreover, the differences between 0% and 20% sediment depth in the drainage of the flooded node ratio were not significant because the presence of sediment was assumed in the open drain channels alone, and the watershed area of the open channel is approximately one-fourth of the total study area. Therefore, to reduce the effects of sediment on flood severity, we need to apply a retrofit from the current open channel drainage system to a closed pipe system or cover the entire open drain channel.

Similarly, the flooded area ratio under the 2-year rainfall with 50% sediment deposition is approximately two times that of the 20-year rainfall with 50% sediment conditions (Figure 6.5). Furthermore, this indicates that the difference in the severity of the flooded area ratio between the 2-year rainfall with 50% sediment depth and 20-year rainfall with 50% sediment conditions exhibited a significant impact on pluvial flood severity.

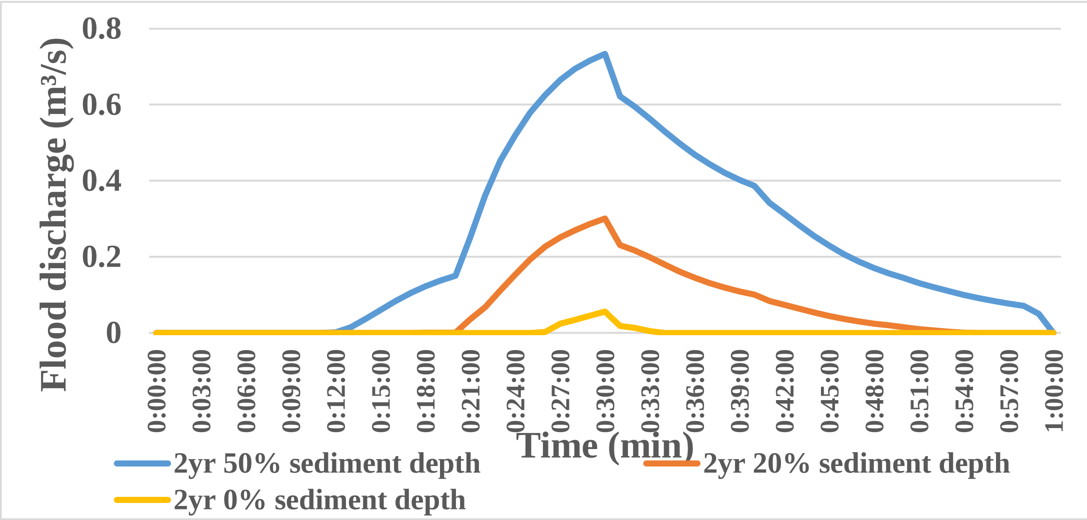

Figure 6.6 Flood discharge variations at the E72 node under the 2year rainfall with varied channel sediment depth

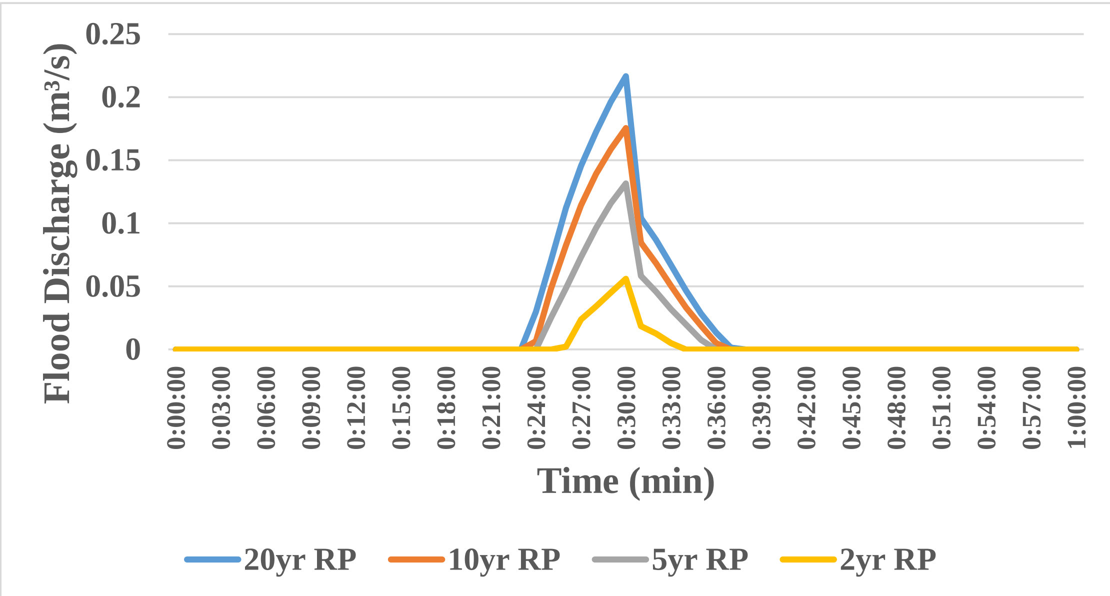

Figure 6.7 Flood discharge variations at the E72 node under the varied return period rainfalls with clear channel conditions

6.3.2 The effects of sediment depth on pluvial flooding

Figure 6.6 presents the different variations in the flooding discharge under the 2-year rainfall with varied sediment depths at node E72, which is the most vulnerable flood node in the drainage system. The maximum difference in flood discharges between the drain channels with 0% and 50% sediment depth conditions reaches approximately 0.7 m^3/s. In this case, the clean channel triggers a flood for 9 min, whereas the channel with the 50% sediment depth triggers a flood for 43 min. The duration difference between the 0% and 50% sediment depth conditions exhibit a significant gap. This result indicates that sediment depth in the drain causes long-duration effects on flood severity. When a node is filled with flood water, the overflowing water enters the nearest node, which can receive the water for draining before moving it to the surrounding area. The presence of sediments in drain channels reduces both the carrying capacities of the channels, as well as the receiving capacities of their connected nodes, and can increase the flood duration. Consequently, this suggests that the sediment deposition in drain channel especially aggravates the flood duration.

6.3.3 The effects of different return period on pluvial flooding

Figure 6.7 presents the variations in the flood discharge at node E72 under different return periods of rainfall with clear channel conditions. The maximum variation in flood discharges between the rainfall conditions of the 2-year and 20-year return periods reaches approximately 0.16 m^3/s. In this case, the 2-year rainfall triggers the flood for only 8 min, whereas the 20-year rainfall does the same for 13 min. The difference between these flood durations is only 5 min. This suggests that rainfall intensity significantly affects the peak discharge of flood under clean channel conditions.

6.3.4 The effects of sediment and garbage blockage

We evaluated pluvial flood events in the typhoon Lan approach in 2017 using simulation and monitoring processes; in addition, we applied water depth loggers for the monitoring approach. When the logger results are compared with the simulation results for the flood situation of the Typhoon Lan approach (Tashiro and Min, 2020), a gap is identified at each station. The water levels of some stations do not coincide, and station 2 is completely different in its logger and simulation results. Although InfoWorks ICM can provide accurate results based on terrain, drainage, and rainfall input data, the simulation results of ICM exhibited non-flooding conditions, whereas loggers exhibited flooding conditions at the same time. According to Section 6.3.2, one of the possible causes of pluvial flood is the presence of sediment in the drain channels. When flood severity is assessed with the same return period and different sediment depth in the drain, the results also indicate that the severity of low rainfall intensity can be serious in drains with sediments, similar to the results observed in a clean condition with high rainfall intensity. Sediments in the channel influence pluvial flood severity based on the simulation results of this study. One of the uncertainties of the logger results is the water level inaccuracies at the logger station. This inaccuracy is usually associated with an unstable water surface (ripples or waves) owing to blockage or clogging in the drain and drain throat, even though the logger itself is properly calibrated (Mark, 2014). Therefore, we need to consider sediment blockage in the drain that could cause inaccuracies in the water level monitoring process.

6.4 Conclusions

This study quantified and visualized the effect of sediments on flood inundation under different scenarios by integrating rainfall–runoff and inundation models and augmenting rainfall data. Specifically, we employed the InfoWorks ICM model to simultaneously simulate the effects of sediments and different rainfall conditions. Furthermore, we developed a method for assessing the effect of sediments by considering multiple-sediment depth conditions. This novel information will help us understand flood risk in low-lying areas. In summary, varied sediment and designed rainfall conditions triggered extreme flood events. Some of the key impacts and findings of this study are summarized as follows:

- The inundation maps, which were created based on simulation results of different sediment depths and rainfall conditions, are effective for decision makers to pay attention to maintenance work.
- According to the obtained flooded-node ratio results, the percentage of the flooded node ratio does not change significantly because of the negligible solid depths, and the remaining capacity may be adequate in preventing the floods caused by several storms at low solid levels. However, the remaining hydraulic capacity is more sensitive to changes in sediment depth at higher levels.
- This research suggests that any modern water authority or engineer can adopt appropriate hydraulic modeling tools to prepare for the possible impacts of sediments in drainage systems, which trigger sever floods.

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Chapter 7

A comparative study between Tsushima and Yangon for flood mitigation measures

7.1. Introduction

In urban area perception, prevention of flooding may be companioned with inadequate drainage systems. People think pluvial flooding is a nuisance flooding and its damage cost is not big like fluvial or coastal flooding. In Japan, approximately USD 1 billion in damage occurs annually due to pluvial floods only (Bhattarai et al., 2015). Even though a huge investment in the improvement of pluvial flood control measures has been made, flooding remains as a severe problem throughout the Europe (Kundzewicz et al., 2013) and the case of Japan is also similar. To mitigate the pluvial flood problem, drainage systems designed to cope with the most extreme storms would be too expensive to construct and operate. In considering tolerable flood frequencies, the safety of the residents and to protect their belongings must be in balance with the technical, economic constraints and environmental degradations. The responses of the drainage systems to rain events in the urban environments are characterized by two main components, the first one being the surface runoffs on the grounds with natural slopes; the second one consisting of the manmade drainage systems. In the most cities with old artificial drainage systems are controlled by combined sewer systems which receive both of storm water and waste water and transport them to the treatment plant. Some of the urban areas in developing countries still rely on open channel system connected to the receiving water bodies for disposing their storm water. Besides, the cities in developing countries are facing greater vulnerabilities to floods than those in developed countries, because of rapid population growths as compared to the existing capacities of infrastructures, which results in the insufficiencies of their adaptation measures towards future climate variabilities (Hunt and Watkiss, 2011).

Although planners must consider with future flood uncertainties due to climate changes and urbanization effects (Godschalk, 2003), flood events can be bigger than what the system are designed for (Liao, 2012), and hence cities should be built with their resilience. The urban resilience to floods could be conceptualized as the capacities to remain in desirable establishments while experiencing floods (Liao, 2012). Even a flood resistant city cannot resist extreme floods, however can learn from historic events with its flexibility and adaptivity. It is in many cases not possible for a city to hold both of its resistant and its resilient facilities. A city that accepts smaller floods, will be better prepared when a bigger flood occurrence.

To be able to handle floods, floodable areas are needed in the city, i.e. areas that can store or convey water without suffering damages (Liao, 2012). However, land scarcity is the big problem in city center for flood water storage. Natural pond and green areas have been disappeared due to land development / encroachments and obstructions caused by utility networks being crossed in the city centers (Dhiman et al., 2019). Most cities in developing countries are regarded as lacking in sustainability due to multiple urban crises that confront them, arising largely from inadequacy or absence of key utilities like access roads, drainages, recreational facilities, waste and urban management systems (Ajibade et al., 2013).

In many cities of the developing world, not much is known about peoples' flood risk awareness and perception; how much resilient facilities they have and what adaptive capacities, socioeconomic, cultural drivers they have influence their risk perceptions and adaptive coping capacities. Besides, flood conveying structures like sewer and drainage systems are inadequate due to illegal waste disposal. There is inadequate coordination between institutional stakeholders responsible for city planning, waste and emergency management in the area. The residents agree to participate some small scale, ineffectively coordinated household level proactive actions to minimize flood impacts, but there are no community level flood early warning systems. These create high flood risks in the area and limit the flood resilience (Mashi et al., 2020). Many researchers studied pluvial flood comparative analyses between the cities of developed and developing countries to apply the effective flood mitigation measures of the developed countries for developing countries. Moreover, they evaluate the solutions are reliable or not to implement in cities of developing countries based on direct observations and reviews on documents (Sörensen and Rana, 2013; Sudirman, 2019).

From the above mentioned viewpoints, I conduct this chapter to make an effort to suggest some flood mitigation measures for the two study locations such as Tsushima and Yangon, reviewing my findings in the previous chapters. This work could help to be references for the Yangon city development committee and the Tsushima city municipality in formulating policies and preparing mitigation measures concerning to tackle the urban flood problems.

7.2 Research methods

The using materials are based on the field investigation and simulation results in each of the study sites by reviewing the studies described in the previous chapters. Each of their conditions and their characteristics are summarized as follows.

7.2.1 Study areas

Tsushima city, which is suffered pluvial flood and Yangon downtown area, where parts of city is flooded every rainy season, is compared. The drainage system of Tsushima, especially combined sewer system was built in 60 years ago, which that of Yangon was as both of open channel storm drain and separate sewer system built nearly 100 years ago. The system in Yangon has, more or less, not been developed since it was built until last several years ago. Some parts of drainage system were rebuilt or retrofit, but most of the drainage system are deteriorated until now. Two cities situated on the lowland area and they are suffering pluvial flood problems.

The storm water drainage (SWD) system in Yangon downtown consists of open channel system, while the SWD system in Tsushima is open, combined sewer system. Besides, different drainage system, there are some similar and different problem facing related to flood mitigation measures (Table 7.1). Japanese cities are now heading to sustainable urban drainage systems (SUDS), Tsushima city also changing conventional storm water management to sustainable system. Other Asian cities also try to develop urban flood resilience applying SUDS (Chan et al., 2018). However, Yangon drainage system is left behind to start the sustainable system. In the case of the CBD areas with its densely populated area and its inherent flood risk for the surrounding rivers, the opportunities for implementation of sustainable drainage systems may only be applicable to new development or re-development.

Table 7.1 Problem facing in Tsushima and Yangon for pluvial flood

Problem	**Facilities**	**Tsushima**	**Yangon**
Same problem	Drainage Type	Open Channel+ Combined Sewerage	Open Channel+ Separate Sewerage
	Topography	Lowland	Lowland
	Drainage capacity	Inadequate	Inadequate
	Flood frequency	High	High
Different problem	Resident altitude for garbage disposal	Dispose at designated area	Illegal dispose
	Population density	Low	High
	Waste management system	Good	Inadequate
	Law enforcement	Good	Lack

7.2.2 Current land use situation and Rainfall in Tsushima and Yangon

We have installed water depth loggers in the drains of Tsushima and Yangon since 2017 and 2018, respectively for flood observations. There were some pluvial flood problems and preparations for mitigation measures in both cities. Firstly, I would like to discuss about the current land use conditions in both of the cities. In Tsushima, the typical forms of land cover have under-gone rapid change; e.g. urbanized land increased from 30% in 1976 to 51% of total area in 2009, whereas the extent of crop fields decreased from 65% in 1976 to 42% in 2009 (Min, 2015). However, Tsushima can apply some open spaces for flood mitigation measures and guttering with infiltration system is also effective reduction for surface runoff volume. Yangon is already urbanized condition and no open space for flood mitigation measures and guttering with infiltration system (Figure. 7.1). So, Tsushima have some open space to create mitigation measures for pluvial flood problem, however Yangon is facing land scarcity problem for flood mitigation measures.

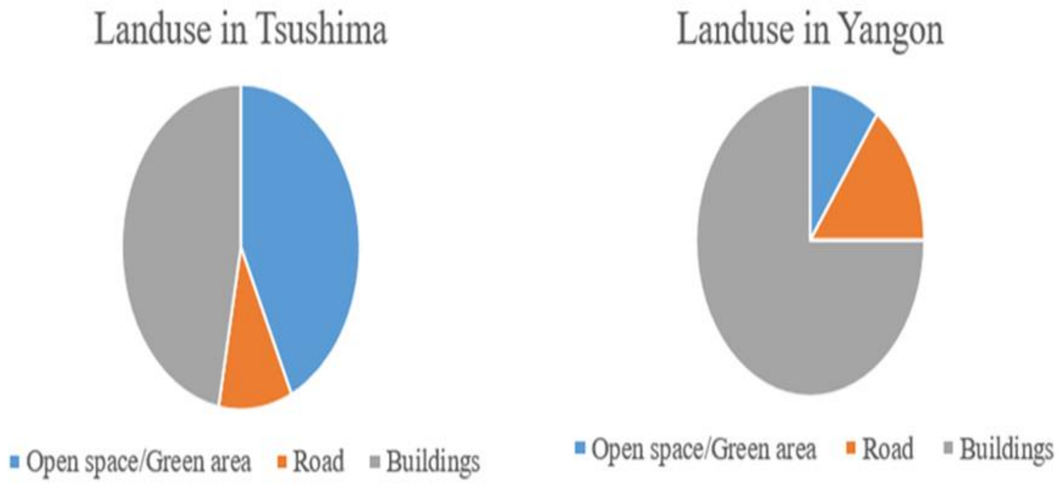

Figure 7.1 Current land use in Tsushima and Yangon

Current rainfall situation of both cities have high annual rainfall, but there are not prominently change rainfall pattern in each city since sever decades ago. (see 1.4.1.2. and 1.4.2.2). However, cities are suffering pluvial flood frequently during the rainy season. So, we should need to identify the causes of pluvial flood occurrence in each city.

7.2.3 Existing storm water drainage facilities of Yangon

During the course of the site visits, YCDC explained that the gates on the existing outfalls are closed to prevent backflow of the river water into the drainage system during high tide. During this period, the drainage system relies upon the available storage to contain the sewage flows, and during the rainy season the storm water flows. Once the high tide has past the gates are opened allowing the storm water and sewage to discharge freely to the river. This can be observed by the relatively short duration of the flooding period, which nevertheless cause significant disruption to the traffic and economy of the city.

During the field visits and subsequent site reconnaissance, it has been observed that there is significant accumulation of sediment and debris in the channel drainage systems. Silt and debris reduce the drainage system capacity, exacerbating the flooding problems during rainfall and tidal events. YCDC carries out regular manual dredging of the drainage system, which was also observed during the field visits.

The majority of the outfalls within the Port Area are not accessible for regular inspection and maintenance and are therefore a liability for YCDC that as they have no control over them.

The conclusions that can be made from this information are that:

- There is insufficient storage capacity in the existing system to provide for the dry weather flow during high tide events. This has probably only started to occur after a reliable water supply has been provided for the inner city which allows water usage per capita to rise.
- There is insufficient capacity in parts of the drainage system to provide adequate storm water drainage
- Tidal and rainfall events occurring at the same time make the problems to worse.

The solutions to the problem clearly point to the requirements for providing significant additional storage within the drainage system to cater for the conditions which occur during the high tidal event and for the combined tidal/rainfall events.

7.2.4 Existing Storm Water Drainage Facilities of Tsushima

In Tsushima, the rainwater discharges to the receiving water bodies through combined sewer and open channels.

7.3. Results and discussions

7.3.1 Sediment effects on open channel and closed conduit system

Sediment yield from urban watershed is between 7 and 1700 t/km2/yr (Russell et al., 2017). I assumed sediment yield of each city based on maximum yield of Russell's reference because I want to compare the possible maximum yield of each city and my various sediment depth scenarios in chapter 3 and chapter 6, the assume scenarios are feasible or reasonable or not. We can check sediment yield from Tsushima and Yangon based on this range. Yangon catchment area is 2.58km2 and sediment yield is about 4386 tons. Total open channel storage capacity of drain is about 27589 tons and 20% of storage capacity of open channel drain is about 5517 tons. So, sediment yield calculation based on the reference is nearly same as 20% of total channel drain storage. Tsushima catchment area is about 0.58km and sediment yield is about 986 tons. Total storage capacity of open channel drain is about 4453 tons and 20% of storage capacity of open channel drain is about 890 tons. When comparing the sediment yield calculation based on the reference is nearly same as 20% of total channel drain storage, and the assumption for 20% sediment depth in the drain is reasonable attempt to check severity of pluvial flooding due to sediment effects. When we compare the flood nodes ratio results of ICM models for Tsushima and Yangon, Yangon suffered more severe than Tsushima because, we designated sediment existence on only in the open channel (Figure 7.2). The whole Yangon drainage system is open channel, but Tsushima drainage system consists of open channel for small part. The total open channel's catchment area of Yangon is bigger than the Tsushima's open channel catchment area about 5 times, consequently Tsushima open channel drain suffer less severity of pluvial flood than the Yangon flood. So, the magnitude of sediment yield existence in the drain based on not only local effects such as rainfall intensity, urbanization but also size of open channel catchment area. Therefore, closed conduit can reduce sediment effects on flood severity and Yangon drainage system should be installed the cover for all channel and kept to prevent sediment and garbage problem. Gully pot or sediment trap is effective solution to assist in protecting drainage system from sediment deposition (Fraser et. al, 2000).

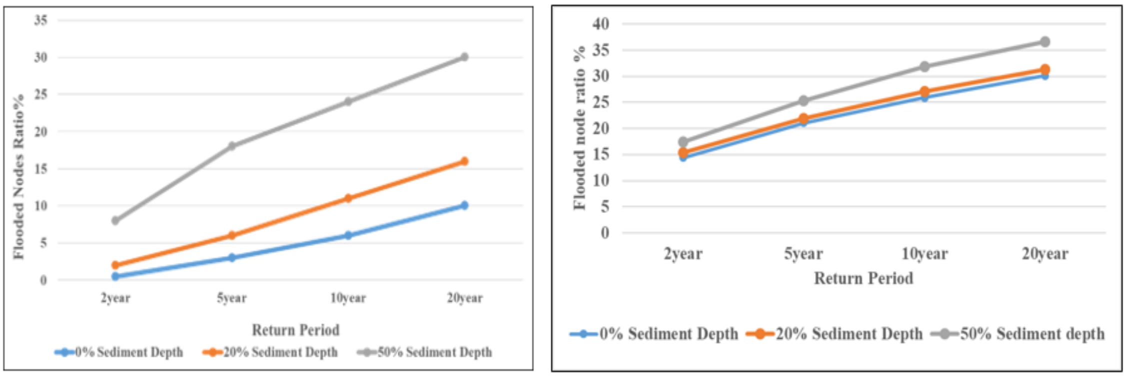

Figure 7.2 Flooded node ratio shows as a function of flood severity in Yangon (left) and Tsushima(right)

7.3.2 Open space

Open space is used for pedestrians, playgrounds for children. It can also serve as flood control places because rain water easily infiltrates there and can support for ground water recharge (Zhou, 2014). Rainwater that falls on the vegetated soil or unpaved surface is more easily infiltrated into the soil. Infiltration is the flow of water into the soil through the soil surface. There are so many parks in Tsushima study area and these facilities is effective for flood mitigation measures. There are twelve parks (about 30.2 ha in area) in the whole of Tsushima City, and two parks (about 0.3 ha in area) in the study area (source: Tsushima City website). Figure.7.3 shows the Imaichiba Park landscape, as an open space located in the center part of study area.

However, parks and open spaces in downtown area of Yangon disappeared several decades ago, because the land price of city centers is expensive and there is still weak for land use management policy. Figure 7.4 shows before and after the construction of hotels where the park situated ten years ago in the city centers of Yangon.

Figure 7.3 Imaichiba park in Tsushima

Figure 7.4 Park and green area of down town Yangon changes 2013 (left) and 2020 (right) source- Google map)

7.3.3 Drainage system

Pluvial flood occurs when the drainage capacity is not adequate to carry the surface water during short period intense rainfall (Kusumastuti.2015). In this study the classification of drainage system is divided into two types, i.e. surface and subsurface drainage. Guttering system is important for rainwater harvesting system that collect the rainfall fall on the roof surface to the drain or infiltration trenches in Tsushima city. So that, abundant water from the roof surface do not directly flow on the surface that cause pluvial flood events. The gutters system applied to buildings in Tsushima is shown in Figure7.5.

In the case of Yangon, most of the building have lack of the gutter system and a few building installed gutter and connected to open drain channels. This situation causes rainwater that flow directly on to the surface through gutter and most of the impervious surface in downtown area of Yangon cannot absorb rain water that resulted in flooding. In the context of the gutter system, there is a difference between Tsushima and Yangon cities.

Figure 7.5 Guttering system in Tsushima

Open channel drainage system

Open channel drainage system is constructed to discharge surface runoff due to rain water through inlet and drain throats. Drain system of Tsushima city is well-constructed and most of the small drain are covered with concrete to prevent the waste entering into the drain is shown in (Fig.7.6). However, some locations of drain in Yangon are not covered and some cover are deteriorated. In Tsushima, all utilities structured are well organized located within the road right of way. This approach has not been implemented in Yangon as can be seen in a number of excavations where utilities pass through existing drainage infrastructure see (Fig.7.7). These crossing have two impacts:

- Location where local blockages and debris can occur.

- Utility infrastructure such as power cables and water supply pipes can be damaged or be affected by corrosion by regular exposure to high water levels.

It is therefore recommending for Yangon the following approach:

- A corridor for the construction of stormwater drainage is allocated within the road right of way.

- The depth of cover for the new stormwater drainage is set such that utilities other than foul sewerage can easily be laid over the top of the proposed new works.

- Foul sewer construction should always be below any storm water drainage system.

- Utility diversions and repositioning are likely to be a component of the construction of the works.

Figure 7.6 Storm drain with cover in Tsushima (left) and storm drain with no cover in Yangon (right)

Figure 7.7 Utilities pipes and cables existence in Yangon drain (source-DWMA Latha)

7.3.4 Garbage clogging effects on pluvial floods

In Tsushima, big storm drain channels are open channels without cover, but we found small amount of garbage organic debris leaves and branches are found in the drain (Figure. 7.8). Some garbage is floating in the open drain, but they are trapped at the trash screen in the drain where garbage can be easily cleaned. The amount of sediment in the drains is a little when comparing the channel depth. So, current drainage system of Tsushima is work properly. In Yangon, all storm drain channels are open channels with cover, but garbage and sediment blockage is a big problem. People dispose garbage into the drainage system and the blockage reduce the drainage capacity. Most of the garbage in the open drain in Yangon are plastic, water bottles, timber and sediments (Figure.7.9). DWMA is facing this problem not only in rainy but also in dry weather condition.

Figure 7.8 Open channel storm drain in Tsushima

Figure 7.9 Garbage and sediment of open drain in Yangon (source-DWMA Latha)

7.3.5 Blockage of constructional material in the drain

One of the desludging materials in downtown area of Yangon is construction materials like sand, gravel, woods and some demolition waste from construction sites (Figure 7.10 and 7.11). I found some gravels, sands in the drainage when I collected sediment from 10 places of the study area for sediment size classification. Generally, most of the sediment size in the drain are bigger than conventional sediment size in the drain. This is a big problem in the study area because there is no strict rule and regulations for this problem and drainage engineer should supervise this problem. So, YCDC should act the rule and regulations to prevent the foreign materials into the drainage system.

Figure 7.10 Construction material extracted from the drainage (source-DWA Latha)

Figure 7.11 Construction materials, gravel and sand at the rear of drainage throats (source-DWA Latha)

7. 4. Existing flood control facilities in Yangon

The study area of Yangon has land scarcity problem for flood mitigation measures, so DWMA enlarge some drain and culvert to increase capacity(Figure.7.12).

Figure 7.12 Cross road culvert 31st street under construction February 2019

7.5. Future flood control facilities in Yangon

DWMA established drainage master plan to reduce flood severity in Yangon (Figure.7.13) (YCDC,2019). In option 1, they would like to increase current drainage capacity by enlarging the current drain. In option 2, they will build underground storage tank or big pipes to increase storage and attenuation during rainfall and increase tidal level coincide situation. In option 3, they will build big box culver or tunnels to increase storage and attenuation during rainfall and increase tidal level coincide situation. Besides, pumping stations also will construct to tackle the severe flood condition for options 2 and 3.

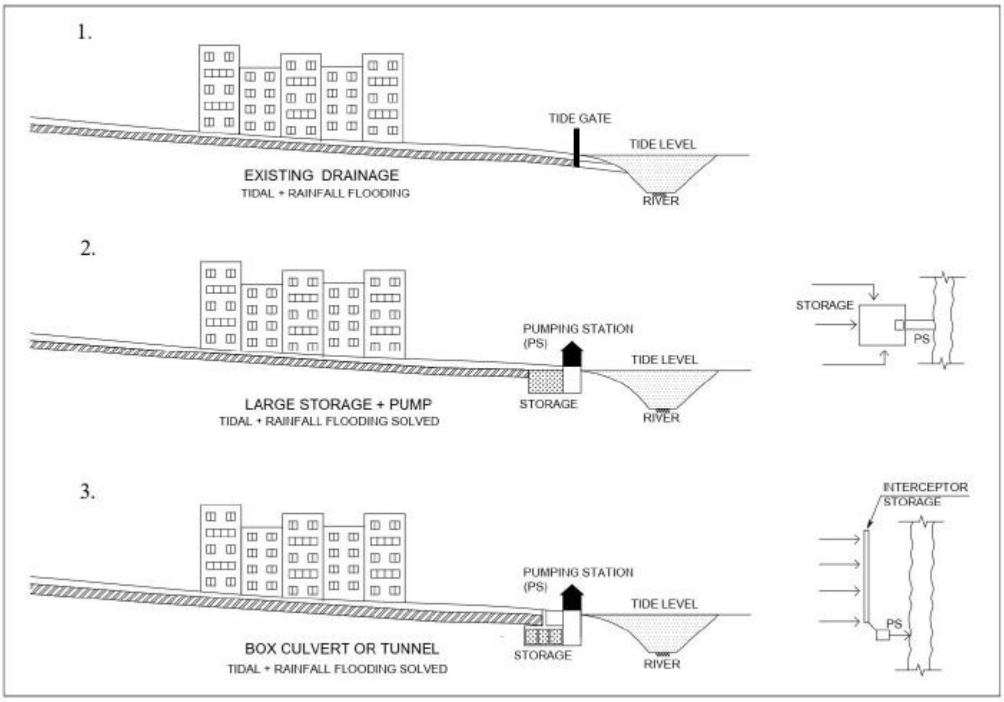

Figure 7.13 Drainage master plan for Yangon downtown area(source-DWMA)

Structural measures alone cannot mitigate increasing pluvial flood risk, although conventional structural measures, such as widening and deepening the storm drain, construction detention pond, continue to play a vital role of mitigation damages. The integrated approach includes land use regulation, sustainable urban drainage facilities, non-structural measures, and emergency response in addition to structural measures. Japan has already established good collaboration among national government, city government, academic expert and local community (Ishiwatari et al., 2018). So, Tsushima also has also well planned collaborative actions. However, DWMA prepared structural flood mitigation measures in the future, but there are so many weaknesses for nonstructural mitigation measures and weak collaboration among the departments for flood mitigation preparations. The author proposes the pluvial flood risk management governance structure of Yangon to tackle the weak collaboration among the departments (Figure.7.14).

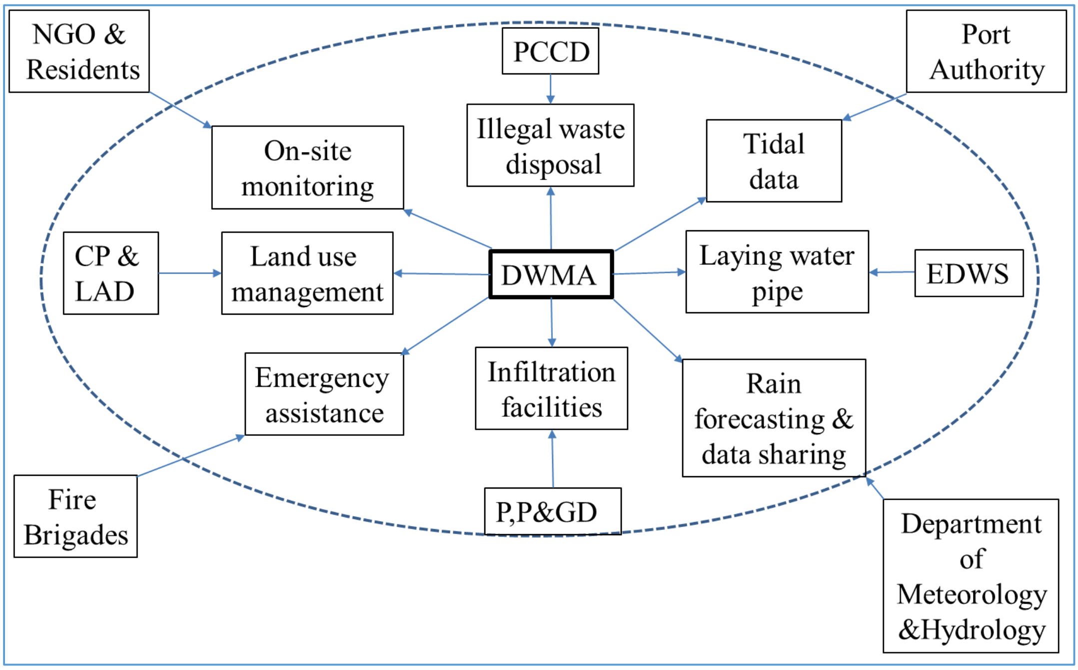

Figure 7.14 The pluvial flood risk management governance structure of Yangon

DWMA -Drainage & Wastewater Management Authority

CP& LAD-City Planning & Land Administration Department

P, P&GD -Playgrounds, Parks & Gardens Department

EDWS -Engineering Department (Water & Sanitation)

PCCD -Pollution Control and Cleansing Department

DWMA is main department for pluvial flood mitigation measures in Yangon. DWMA and PCCD should prepare for garbage and sediment dredging in Yangon to avoid overlapping activities. DWMA and CP & LAD should discuss good planning for flood adaptation and mitigation in the study area. DWMA and P, P & GD should negotiate some facilities should implement at the park and garden of study area. DWMA and EDWS should discuss to relocate water pipes and other utilities in the open drain channel to avoid garbage clogging effects and increase flood severity. Besides, DWMA should create one working group committee for flood mitigations measures with other departments of different ministries.

7.6 Existing flood control facilities in Tsushima

Some of the houses near the open channel adapts some resilient measures like elevated the plinth level of building (Figure 7.15) in Tsushima. Tsushima city authority also encourage to build the houses with special design for disaster prevention and mitigation and they hold competition for "Tsushima-type housing model" title to attract the citizen's interest for disaster mitigation in October 2014. Besides, Tsushima city authority provide subsidy to the houses for water harvesting system. So, the citizens' willingness to participate for the flood mitigation measures are increasing for their city (Tsushima city website).

Figure 7.15 Elevated houses near logger station 3 of open channel front view (left) and back view (right)

7.7. Future flood control facilities in Tsushima

In Tsushima, all open channel drainage outfall has no flood gate to control the back water effects (Figure 7.16). Zenta River is one of the receiving water bodies connected to the drainage open channels of study area. The Zenta River is one of the branches of the Nikko River System, and origins from the area in Tsushima City and flow into the Nikko River in Kanie Town (southern neighbor town of Tsushima City), having 20.4 km^2 basin area and 12.0 km mainstem length (source: Aichi Prefecture website). So, if the Zenta River level rises, storm water cannot discharge, and overflowing will occur at the upstream channels due to the backwater effect. Consequently, flood gate should install at each of the outfalls along to the Zenta River in the study area.

Figure 7.16 Outfalls conditions of Tsushima outfall 1 (left) and outfall 2(right) (Source-Google map)

7.8 Conclusions

In this chapter, the results showed that the type of flood control in Yangon city rely on structural measures and difficult to prepare sustainable urban drainage system like Tsushima city's existing flood mitigation plan because of land scarcity and inadequate technology, guideline, rule and regulations. Besides, drainage system of Tsushima is developed annually, but drainage system of Yangon is rarely maintained and developed annually for some parts of the system are seriously deteriorated. Tsushima open channels are not directly suffering water level fluctuations of receiving water bodies, but Yangon city struggles with rising tidal level in the future because it situated along the bank of Yangon river. According to the simulation results of two cities, open channel storm drainage system suffers more severe pluvial flood events than closed conduit storm drain system. The main problem in the Yangon drainage system is clogging from solid waste and sediment, overlapping responsibilities for sediment dredging of different departments, lowest level of awareness among citizens. DWMA of YCDC is working on all aspects of flood prevention and control, but economic instability is a huge drawback. They are working mainly with flood forecasting and management systems, emergency response, de-silting of main drains before and during monsoon season, cleaning garbage in the drain throat and drain, and redevelopment of drainage system. However, if illegal waste disposal is still increasing, the widening the drainage channel is not effective. So, YCDC should enforce the residents to pay fine for illegal waste disposal into the drain.

Our recommendation, for both cities, should develop the storm water systems with sustainability and resilience perspectives. However, to implement sustainable drainage system in Yangon city has some barriers like budget, technology and land scarcity. The problems in Yangon are much bigger, because of the insufficient storm water system and high rainfall, and difficult to solve this problem, as the population density is very high. In Tsushima, the low frequency of pluvial floods occurred current condition and people have good manner for illegal waste disposal into the drain. So, the houses in Tsushima city should install some resilient measures like flood proof door, and raised electricity points. In this perspective, Yangon city authority also should consider to implement not only the structural mitigation measures but also nonstructural mitigation measures for pluvial flooding.

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Chapter 8

Conclusions and Recommendation

This chapter presents the research conclusions. The chapter summarizes the research aim and objectives, including how they were approached and achieved.

8.1 Summary

The aim of this study is to assess the causes and severity of pluvial flood in cities of developed and developing countries.

The research aim was realized through four research objectives, stemming from the four research questions shown below:

Q1. Which data are preferable to track the pluvial flood?

Q2. How to identify the gap between the observed and simulation data for pluvial flooding?

Q3. What factors influence the causes and severity of pluvial flood and how do they effect in the urban drainage system?

Q4. What are the difficulties to prepare pluvial flood mitigation measures in developing country comparing with developed country's strategies?

The first question was about developing a relevant data collection method to estimate the pluvial flood event. The second one was to investigate the gap between monitoring results and simulation results by using sensing and modelling approach. The third one was to evaluate the factors influencing on pluvial flood causes and severity and analyze the effects of influencing factors on flood severity. Finally, the fourth one analyze the different mitigation measure of pluvial flood for each city current and future situation.

8.1.1 Objective 1: To track pluvial flood event by using logger data and high resolution altitude distributions

Most of the cities in the world have already established to track the flood situation for river, by using different types of sensor to measures water level variation at the river. However, tracking for pluvial flood has different barrier because this flood is difficult to predict the place and time for flood occurrence. Conventional flood event observations cannot provide the actual flood characteristics and this study propose sensing method to track the pluvial flood events.

The first objective was considered to track the flood condition in urban area (Figure 4.3, Chapter 4). The first objective was achieved by combining the logger results and high resolution terrain data (section 4.2, Chapter 4).

8.1.2 Objective 2. To introduce an effective data collection system, then these data will apply for evaluating the pluvial flood event with a simulation model results

Firstly, I interviewed the drainage engineers of each city, then install water depth loggers for flood events data. Secondly, I prepare computational domain for modelling process. Thirdly, this objective was achieved comparing logger data and simulation results Figure 2.11,2.12,2.13,2.14 and Figure 5.9,5.10,5.11,5.12. We identified pluvial flood based on these results and suggested possible causes and severities of pluvial flooding in these chapters.

8.1.3 Objective 3. To analyze flood inundation under different scenarios via the incorporation of increase rainfall and sediment depth in the drain.

First priority of the current drainage system is to check the capacity to carry the surface water into the receiving water bodies. Then to evaluate how the flood severe condition will occur due to increase rainfall intensity and sediment depth in the drain. Sediment existence in the drain is inevitable problem with the open channel drainage system for not only in developing countries but also in developed countries. But sediment existence depends on cleaning and waste management system of each city. So, we need to consider the effect of sediment in the drain for pluvial flood severity.

This objective was realized by investigating the effects of increase rainfall intensity and sediment using different factors such as surcharge state, flooded nodes and flooded area Fig.3.5and 3.6, Chapter 3) and (Fig.6.4 and 6.5, Chapter6).

8.1.4 Objective 4 To quantify and visualize the sediment effects on inundation under different rainfall intensity. This objective was fulfilled because ICM provided the inundation map for pluvial flood current and future severe cases Fig 3.4, Chapter 3 and Fig 6.3, Chapter 6)

The novelty of this study can be summarized as the following two points: assessment of sediment effects on pluvial flood inundation and introduction effective sensing method to track the pluvial flood and identify the occurrence of pluvial flood.

8.2 General discussion and recommendations

8.2.1 Monitoring pluvial flood data by using water depth logger

Several studies about pluvial flood problem have been applied the model to evaluate flood risk analysis because of climate change and increase urbanization problem. Then, they provide flood risk map for future possible severity based on simulation results. This approach is feasible for fluvial and coastal flooding, but pluvial flood is more complex and the flood plain in urban area is difficult to define because there are many building, street furniture, curb height etc. Besides, to get the actual capacity of the drainage structure and design capacity, adequate and high quality input data for model is difficult to assess. So, we cannot provide the accurate inundation map based on simulation results. In this study, the inundation map is prepared by using logger data and high resolution terrain data that provided the accurate locations and flood depth in study area. When installing the water depth sensor or flow meter in sewer system, most of the researcher install them at the manholes because flood will occur at this location. However, when installing the water depth sensor or flow meter in open channel drainage system, prediction of flood prone locations is more difficult to decide than sewer system. Overflow can occur anywhere this drainage system. So, we have to discuss the flood prone location in open channel drainage system with local drainage engineers. Besides, we need to check the characteristic of the open channel drainage system especially blockage risk location such as trash screen, grills and other blockage-prone location. Pluvial flood occurs during a short time with high rainfall intensity, so rainfall data is very important for pluvial flood analysis and rain gauges should densely install in the study area to reduce spatiotemporal rainfall data error. Besides, water depth logger also should install densely to clarify flood characteristics for pluvial flood.

8.2.2 Analysis of pluvial flood by using simulation models

Researchers used different models to analyses for pluvial flood problems. Some are open source and some are commercial that depend on wide range of capabilities, spatial and temporal resolutions. Among them EPA SWMM model is widely used for storm water management system, but it can handle only one dimensional analysis. Now other 1D 2D model are available for different purposes. In this study, I applied NILIM model to analyze the pluvial flood problem during Typhoon approach. It can provide, flood area and flood time, but some of the flood characteristics are cannot provide from this model especially detailed flood depth that will compare to water depth logger results and calibration process. So, I use Infoworks ICM model to analyze pluvial flood events in two study areas. One of the special features of this model is sediment depth effects can be considered in the drain. This feature is also important for my study because sensitivity analysis of sediment can handle by this model. Besides, this model can provide more accurate results than NILIM, so this result can be applied for decision making process in the study area.

8.3 Conclusions

The previous seven chapters elaborate causes and severity of pluvial flood based on monitoring and flood simulation with two case studies. It firstly proposed pluvial flood inundation map, which integrates water depth logger results and terrain data. Then, based on the various methods and tools, results and discussion are denoted. The research has investigated two case studies with same concerns and offers different solutions for pluvial flood risk mitigation measures and investigation process.

From the perspective of the first case study, analysis for flood event occurrence and create inundation map based on previous floods data. Identify the severity of pluvial flood due to sediment depth in the drain and evaluate the drainage capacity of storm water and combined sewer system in study area. In addition, the second case study focuses more to investigate the pluvial flood due to the increase rainfall intensity and sediment depth in the drain. The two cases are designed for same aims.

The main aim of this research was studied the causative factors of pluvial flooding, factors affecting the serious pluvial flood events and the estimate method of pluvial flood inundation map in Tsushima and Yangon city. There are consistent problems of pluvial flooding in the two study areas under investigation in Tsushima and Yangon city. These problems have become increasingly problematic in the last several years ago in two cities despite preparations for some mitigation measures by local authorities. However, the causes of the pluvial flood events are complexed and difficult to identified. So, clarification for the causes of pluvial is essential step for flood mitigation measures. Accordingly, Chapter 1 focused on conventional study for pluvial flood event and causes of pluvial flooding. Aside from identifying the aim, objectives, motivation and gap in current knowledge, this chapter showed how the research approached the problem and achieved the research objectives in terms of an appropriate method and methodology.

Chapter 2 identified the pluvial flood events in Yangon, city of developing country where complex causative factors for pluvial flood events. Monitoring and modelling methods were selected to explore the cause of pluvial flood events. The purpose behind the mixed method was to compare the results and to clarify the problems. The main deliverables of this chapter data collection methods, problem identification approach and findings for common problematic factors of pluvial flood in city of developing country.

Chapter 3 evaluated rainfall intensity and sediment depth in the drain effects on pluvial floods severity. Within case analysis were carried out using modelling approach to understand the influence effects of rainfall and sediment depth, and forecast the flood prone locations in study area. This chapter delivers the suggestions sediments effects cause severe flood situation such as increase flood prone locations and clear explanation for flood severity with and without sediment depth considerations even the same rainfall intensity used for simulation.

Chapter 4 provided to track the pluvial flood process by using logged observation data in storm drainage system and high resolution altitude distributions. The researcher then built the simulation processes and evaluate the difference between with storm drain and without storm drain effects on flood severity in the study area. Finally, the research discussed the accuracy of the model by comparing actual flooding data with spatiotemporal data collected using the new method. The main deliverables of this chapter were preparation for inundation map, evaluation for pluvial flood event during typhoon approach and open channel effects on flood severity.

Chapter 5 presented the comparison the results of modelling and water depth logger results. Moreover, the research suggested the possible causes the gap between simulation depth and flood depth at each logger station. Besides, the results of each models compared with inundation map that created based on logger and high resolution altitude distribution. The accuracy of Inforworks

ICM is better than new integrated lowland inundation model. The flood severity is related to the characteristic of drainage channel, garbage blockage and receiving water level variation in study area.

Chapter 6 highlighted the sediment effects on the pluvial flood severity in integrated drainage system especially combined and open channel system. Flood duration with high sediment depth existence is prominently longer than the without sediment existence in the drain. So, outcomes of this chapter showed sediment existence in the drain will be huge impact of flood severity.

Chapter 7 presented the analysis of two case studies for flood risk mitigation measures based on simulation and field investigation methods. Closed pipe system suffered less reduced capacity due to sediment effects than open channel storm drainage system based on simulation results of two study areas. Finally, the researcher proposes some mitigation measures for both cities with feasible solutions.

8.4 Limitations

Although the research has achieved its objectives, there were some unavoidable limitations. First, because of the data limitation such as some drainage capacity (survey data) in Yangon are not same as actual capacity because some part of the drainage is deteriorated and cannot work properly due to old system itself and blockage problem. Some small drainage channels are not included for simulation process, according to the limitation of model like NILIM that cannot consider the small channel, less than 600 mm. Flood report of the drainage department of both cities are rarely provided and there are difficult to identify the actual causes of flooding. Pluvial flood risk assessment refers to a number of inputs information with uncertainty. Besides, sometimes observed data itself could be uncertainty due to clogging effects.

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