

**MATHEMATICAL MODELLING OF WASTEWATER
COLLECTION SYSTEM IN CHA-AM MUNICIPALITY BY
USING PCSWMM**



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**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
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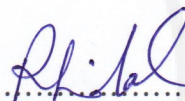
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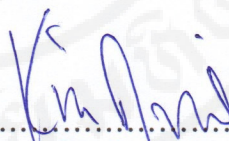
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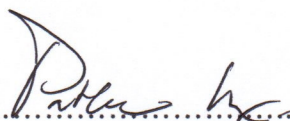
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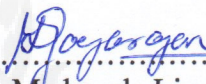
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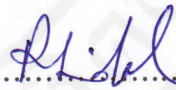
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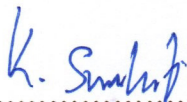
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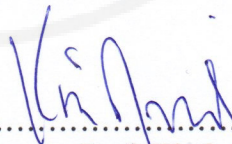
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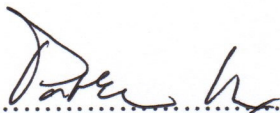
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MATHEMATICAL MODELLING OF WASTEWATER COLLECTION SYSTEM IN CHA-AM MUNICIPALITY BY USING PCSWMM

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ABSTRACT

This study aimed at modelling the wastewater collection system in Cha-Am Municipality using PCSWMM to investigate the quantity of combined sewage delivered to the aeration lagoon treatment system (ALTS) as well as to determine whether or not the capacity of the current collection system would be sufficient to convey peak flow under different land use and development scenarios in Cha-am in near future. Cha-Am is a small sea resort town in Petchaburi Province located about 175 km southwest of Bangkok and is facing increasing development so it is important to understand current system performance and plan for future build out. PCSWMM was calibrated using observed ALTS inflow data for the period 15 June to 20 July 2015. The model was validated using observed ALTS inflow data for the periods 19 July to 20 October 2015. The 1:1 lines between modeled and observed peak flow and event volume for the calibration events qualitatively showed good correspondence. The r² values between modeled and observed peak flow (99%) and event volume (89%) also were strong. The calibrated model was used to examine the quantity of wastewater discharged by the community under the proposed future development scenario in Cha-Am. Based on the model results, the quantity of wastewater discharged by proposed development area combined with old wastewater collection system did not exceed the capacity of the treatment plant.

KEY WORDS: COMBINED SEWER SYSTEM / MATHEMATICAL MODELLING / PCSWMM / WASTEWATER COLLECTION SYSTEM/

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CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Cha-Am is a small sea resort town on the west coast on the Gulf of Thailand in Petchaburi Province, situated approximately 175 km from Bangkok and about 25 km from Hua Hin, another popular sea resort town. The district was founded in 1897 in the name of Prince Na Yang. In 1914 the center of the district was moved to Ban Nong Chok (now in Tha Yang district) and its name was changed to Nong Chok District. The government office was shifted to Cha-Am and also modified the name of the district to Cha-Am after World War II (WHE, 2015).

A population of Cha-Am is approximately 53,891 people and roughly 14855 households (Census, 2010). Cha-Am is a popular address for local Thai and foreign day visitors as well as weekend visitors probably due to its long strip of beach and relatively inexpensive seafood. The population of Cha-Am increases with the number of foreign tourists who decide on spending their time for a number of weeks or even months at a time. This tends to increase the population of the town usually from September to December when the weather tends to be a little cooler. The population of the town also increases at all other times of the year, especially at weekends as tourists from Bangkok and other districts can also spend time in the town (Thai Visa, 2015).

Population growth results in increased wastewater production, leading to the situation where the environment is increasingly less capable to absorb pollution loads. This introduces a good deal of challenges to the town planners, engineers, and technologists who maintain, design, and operate wastewater and stormwater management systems. The used water from residential, commercial and industrial areas was collected by wastewater collection systems and was transferred to a place where the wastewater may be treated. However, accidental or illegal connections frequently result in invading of unwanted flows into the collection pipe network.

Unfortunately, during the heavy rain event the wastewater treatment plants operated by combined sewer systems often became hydraulically overloaded and washed out into the receiving water body causing a complete treatment system failure (Walski et al., 2007).

A failure at any point within the wastewater collection system can cause wastewater to overflow onto roads and public and/or private property and/or waterways, thereby increasing the risk of a public health hazard and contamination of the environment.

Wastewater collection systems analysis and engineering development options support by using a modelling approach to handle current and future requirements can offer enormous benefits. These benefits may include operational savings and significant capital, and more importantly an assurance that any solutions implemented, will accomplish the targeted objectives (Lind & Cantrell, 2009).

1.2 Background Information

Wastewater collection systems collect the used water from domestic, commercial, and industrial sources (as well as stormwater in many cases) and deliver them to a wastewater treatment plant and discharged directly to a receiving water body, or applied to the land for irrigation purpose, or ultimately reclaimed for recycling or reuse. There are two types of wastewater collection system, combined sewer system and separate sewer system.

A combined sewer system is designed for collecting surface runoff and wastewater (sewage) in a single pipe system. Large variations in flow between dry weather and wet weather in a combined sewer system can occur serious problems with water pollution because of combined sewer overflow (EPA, 2004). In building new communities, the combined sewer system design is modified by modern design which separates sanitary sewer from surface runoff, but many older cities continue to operate combined sewers (Metcalf & Eddy, 1972). As an effect of the Industrial Revolution, many cities in Europe and North America grew in the 19th C, often contributing to crowding and increasing worries about public health (Burian et al., 2000). As part of a

movement of municipal sanitation programs in the late 19th and 20th centuries, many cities implemented extensive sewer systems such as a separate sewer system to help control outbreaks of disease such as typhoid and cholera (Staely & Pierson, 1899).

A separate sewer system is designed to contain two different sewer pipes running one on top of the other, the sanitary pipe is under the storm pipe in most cases. The sanitary sewer pipe collects and transfers the sanitary sewage from the laterals pipe network that connected to households, businesses place, and industrial area to the treatment facilities. The stormwater sewer pipe transports the stormwater gathered from building downspouts, road inlets, and other lateral storm sewer network in a nearby receiving stream and is discharged through a Stormwater Outfall (PWD, 2015). Sanitary sewers are distinguished from open sewage collection system in that the sanitary system is constructed with enclosed pipe in order to control the contact between the sewage and the surrounding area that flow through. They are different from combined sewers system, which handle not only surface runoff derived from precipitation but also wastewater from various sources. The open sewage collection system that construct with of urban streambeds and gutters were being famous all over the world before the 20th century. Through the twentieth century there was an effort to separate sewer systems and treat and temporarily store the discharge from combined sewer. (Burian et al., 2000).

The wastewater quality and quantity in a wastewater collection system convey to a wastewater treatment facility affect the treatment efficiency and if it overflows that impact to the water quality of the receiving body. High levels of infiltration/inflow in a sewer system can decrease treatment plant efficiency and it tends to discharge high levels of pollutants into receiving water bodies. Overflows must be excluded in separate sewer systems, while in combined sewer systems they must be reduced to minimize water quality impacts (Walski et al., 2007).

Wastewater collection system models can help the modeler to know the location, time, and the reason of sewer overflow and to evaluate mitigation measures, which can increase the quality of water from sewer overflow. Models can also help in the demonstration of wastewater collection system and wastewater treatment system, whether the system has adequate capacity to handle the inflow in different situation and its effect on water quality. A modelling plan can be helpful in wastewater

collection system planning to minimize the effect of urbanization by developing different land use scenarios (Jang et al., 2007).

1.3 Objectives

The objectives of the research are-

1. To investigate the quantity of flow of Cha-am Municipality wastewater collection system delivered to the municipal treatment plant using mathematical modelling.
2. To determine whether or not the capacity of the current collection system would be sufficient to convey peak flow under different land use and development scenarios in Cha-am in near future.

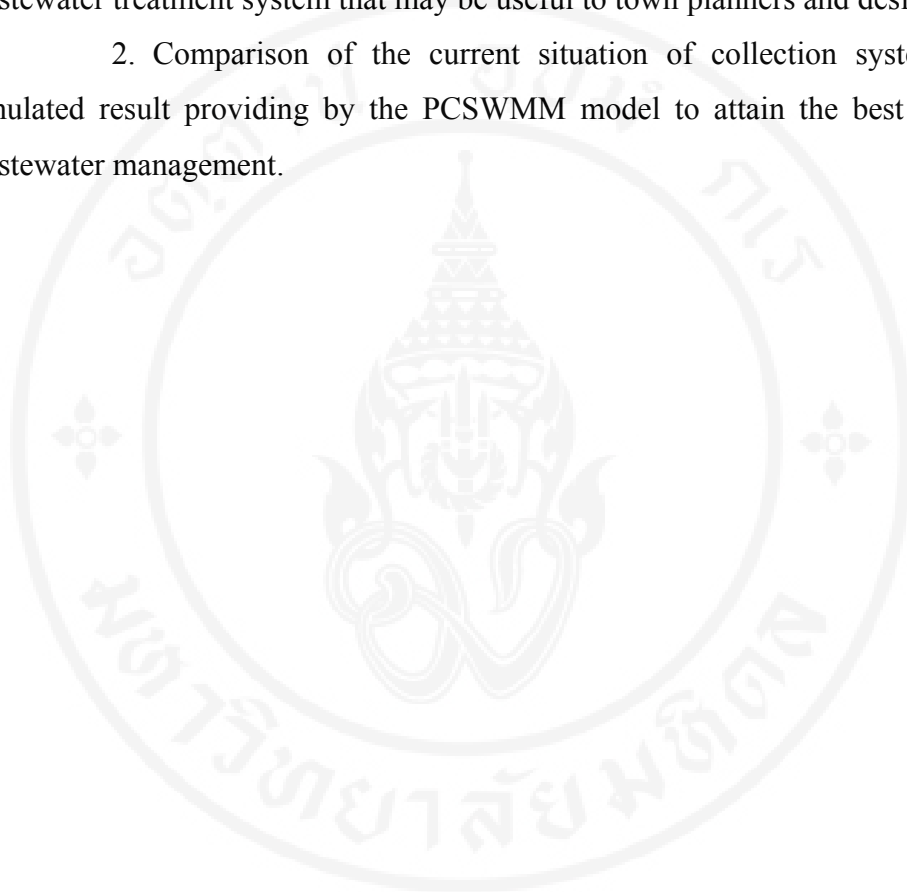
1.4 Scope

- Investigation of the quantity of flow in the current wastewater collection system in Cha Am municipality area by using PCSWMM modelling software.
- Studying of wastewater collection system by PC SWMM modeling to know the measure of the flow of wastewater collection system.
- The steps of modelling process are-
 - Defining data requirement
 - Identifying data sources
 - Data Collection (physical properties, loading data, operational data)
 - Building model
 - Calibrating model
 - Validating model
 - Developing future development scenario
 - Running model
 - Result & Discussion

1.5 Expected Results

The anticipated outcomes of the research include:

1. Obtaining information about the quantity of wastewater flow in the collection system and fluctuations in the inflow to the Cha-am municipality wastewater treatment system that may be useful to town planners and designers.
2. Comparison of the current situation of collection system with the simulated result providing by the PCSWMM model to attain the best approach of wastewater management.



CHAPTER II

LITERATURE REVIEW

2.1 Wastewater Collection Systems

Wastewater collection systems are utilized to gather and convey wastewater to a centralized or decentralized treatment plant. The collection system seems like a tree that branches out from the treatment plant to gather the liquid waste from across the system (Fig 2.1). Wastewater from single household go into the wastewater collection system through a service pipe line. Laterals or branch lines typically lay beneath the suburban streets to collect the flow from each service pipeline. They flow into bigger pipelines called mains, like a stream flows into the river. Mains lines meet to form the largest lines in the system called trunk lines. A trunk sewer line is a transmission line that does not have any mains branching off of it. The trunk line is the largest pipeline that carries wastewater into the wastewater treatment plant (Ragsdale & Specialist, 2014).

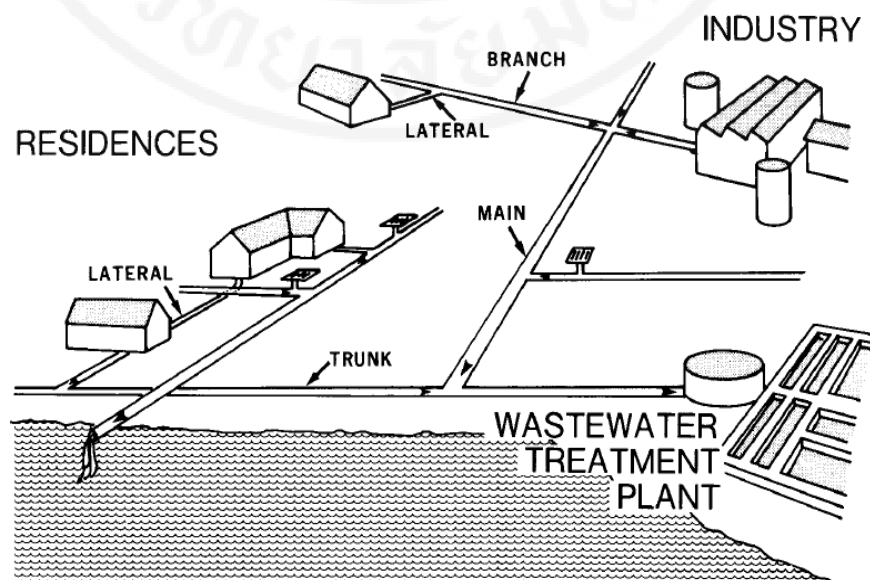


Figure 2.1 Wastewater Collection System

Manholes are installed in a wastewater collection system for the purposes to provide access for emergency service, maintenance, and inspection. It should be placed at sewer junctions or there is a change of elevation, direction or slope of a pipe line. They are typically installed 90–150 m apart to provide an adequate number of entry points for maintenance. Large pipes can have larger distances between manholes. Although they should be large enough to enter and work with, they can have harmful airs inside that can threaten workers (Ragsdale & Specialist, 2014).

Collection lines are set with a downhill slope that lets the flow to travel along the system using gravity force. This minimizes the necessity of pumping station that must take place to force the wastewater to the treatment facilities. The slope should be set to keep minimum self-cleaning velocity 0.6 to 0.75 ms^{-1} in the pipe line. In a wastewater collection system, lifting station are installed where the sewer lines reach a certain depth the flow must be raised. The sewage then flows again by gravity to the next pumping station or until it reaches its destination (Ragsdale & Specialist, 2014).

It is also important for the wastewater collection systems to handle peak flow conditions for both dry and wet weather conditions. The pipe size and type, and the downhill slope of the pipeline control the quantity of flow that a collection line can manage. A wastewater collection system should also be planned to handle the infiltration and inflow which may occur when groundwater invades the system through leaking joints or cracked pipe in wet weather conditions. The wastewater collection system directly receives the inflow from the surface runoff (e.g. flooding road), inundated manhole covers, and illegal service connections that direct stormwater flows into the system. The leakage of sewage from the cracked pipeline may occur the exfiltration of wastewater into the adjacent soil. The inflow and infiltration that unintentionally enter the system can control through local sewer use regulations (Ragsdale & Specialist, 2014).

Flows in wastewater collection systems are commonly divided into two types. Wastewater (also known as dry weather) flows, that might generated from commercial, residential, industrial, or commercial sources, are the intentional discharges into the collection system. Wastewater collection systems also receive infiltration and inflow (I/I), which mainly from precipitation. The wastewater flow in a

wastewater collection system during the dry weather periods with minimum infiltration is known as dry weather flow. The retention time of the wastewater in the collection network was increasing, that can occur unwanted sedimentation of solid particles and unwanted chemical and biological reactions, due to inadequate flow rates during dry weather periods if pipes and channels are not designed correctly (GTB, 2015). Wet Weather Flow generally refers to the snowmelt or stormwater runoff that contributes directly to a combined sewer system, or to the flow in excess of dry weather flow that enters a separate sanitary drainage system through defects in the manholes or pipes. When the extreme rainfall occur, the water result from rainfall may exceed the capacity of the wastewater collection system that result to overflows the untreated wastewater into the environment. This can negatively affect environmental through pollution and inundating. Wet weather flow pollutants discharges from many sources remain largely uncontrolled. The urban wet weather flow discharge can be divided into two types: Combined Sewer Overflow (CSO), Sanitary-Sewer Overflow (SSO) (EPA, 2014).

Even though most waste water collection systems are intended to operate partially full gravity flow, there are five types of flow conditions in reality that can occur in a wastewater collection system, as illustrated in Figure 2.2.

- Partially full gravity flow –the pipe with a free water surface inside.
- Surcharged gravity flow – the pipe crown is below the depth of flow in the gravity pipe as a result of a downstream control.
- Pressure flow in force mains – wastewater is pushed along stretches where the sewage cannot flow by gravity.
- Pressure sewers – each client has a pump that pushed the sewage to a pressure sewer.
- Vacuum sewers –vacuum pumps pull the flow through the sewer system.

Even though most collection system pipes fall into the first category, systems can have a combination of all five types of flow (Walski et al., 2007).

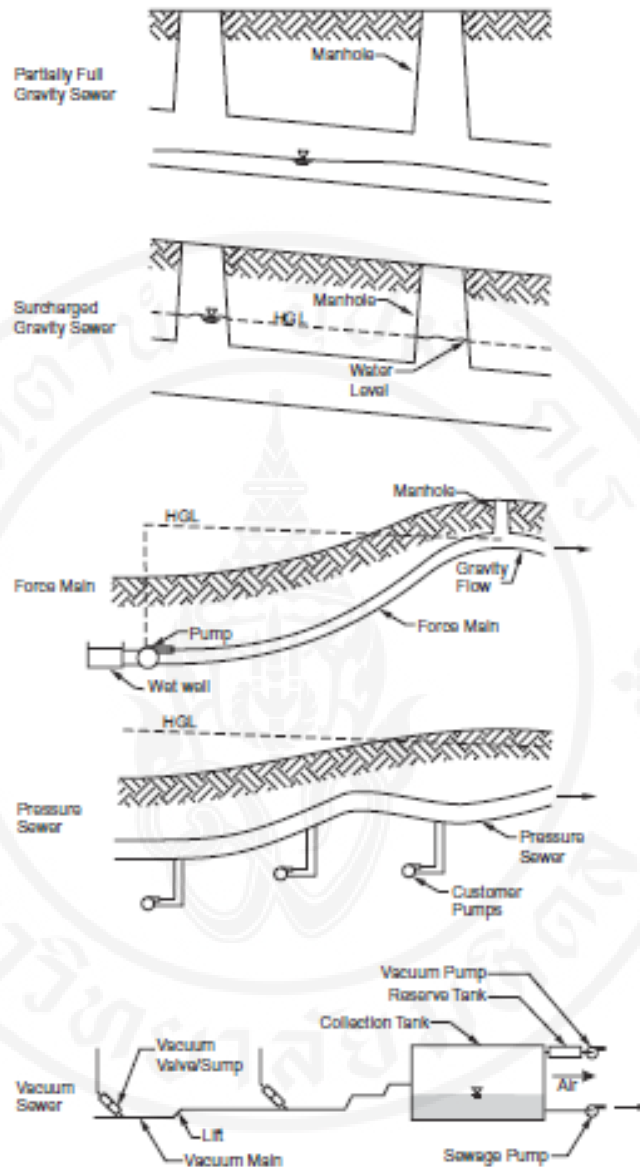


Figure 2.2 Flow condition found in various type of sanitary sewer

2.1.1 Combined Sewer System

The combined sewer system consists of large networks of pipes laying underground that transport sewage from private homes, wastewater from industrial and commercial area and stormwater runoff in the single pipe system to a wastewater treatment plant (WWTP) as shown in Figure 2.3. They are mostly found in older urban area. They carry all of the combined sewage to a WWTP where it is managed or treated and discharged to a receiving water body. The wastewater collection system must be planned to keep self-cleansing velocity (i.e. a flow that will not settle the

particles the contained in the wastewater), commonly achieved with a minimal flow of 0.6 to 0.75m/s, because the wastewater is not treated before it is transported.

A constant downhill slope must be assured along the length of the sewer line to achieve self-cleansing velocity. A pump station or lift station must be installed when the required slope cannot be enough to transport the wastewater by gravity. The main sewer lines are set up beneath the roads with 1.5 to 3 m minimum depth to avoid unwanted damages that might be caused by traffic loads. Access manholes are installed at regular intervals along the sewer, at intersections of the pipes, at changes in sewer line direction and at changes in gradient or alignment. The ultimate health and environmental impacts are determined by the treatment provided by the downstream wastewater treatment facility. The initial cost and maintenance cost are high compared to decentralized systems and consists mainly of inspection, unblocking and repair. The system expansion can be costly and difficult. They are appropriate for urban areas with resources to implement, maintain and operate the system and also suitable when the area have the centralize treatment facility. Planning, construction, operation and maintenance of combined sewer system requires expert knowledge. There might have a performance problem related with infiltration/inflow (Tilley et al., 2014).

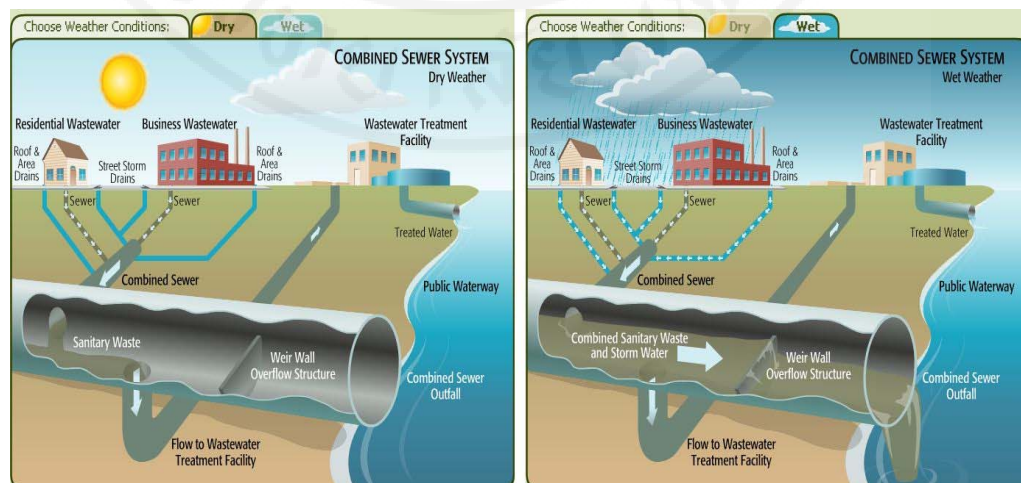


Figure 2.3. Combined Sewer System

Source >> www.hkywater.org

Figure 2.4 shows the combined sewer over flow pipe to the canal in Cha-Am during dry weather condition. It is located near fresh market just beside the canal.



Figure 2.4 Combined sewer pipe flow to the canal

2.1.2 Separate Sewer System

Separate sewer systems are designed to collect stormwater and wastewater in separate pipes system as showed in Figure 2.5. The sanitary sewer systems gather and convey sanitary sewage from various sources while the storm sewer systems gather and convey stormwater runoff that come from precipitation. Sanitary sewer systems may also receive unwanted wet weather flow via illegal connections from storm sewers or house drains, as well as through manholes and pipe cracks. As two separated pipe networks are required in the separate sewer system, the construction cost of separate sewer system higher than the combined sewer system. They offer a high level of hygiene and comfort in public. The sanitary sewage is conveyed in a closed pipe system directly to the WWTP and cannot overflow into the surrounding in a properly constructed separated system. Especially suitable in areas where irregular, heavy rainfall is expected to avoid frequent combined sewer overflows (Stauffer & Spuhler, 2012).

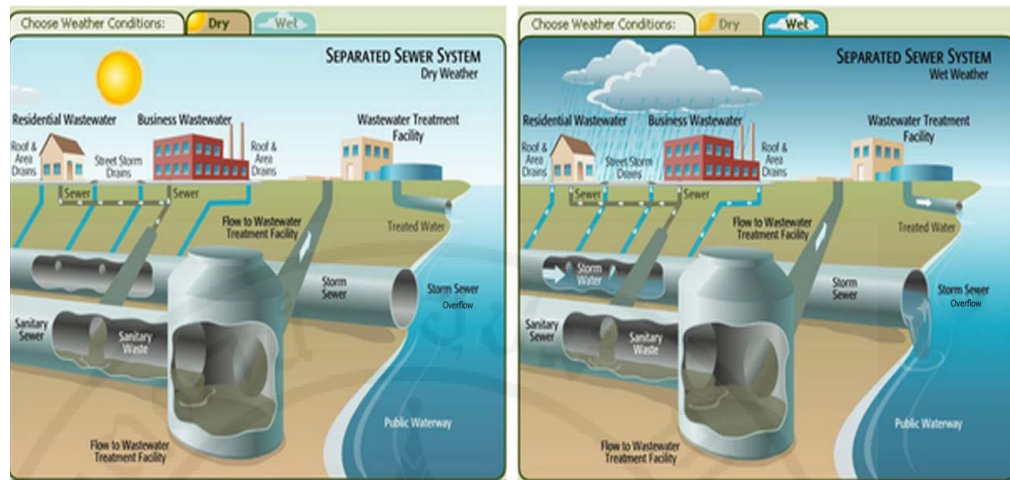


Figure 2.5. Separate Sewer System

Source >> www.hkywater.org

2.2 Advantages and Disadvantages of Combined and Separate Sewer System

(a) Combined Sewer System

The advantages and disadvantages of combined sewer system are:

| Advantages: | Disadvantages: |
|--|--|
| <ul style="list-style-type: none"> • Convenience (minimal intervention by users) • Low health risk not if there is an overflow • No nuisance from smells, mosquitoes or flies • <u>Stormwater</u> and <u>greywater</u> can be managed at the same time • Moderate operation and maintenance costs | <ul style="list-style-type: none"> • Difficult to construct in high-density areas, difficult and costly to maintain • Recycling of nutrients and energy becomes difficult • Unsuitability for self-help, requires skilled engineers and operators • Problems associated with blockages and breakdown of pumping equipment • Adequate treatment and/or disposal required |

(b) Separate Sewer System

The advantages and disadvantages of separate sewer system are:

| Advantages: | Disadvantages: |
|---|---|
| <ul style="list-style-type: none"> • Surface run-off, <u>greywater</u> and <u>blackwater</u> can be managed separately • Limited of sewage overflow • Low health risk • No nuisance from smells, mosquitoes or flies • No problems related to discharging industrial wastewater • Moderate operation costs • Surface run-off and rainwater can be reused (e.g. For landscaping or agriculture) | <ul style="list-style-type: none"> • Difficult to construct in high-density areas, difficult and costly to maintain • High capital costs • Requires skilled engineers and operators • Problems associated with blockages and breakdown of pumping equipment • Adequate treatment and/or disposal required • Higher risk of water pollution by accidents |

Source >> Sustainable Sanitation and Water Management (SSWM)

2.3 Mathematical Modelling

An explanation of a system using mathematical equation and concepts is known as a mathematical model. Mathematical modelling is the procedure for developing mathematical model. It is also a physical or mathematical representation to describe the construction or operation of something. There are various types of models regarding to wastewater collection system.

- A mathematical model is an equations set that defines specific physical process. The Manning equation, it is one of the mathematical expressions that describe the relation between size, velocity, surface roughness, and hydraulic grade line slope in pipe or channel. It can be solved either logically or statistically.

- A computer package demonstrating a physical system that come close to or mirrors exact performances of that system are called a computer model. It generally consists of one or more mathematical models inside the computer package. For example, a computer program such as PCSWMM can model flow, volume, and velocity in a wastewater collection system.
- The model that consists of the computer model together with all compulsory data for a specific system is called a system model.

Using mathematics to realize a condition in the real system, after that maybe use it for taking action or even for predicting the coming situation, both the ensuing mathematics and the real-world situation are considered in earnest. The questions and the circumstances related with them may be any scope from big to small. The process of “interaction” between the mathematics and the real world is the same even though the problem is big or small: the actual condition usually has so many aspects that we cannot take everything into account, so we choose which facets are most essential and hang onto those. Firstly, we have a perfect form of the real-world condition, which we can translate into mathematical terms. We have a mathematical model of the idealized question now. We apply our mathematical knowledge and instincts to the model, and gain interesting insights, examples, theorems, approximations, and algorithms. We interpret this into the real-world condition, and we then have a theory for the idealized question. But we have to check back: (a) the results are practical or not, (b) reasonability of the answers and (c) acceptableness of the consequences. It would be great if all are okay! If not, we have to take another look at the selections we made at the first time, and try again. This whole procedure is called mathematical modeling (Gould et al., 2012). Forecasting of the future behavior of the real-world condition using mathematical equation is what we called mathematical modelling.

Mathematical models are applied in many areas, for example, natural philosophy, biology, earth science, weather forecasting, computer science, artificial neural network, economics, psychology, sociology, and political science etc. Physicists, engineers, statisticians, operations research analysts, and economists use mathematical models most extensively. By using mathematical model, it may support

to clarify a system and learning the effects of different components, and to make predictions about behavior that might come in the future.

A mathematical description of a real sewer system is known as a sewer network model. The design engineers, wastewater system managers, and the town planners used a sewer network model to simulate the condition of existing and proposed sewers system under a various development and scenarios. The sewer network model can be helpful to evaluate expansion of existing systems, various designs in new sewer systems, degraded systems and the rehabilitation of overloaded in the system, and the operation of sewer networks. The sewer system model simulation could also help designers to evaluate the trade-offs between options and decide a cost-effective design that meets the aims of owner of the system (Walski et al., 2007).

2.4 Sanitary Sewer Model

Sanitary sewer models are used for the purpose to conduct long-range master planning, design purpose, rehabilitation of the system, operational analysis, water quality studies, regulatory compliance and capacity assessments. The calibration, development and maintenance of a model include a continuous procedure for the wastewater collection system operator. Some applications are described below.

Long-Range Master Planning. Master planning projects may include projecting system growth and sewer flows up to twenty years or more. A model can be used in order to classify probable difficulties (e.g. sanitary sewer overflow locations or inadequate flushing velocities) and to stage, size, and locate the construction of new trunk lines and pumping stations in concert with growth and development. This type of study usually involves trade-offs between size (cost) of facilities and the ability to handle future loads. During these studies, alternative configurations and cost estimates are developed. Long-range planning usually involves projecting when sewers will be installed in a drainage basin, what flow will be generated from that basin, and when facilities should be brought on line. Analyses often involve trade-offs between small

facilities needed to serve the initial customers in a basin vs. much larger facilities needed to serve that basin on full buildout (Walski et al., 2007)..

Design. In the expansion of current systems or the design of new sewer systems, hydraulic models simulate the performance of the specific components and the whole collection system. During the design process alternatives, numerous configurations, and loadings may be calculated to define the size of the pipes, raise of the pipes, and position of the pipes. Checking the pipe size or the proposed pump performance under future conditions are examples of the usage of the model in the design purpose (Walski et al., 2007).

Rehabilitation. In a rehabilitation study, a model may be used to quantify degraded hydraulic performance caused by I/I, partially blocked lines, and collapsed structures. The extent of improved hydraulics resulting from fixing or replacing degraded structures or installing relief sewers can be determined. Models can be used to identify areas where I/I reduction can lead to reduction or elimination of overflows. Model results are used both to define short-term repairs and to develop a cost-effective, long-term rehabilitation plan (Walski et al., 2007).

Operations and Maintenance. Models can help operations and maintenance staff identify the effects of proposed actions. With a model, it is possible to test the effects of changes to pump-on and pump-off settings in wet wells, control settings of variable-speed pumps, and the operation of flow-control structures before such actions are implemented (Walski et al., 2007).

Water-Quality Studies. A sewer network model may be used to provide input or be incorporated into a watershedwide water-quality model. The sewer network model quantifies the flows (quantity and frequency) and loads of contaminants discharged to surface waters. It can then be used to improve operation and reduce frequency and volume of overflows. Linkage may be dynamic or the sewer network model may be run separately and the output imported into the water-quality model (Walski et al., 2007).

Regulatory Compliance. In the United States of America, operators of wastewater collection systems are required to demonstrate that their systems have adequate capacity. Utility operators may demonstrate compliance with these regulatory requirements using hydraulic sewer models. For combined sewers or

systems where overflows occur, operators may need to quantify the frequency and duration of the overflows. The network model used for this analysis must adequately quantify I/I, and may need to simulate as much as a year's operation (Walski et al., 2007).

2.5 Modelling Tools (EPA SWMM and PCSWMM)

The Storm Water Management Model (SWMM) that was developed by the U.S. Environmental Protection Agency is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of stormwater runoff quality and quantity from mainly urban areas. The runoff component of SWMM runs on a collection of subcatchment areas that obtain rainfall and create surface runoff and contaminant. The routing portion of SWMM carries this surface runoff through channels, a pipe networks, treatment/storage structure, regulators and pumps. SWMM tracks the quality and quantity of runoff generated within each sub-catchment, and the flow depth, flow rate, and quality of water in each channel and pipe during a simulation period involved multiple time steps.

In 1971, EPA SWMM was first developed, and has since experienced various major improvements since then. It remains to be extensively used all over the world for analysis, design and planning associated to rainfall runoff, sanitary sewers network, combined sewers network, and other drainage systems in urban areas as well as in non-urban areas with many usage. The recent update, Version 5, is a complete re-write of the earlier release. Running under Windows, SWMM 5 provides an integrated environment for editing study area input data, running hydraulic, hydrologic and simulations of water quality, and a variety of formats to viewing the results of the model running. These contain conveyance system maps, color-coded drainage area, time series graphs and profile plots, tables and statistical frequency analyses (EPA, 2015).

PCSWMM is a completely contained urban wastewater and drainage system modeling package, without limitations on size of the model or complexity. PCSWMM covers a whole GIS system tailored to urban wastewater and drainage

modeling which supports most datums, projections, and ellipsoids, offers collaboration with a various GIS formats, as well as topological operations and querying.

PCSWMM offers innovative types of all of the typical urban drainage modeling visualization techniques, including animated energy grade line and hydraulic grade line profiles, animated thematic rendering and plan-view static, powerful plotting tools, as well as on-the-fly statistical, calibration and error analysis.

With thousands of users in over 70 countries, PCSWMM has been the software of choice in tens of thousands of water quantity and quality modeling projects for LID/BMP source control, major/minor drainage design, RDII reduction, real-time control optimization, floodplain analysis, capacity management, real-time flood forecasting and master planning. PCSWMM uses the open-source US EPA SWMM5 engine and popular formats for all data for all hydraulics/hydrology calculations.

PCSWMM accounts for various hydrologic processes by integrating the official US EPA SWMM5 engine, that produce runoff from urban and rural areas. These include:

- Standing surface water evaporation
- Spatially varying and Time-varying rainfall
- Snow melting and accumulation
- Permeation of rainwater into unsaturated soil layers
- Rainfall interception from depression storage
- Infiltrated water percolation into groundwater layers
- Interflow between the drainage system and groundwater
- Overland flow nonlinear reservoir routing
- Adjacent areas derived run-on
- Runoff storage and infiltration from low impact development (LID)

devices

PCSWMM also include a flexible set of hydraulic modeling abilities that can be used to route rainfall-dependent infiltration/ inflow (RDII), runoff, dry weather sanitary flow (DWF), and external inflows through the drainage system network of channels, pipes, diversion structures and treatment/storage units. These contain the ability to:

- use a wide range of typical open and closed conduit shapes as well as natural channels.
- model different components such as treatment/storage units, culverts, pumps, flow dividers, orifices and weirs.
- apply water quality inputs and external flows from groundwater interflow, surface runoff, dry weather sanitary flow (DWF), rainfall-dependent infiltration/ inflow (RDII), and user defined inflows.
- utilize either full dynamic wave or kinematic wave flow routing methods
- model several flow systems, such as surcharging, backwater, surface ponding, and reverse flow.
- apply priority-based, dynamic control rules to simulate the operation of orifice openings, pumps and weir crest levels.

In addition to modeling the generation and transport of runoff flows, PCSWMM can also estimate the production of pollutant loads associated with this runoff including:

- contaminant wash off from precise land uses during rainfall occur
- direct impact of rainfall sworm testimony
- dry-weather contaminant accumulation over different land uses
- decrease in dry-weather accumulation caused by street cleaning
- entry of dry weather sanitary flows and user-specified external inflows at any point in the drainage system
- reduction in wash off load due to BMPs/LIDS
- routing of water quality component through the drainage system
- reduction in component concentration through treatment in storage units or by natural processes in channel and pipes

PCSWMM has been the chosen spatial decision support system for EPA SWMM for over 25 years. PCSWMM has been widely used in tens of thousands of combined and separated wastewater collection system, stormwater and watershed studies in over 70 countries around the world since its inception in 1984. Equally suited to both design, construction, analysis and management, PCSWMM's most common applications include:

- Dual drainage design
- Detention pond design
- Existing storm/ sanitary/ combined sewer remediation
- Real-time control optimization
- Wasteload allocation studies
- Low impact development analysis (LID)
- Floodplain Analysis
- Integrated catchment/ watershed management modelling
- Rainfall processing and design storm analysis

2.6 Laws and Regulation

2.6.1 United States Laws and Regulations

Until the middle of the twentieth century, water pollution was mainly considered a state and local problem. No federal objectives, goals, limits, or even guidelines existed. Initially, federal involvement was in enforcement and was strictly limited to matters involving interstate waters, but only with the consent of the state in which the pollution originated.

The first federal legislation pertaining to water pollution was the Rivers and Harbors Act of 1899, which prohibited the dumping of any material other than sewage or runoff into navigable waterways without a permit from the U.S. Army Corps of Engineers (Zwick and Bernstock, 1971). Beginning in the middle of the twentieth century, a number of legislative statutes have been put in place in an effort to reduce water pollution and improve water quality.

Clean Water Act

While the 1948 FWPCA provided federal assistance to municipal dischargers, the subsequent amendments extended federal involvement to enforcement programs for all dischargers. During this period, federal authority was extended to contain not only navigable interstate waters, but intrastate waters as well. In 1965, water quality standards also became a feature of federal law through the

Water Quality Act, which required states to set standards for interstate waters that would be used to determine actual pollution levels (Copeland, 1999). Table 2.1 lists the dates of CWA legislation and subsequent major amendments.

Table 2.1 Clean Water Act and Amendments (from Copeland, 1999)

| Year | Act | Public Law # |
|-------------|---|---------------------|
| 1948 | Federal Water Pollution Control Act | P.L. 80-845 |
| 1956 | Water Pollution Control Act of 1956 | P.L. 84-660 |
| 1961 | Federal Water Pollution Control Act Amendments | P.L. 87-88 |
| 1965 | Water Quality Act of 1965 | P.L. 89-234 |
| 1966 | Clean Water Restoration Act | P.L. 89-753 |
| 1970 | Water Quality Improvement Act of 1970 | P.L. 91-224, Part I |
| 1972 | Federal Water Pollution Control Act Amendments | P.L. 92-500 |
| 1977 | Clean Water Act of 1977 | P.L. 95-217 |
| 1981 | Municipal Wastewater Treatment Construction Grants Amendments | P.L. 97-117 |
| 1987 | Water Quality Act of 1987 | P.L. 100-4 |

U.S Federal Regulation

The United States Code of Federal Regulations (CFR) is the codification of the general and permanent rules published in the Federal Register by the executive departments and agencies of the Federal Government. Regulations of the Environmental Protection Agency (EPA) are located in Title 40 of the CFR. Many states have adopted the federal regulations either in whole or with minor modifications.

Table 2.2 presents a list of the most important EPA regulations applicable to sanitary sewers. For example, 40 CFR 35 specifies the maximum allowable rates for inflow and infiltration. Strictly speaking, these allowable rates are only applicable to recipients of grants under the CWA. However, they have evolved into de facto standards for sewer systems where alternative infiltration and inflow rates are not justifiable by engineering and economic evaluations. Other related regulations found in 40 CFR 122 are associated with National Pollutant Discharge Elimination System (NPDES) permits, which are described in the next subsection (USEAP, 2003).

Table 2.2 Important Federal regulations concerning sewers

| Citation | Title and Applicability | Regulation Text |
|----------|--|--|
| 35 | Inflow and Infiltration | 35.2005(a) (16) Excessive inflow/infiltration. The amounts of inflow/infiltration which can be economically excluded from a sewer system as determined in a cost-effectiveness analysis that compares the costs for correcting the inflow/infiltration conditions to the total costs for transportation and treatment of the inflow/infiltration. |
| 35 | State and Local Assistance; Standards applicable to recipients of federal financial assistance | 35.2120(b) Inflow. If the rainfall-induced peak inflow rate results or will result in chronic operating problems during rainfall events, or the rainfall-induced total flow rate exceeds 275 gpcd during storm events, the applicant shall perform a study of the sewer system to determine the quantity of excessive inflow and to propose a rehabilitation program to eliminate the excessive inflow. All cases in which facilities are planned for the specific storage and/or treatment of inflow shall be subject to a cost-effectiveness analysis. (c) Infiltration. (1) If the flow rate at the existing treatment facility is 120 gpcd or less during periods of high groundwater, the applicant shall build the project including sufficient capacity to transport and treat any existing infiltration. However, if the applicant believes any specific portion of its sewer system is subject to excessive infiltration, the applicant may confirm their belief through a cost-effectiveness analysis and propose a sewer rehabilitation program to eliminate the specific excessive infiltration. |

Table 2.2 Important Federal regulations concerning sewers (cont.)

| Citation | Title and Applicability | Regulation Text |
|-----------------|--|---|
| 122 | NPDES Permitting; Information required in an NPDES permit application for new and existing POTWs | 122.21(j) (vii) Collection system. Identification of type(s) of collection system(s) used by the treatment works (i.e., separate sanitary sewers or combined storm and sanitary sewers) and an estimate of the percent of sewer line that each type comprises. 122.21(j) (viii) Outfalls and other discharge or disposal methods. Extensive list of information required for each outfall. |
| 122 | NPDES Permitting; Stormwater discharges-prohibits cross connections between storm and sanitary sewers | 122.26(b) (2) Illicit discharge means any discharge to a separate municipal storm sewer that does not consist entirely of stormwater. |

Table 2.2 Important Federal regulations concerning sewers (cont.)

| Citation | Title and Applicability | Regulation Text |
|----------|---|--|
| 122 | NPDES Permitting; Conditions applicable to all permits | <p>122.41(d) Duty to mitigate. Permittee shall take all reasonable steps to minimize or prevent any discharge.</p> <p>122.41(e) Proper operation and maintenance. The permittee shall at all times properly operate and maintain all facilities and systems of treatment and control (and related appurtenances) which are installed or used by the permittee to achieve compliance with the conditions of this permit. Proper operation and maintenance includes adequate laboratory controls and appropriate quality assurance procedures. This provision requires the operation of backup or auxiliary facilities or similar systems which are installed by a permittee only when the operation is necessary to achieve compliance with the conditions of the permit.</p> <p>122.41(l)(6) Twenty-four hour reporting. The permittee shall report any noncompliance which may endanger health or the environment. Any information shall be provided orally within 24 hours from the time the permittee becomes aware of the circumstances.</p> <p>122.41(m)(4)(i) Prohibition of bypass. Bypass is prohibited.</p> |

*Citation number denotes part of 40 CFR (Code of Federal Regulations).

National Pollutant Discharge Elimination System Permits.

Title IV of the CWA created the National Pollutant Discharge Elimination System (NPDES) for permitting wastewater discharges (Section 402).

Under NPDES, all facilities that discharge pollutants from any point source into waters of the United States are required to obtain a permit, which is a license for a facility to discharge a specified amount of a pollutant into a receiving water under specified conditions. More than 65,000 industrial and municipal dischargers must obtain NPDES permits from the Environmental Protection Agency (EPA) or qualified states. Currently, 44 states and one territory are authorized to implement the NPDES program on behalf of the EPA.

The NPDES permit program provides two levels of control: technology-based limits (based on the ability of dischargers in the same industrial category to treat wastewater), and water-quality-based limits (if technology-based limits are not sufficient to provide protection to the receiving water body). Sewage treatment plants with NPDES permits are required to submit information on their collection systems, including documentation on system operation and maintenance, and reporting on noncompliance with permit requirements.

The two basic types of NPDES permits issued are individual and general permits. An individual permit is specifically tailored to an individual facility and is usually used for more distinct and complex dischargers. Once a facility submits the appropriate application(s), the permitting authority develops a permit based on information in the application, such as type of activity, nature of discharge, and receiving water quality. The authority issues the permit to the facility for a specific time period (not to exceed five years), with a requirement that the facility reapply before the expiration date.

General permits offer a cost-effective option to permitting agencies addressing a large number of facilities under a single permit. These permits typically cover categories of point sources having common elements, such as stormwater point sources, facilities that involve the same or substantially similar types of operations, facilities that require the same permit conditions, or facilities that require the same or similar monitoring.

The initial focus of the NPDES program was on treatment technology and contaminant-specific effluent limitations. Since then, two trends have developed. The first is an increase in the administrative requirements for permittees, including the development of management plans, record keeping, reporting, and public

participation. Second is that the NPDES requirements have expanded from covering the discharge and treatment method to addressing the entire collection system.

Combined Sewer Overflow (CSO) Control Policy.

Section 502(4) of the CWA defines a combined sewer system (CSS) as a wastewater collection system, owned by a state or municipality, which conveys sanitary wastewaters (domestic, commercial, and industrial) as well as stormwater through a single-pipe system to a publicly owned treatment works (POTW). A combined sewer overflow (CSO) is the discharge from a CSS at a point before the POTW.

The US EPA issued the National Combined Sewer Overflow Control Strategy on August 10, 1989 (54 FR 37370). This strategy reaffirmed that CSOs are point-source discharges subject to NPDES permit and CWA requirements. The EPA then issued the Combined Sewer Overflow Control Policy on April 19, 1994 (US EPA, 1994) as a national framework for CSO control through the NPDES permitting program. The Policy provides guidance to municipal, state, and federal permitting authorities for meeting the CWA's pollution control goals in a flexible, cost-effective manner.

The four key principles of the CSO Control Policy are:

- Clear levels of control to meet health and environmental objectives
- Site-specific considerations to assure flexibility for developing the most appropriate solution
- Phased implementation of CSO controls to accommodate a community's financial capability
- Review and revision of water quality standards during CSO control plan development to account for wet weather impacts.

NPDES permit conditions for CSOs require an accurate characterization of the adjoining sewer systems to demonstrate adequate implementation of the following nine minimum control measures:

- Proper operation and regular maintenance programs for the sewer system

- Maximum use of the collection system for storage
 - Review and modification of pretreatment requirements
- to mitigate CSO impacts
- Maximization of flow to the POTW for treatment
 - Elimination of CSOs during dry weather
 - Control of solid and floatable materials in CSOs
 - Pollution prevention
 - Public notification of CSO occurrences and CSO impacts
 - Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls.

Permittees with CSOs must submit documentation addressing each of the measures and are responsible for developing and implementing long-term CSO control plans that will ultimately result in compliance with the requirements of the CWA. The long-term plans should consider the site-specific nature of CSOs and evaluate the cost effectiveness of a range of control options and strategies. The selected controls should be designed to allow cost-effective expansion or retrofitting. The minimum elements of the long-term control plan are:

1. Combined sewer system characterization, monitoring, and modeling
2. Public participation
3. Sensitive area analysis
4. Evaluation of alternatives
5. Cost and performance considerations
6. Operational plan development
7. Existing POTW treatment maximization
8. Implementation schedule development
9. Postconstruction-phase compliance monitoring.

Sanitary Sewer Overflow Proposed Rule.

A sanitary sewer overflow (SSO) is defined as an overflow, spill, release, or diversion of wastewater from a sanitary sewer system. SSOs do not include combined sewer overflows (CSOs) or other discharges from combined sewers. On January 4, 2001, the US EPA published proposed rules that address NPDES permit requirements for municipal sanitary sewer systems and SSOs. On January 24, the SSO Proposed Rule was withdrawn to give the new administration an opportunity to review it (US EPA, 2001). In the meantime, several state regulatory agencies officially adopted the SSO Proposed Rule, and portions of the rule frequently appear in regional EPA enforcement mechanisms. Even without adoption of the SSO Proposed Rule by the EPA, any discharge of wastewater from a collection system at a point not allowed under the NPDES permit is prohibited and is subject to enforcement.

The SSO Proposed Rule (US EPA, 2001) defines SSOs as:

- Overflows or releases of wastewater that reach waters of the United States
- Overflows or releases of wastewater that do not reach waters of the United States
- Wastewater backups into buildings that are caused by blockages in a sanitary sewer other than a building lateral.

Some wastewater utilities have expressed the view that the EPA has exceeded their authority under the CWA to include releases in the definition that do not reach waters of the United States. The CWA only prohibits SSOs that reach waters of the United States.

Under the SSO Proposed Rule, the standard permit conditions to be included in NPDES permits for POTWs and municipal sanitary sewer collection systems are:

- Incorporation of a capacity assurance, management, operation, and maintenance (CMOM) program
- Establishment of a public and health authority notification process
- Prevention of overflows.

In addition, the SSO Proposed Rule calls for expanded permit coverage to satellite systems (i.e., collection systems where no treatment is provided and the owner/operator is different from the owner/operator of the facility providing treatment).

2.6.2 Canadian Laws and Regulations

(Environment Canada, 2004) The management of sanitary and combined sewer systems is both a federal and provincial responsibility. At the federal level, there is no national standard. Instead, Environment Canada and Health Canada are responsible for preventing environmental and human health impacts.

Sanitary Sewer Systems

Most Canadian provinces have established minimum guidelines for the sizing and construction of sanitary sewer systems and for environmental assessments. However, the detailed design, construction, and operation of sanitary sewer systems is ultimately the responsibility of individual municipalities, and their requirements may be more stringent. The following section highlights the current regulations, policies, guidelines, and practices in the Province of Ontario. Similar regulations, policies, guidelines, and practices are in place in the other provinces of Canada.

Under the Ontario Water Resources Act, the Ontario Ministry of the Environment reviews and approves applications for all new sanitary sewer works in the province. Local and regional municipalities also review and approve these applications, and in some cases, may complete the review on behalf of the Ministry. The province has prepared guidelines (Ontario Ministry of the Environment, 1985) that describe the minimum acceptable levels of sanitary servicing to assist consulting engineers and municipalities in designing sanitary sewer systems. Key elements of the provincial guidelines are:

- All new sewers are to be separate. New combined sewers or connections to existing combined sewers are not permitted, except as an interim measure where circumstances allow no alternative.

- The design of new sanitary sewers is to be based on the ultimate sewage flows expected from the tributary area. The design period is to extend a minimum of twenty years.
- Sanitary sewers should be designed using Kutter's or Manning's formula with a minimum roughness coefficient of 0.013 and sufficient slope such that a minimum velocity of 2 ft/s (0.6 m/s) will be achieved under full-flow conditions. A minimum velocity of less than 2 ft/s (0.6 m/s) will be considered appropriate where a higher slope would require extensive deepening of a sewage collection system or the addition of a pumping station, provided the municipality accepts that there may be increased maintenance requirements.

Combined Sewer Systems

All provinces in Canada have municipalities served by combined sewers, but in most cases, the construction of new combined sewers is not permitted except where there is no other alternative. Where new combined sewers are planned, they are designed to convey both sanitary and peak storm flows.

The management of CSOs in Canada is a multi-jurisdictional responsibility. The following sections present an overview of provincial regulations and guidelines and how modeling is being used to achieve compliance. Some provinces, such as Ontario and British Columbia, have established CSO procedures or regulations. In other provinces, no formal guidelines, procedures, or regulations have been developed, so individual communities have developed CSO control programs in consultation with provincial authorities.

The following provinces do not have formal CSO control policies:

- Newfoundland
- Nova Scotia
- Prince Edward Island
- Saskatchewan
- Yukon Nunavut
- Northwest Territories

New Brunswick. The Province of New Brunswick currently does not have any specific guidelines or regulations for CSO control and does not permit the construction of new combined sewers. Instead, individual municipal agencies, such as the Greater Moncton Sewerage Commission (GMSC), have identified CSOs as a wastewater management issue and developed CSO control targets and strategies to manage them. The GMSC reviewed various CSO control regulations in other North American jurisdictions, and based on their review, identified the following targets:

- A CSO abatement control target for the GMSC system of 85% wet weather flow capture. The 85% level of control corresponds to the level of control set by the US EPA and has been adopted by a number of major municipalities in Canada, such as the Cities of Winnipeg and Edmonton. Captured CSO flows are to receive equivalent-to-primary treatment, not necessarily including disinfection.
- Additional management objectives, including improving system reliability by decreasing the number of overflow structures, ensuring the proper operation of the overflows under extreme conditions, reducing the level of surcharging, and reducing the risk of flooding from the operation of the GMSC system.

GMSC has addressed these targets with the development of a short-term plan (3-10 years) and a long term plan (10-20 years). The short-term plan includes measures that address the hydraulic performance of the collector system, system reliability, and risk of basement flooding. The long-term plan includes provisions for new storage and treatment facilities.

A fully dynamic hydraulic model capable of long-term continuous simulation is used to assess the current performance of the collection system and to develop short- and long-term plans that meet control targets.

Ontario. In Ontario, the construction of new combined sewers is not permitted except where there is no alternative. Management of CSOs from existing combined sewers is governed by Procedure F-5-5, Determination of Treatment Requirements for Municipal and Private Combined and Partially Separated Sewer Systems (Ontario Ministry of the Environment, 1997). This procedure is a

supporting document for Guideline F-5, Levels of Treatment for Municipal and Private Sewage Treatment Works Discharging to Surface Waters.

Procedure F-5-5 is prescriptive and includes the following:

- Minimum CSO volumetric control and treatment criteria. The volumetric control criterion for CSOs is applied to the flow collected by the sewer system immediately upstream of each overflow location, unless it can be shown through modeling and/or ongoing monitoring that the criterion is achieved system wide. No increase in CSO volumes above existing levels at each outfall is allowed, except where the increase is due to the elimination of upstream CSO outfalls. The minimum level of treatment required for CSOs is primary treatment or the equivalent. Table 2.3 presents the specific quality and quantity guidelines specified in F-5-5.

- A requirement for the development and implementation of pollution prevention and control plans.
- Additional controls for beaches impaired by CSOs. Effluent disinfection is required where the effluent affects swimming and bathing beaches or where there are other public health concerns. Where chlorination is used, any adverse effects from chlorine residuals must be minimized.
- Provisions for new sanitary and storm connections to combined sewer systems.

Table 2.3 Procedure F-5-5 quantity and quality requirements

| Parameter | Guideline |
|--|--|
| Volumetric control | 90% capture of wet weather flows ¹ |
| Carbonaceous biochemical oxygen demand (BOD) | 30% removal ¹ |
| Total suspended solids (TSS) | 50% removal ¹ and not to exceed 90 mg/L for more than 50% of the time |
| Disinfection | Monthly geometric mean not to exceed 1,000 E. coli per 100 mL during wet weather |

¹ Over a 7-month period commencing within 15 days of April 15 during an average rainfall year.

Manitoba. Manitoba does not have a formal CSO control policy. However, specific municipalities, such as Winnipeg, are working to formulate a CSO management program in consultation with the Manitoba Clean Environment Commission. In setting the scope for Winnipeg's management plan, the commission considered CSO regulations across Canada, the United States, and Europe. Highlights of the proposed plan include:

- Adoption of the US EPA standard of CSO reduction (four overflows per recreational season or 85% volumetric control), and compliance with the Manitoba Surface Water Quality Objectives.
- Optimization of existing infrastructure and the development of new initiatives through a progressive, staged program.
- Enhancements to the existing collection system, including raising weirs, dewatering latent storage, modifying interception rates, and keeping a monitoring system in place.
- Establishment of an in-line storage demonstration project before the actual implementation of the in-line program.

Alberta. Only a few communities in Alberta have combined sewers. As a result, the Province of Alberta has not yet developed a formal CSO control policy. The City of Edmonton is the largest community served by combined sewers.

Despite the lack of a formal policy, the City of Edmonton has developed a CSO control strategy as part of its Towards a Clean River campaign for the North Saskatchewan River. The CSO control strategy is a 16-year-long program that includes an Early Action Control Plan (EACP) and a Long-Term Control Plan (LTCP). The implementation process begins with the EACP, which carries out selected CSO controls over a 10-year period. Key elements of the EACP include the following:

- In-line system storage to enable downstream sewer systems to transport and treat more wastewater with fewer overflow occurrences.

- Separation of storm and sanitary sewers as city sewers are upgraded.

- Floatables and solids control.

Key elements of the LTCP include:

- Increased system conveyance capacity.
- Construction of new storage facilities.

The City of Edmonton has developed and continues to develop a sophisticated hydrologic and hydraulic model of their sanitary and combined sewer system. The hydrologic model has been calibrated with extensive historical data and provides flow inputs into a continuous, fully-dynamic hydraulic model with the ability to simulate real-time controls, such as modulating gates and weirs.

British Columbia. Historically, CSO control in British Columbia has been accomplished on a voluntary basis through the development of municipal liquid-waste management plans. The province has moved to codify the development and implementation of these plans, making them a requirement under the new Waste Management Act, which came into force on January 1, 2004. The act applies to all municipalities, but imposes different requirements depending on the municipal population, as shown in Table 2.4.

Table 2.4 Waste Management Act Requirement.

| Population > 10,000 | Population < 10,000 |
|---|--|
| The liquid-waste management plan must address existing CSOs, including measures to eliminate overflows. | Either a liquid-waste management plan shall be developed or a study conducted to lead to implementation of measures to eliminate CSOs. |

The Municipal Sewage Regulation, made under the Waste Management Act, describes municipal responsibilities concerning combined sewer systems and control of CSOs. The regulation defines a combined sewer system as ditches, drains, sewers, treatment facilities, and disposal facilities that collect, transport, treat, or dispose of a combination of municipal sewage and stormwater in a single system. The regulation stipulates that:

- No one is allowed to construct or expand a combined sewer system.
- Emergency repairs to existing combined sewer systems are permitted; however, the feasibility of sewer separation is to be assessed, and, wherever possible, the storm and sanitary sewers should be separated at the time of repair.

A focus of British Columbia's legislation is the eventual elimination of CSOs by replacing combined sewers with separate storm and sanitary sewers. To that end, storage or conveyance facilities may not be employed to reduce the amount of sewer separation required, unless the facilities immediately reduce and ultimately prevent the occurrence of CSOs.

2.6.3 European Union Laws and Regulations

European Union (EU) member countries have adopted several Directives for controlling urban pollution, particularly with regards to overflows. The Directives include the EU Urban Wastewater Treatment Directive (UWWTD), the proposed Water Policy Framework Directive (WPFDD), the Integrated Pollution Control and Prevention Directive (IPPC), and some of the Product Directives. The following sections outline the requirements of the Directives and how they are being implemented.

Urban Wastewater Treatment Directive (UWWTD)

The UWWTD (CEC, 1991) provides the main legislation for the control of urban pollution in the EU. The aim of the UWWTD is to avoid the pollution of fresh and marine waters from urban sewage systems, and it requires the following:

- All agglomerations greater than 2,000 Pe must discharge into collection systems for urban wastewaters. (1 Pe is defined as the organic loading with a 5- day biochemical oxygen demand [BOD₅] of 60 g/day.)
- The effluent from sewage treatment plants must meet the minimum effluent standards, which depend on the sensitivity of the receiving waters.

- Sewage discharges to “less sensitive” waters, defined as estuarine and coastal waters with a high dispersion capacity, may undergo only primary treatment.
- Sewage discharges to “normal” waters must receive biological treatment, as described in Table 2.5.
- Sewage discharges greater than 10,000 Pe to “sensitive” waters must be subjected to both biological treatment and nutrient removal (see Table 2.5).

Table 2.5 Requirements for discharges from urban wastewater treatment plants (from CEC, 1991).

| Parameter | Concentration, mg/l | Minimum Reduction, % |
|---|--|----------------------|
| Requirements for discharges to “normal” water | | |
| Carbonaceous biochemical oxygen demand (BOD ₅ – 20° C) | 25 mg O ₂ /L or 40 mg O ₂ /L | 70–90 |
| Chemical oxygen demand (COD) | 125 mg O ₂ /L | 75 |
| Total suspended solids (TSS) | 35 | 90 |
| | 35 | 90 |
| | 60 | 70 |
| Additional requirements for discharges to “sensitive areas” | | |
| Total phosphorus (P) | 1 mg P/L (Pe of 10,000–100,000) | 80 |
| | 1 mg P/L (Pe > 100,000) | |
| Total Nitrogen (N) | 15 mg N/L (Pe of 10,000–100,000) | 70-80 |
| | 10 mg N/L (Pe > 100,000) | |

Control of CSOs in EU Member States

Whereas the effluents from sewage treatment plants are licensed in all countries, current practices for the permitting and monitoring of CSOs vary widely throughout the EU (Table 2.6). In most countries where CSOs require authorization, the permits are related to the spill frequencies. In terms of monitoring,

only a low proportion of CSOs are monitored; although, depending on the country (e.g., Germany, UK), major new CSOs may require permanent monitoring facilities.

Table 2.6 CSO discharge permits in some European countries, modified from European Waste Water Group 1995 (Milne et al., 1997).

| Country | Regulatory Body | Comment |
|-----------------------|---|---|
| Belgium (Flanders) | Environmental Agency (VLANSREM) | Discharge permit may specify overflow frequency. |
| Denmark | Regional Authority | Discharge permit specifies overflow frequency, but it is rarely checked. Some municipalities monitor “problem” CSOs. |
| France | Departments | Permit required if polluting load exceeds 500 Pe. 1–2% of CSOs are monitored, mainly near bathing waters and shellfish waters. |
| Germany | States (Länder) | Permits required for all wastewater discharges, including CSOs. Monitoring, regulation, and sampling procedures vary between individual states. Some states require new CSO structures to be equipped with a monitoring/telemetry facility for operational and regulatory reasons. Monitoring allows compliance with A128 guidelines. |
| Ireland | Environmental Protection Agency | Legislation proposed that will require discharge licenses. |
| Luxembourg | Ministry of Environmental Affairs | New CSOs require authorization (approval permits). Existing CSOs must be registered. |
| Netherlands | Water Boards | Discharge permit sets limit on overflow frequency. This is rarely checked except for problem CSOs causing public complaint (<5%). Monitoring facilities are being added to many systems. |

Table 2.6 CSO discharge permits in some European countries, modified from European Waste Water Group 1995 (Milne et al., 1997). (cont.)

| Country | Regulatory Body | Comment |
|------------------------------|---|---|
| Spain | National River Authority, Regional Authorities | All CSOs must be registered; formal permits (with conditions) are not issued at present. |
| UK – England and Wales | Environment Agency | Discharge consents are required for CSOs. Monitoring of “problem” CSOs only at present by Environment Agency. Spill frequencies assessed by short- or long-term monitoring, plus modeling studies by water companies. Major new CSO structures may include permanent monitoring facilities. |
| UK– Scotland | Scottish Environmental Protection Agency (SEPA) | Same as England and Wales, except monitoring and regulatory functions are performed by SEPA. |

2.7 Past Studies

Mathematical modeling has been extensively used by researchers and designers to have enough idea about impact of changing scenarios on the wastewater collection and treatment systems in near future. Many studies have been reported in literature about wastewater collection systems in the cities and towns in various parts of the world.

2.7.1 Past Studies on Wastewater Collection Systems

Wastewater collection system infrastructure research needs in the USA was reviewed by (Tafari & Selvakumar, 2002). In the framework of their paper, sustainable development would offer new and better solutions to current and upcoming problems related with sewer system infrastructure. They focus on technical issues and research needs in three major areas: (1) evaluation of system integrity; (2) rehabilitation, maintenance, and operation; and (3) new construction.

From their summary part, it was concluded that existing programs should be utilized and new approaches must be established that address both technology and management innovation. To be successful, these new approaches must emphasize federal government cooperation with the States, encourage growth of private sector technology, and promote the application of existing and new domestic and international technologies.

On-site wastewater treatment systems in the WWTPs service areas in Thailand: scenario based pollutant loads estimation was studied by a group of scientists (Tsuzuki et al., 2009) in Bangkok, Thailand. Their research focused on the important of assessment of the presence of on-site treatment facilities in WWTPs service area. They developed three scenarios to guess pollutant releases per capita (PDCs) from domestic wastewater treatment systems in Thailand. PDCs estimation results showed that pollutant releases to the receiving water are still higher even in the WWTPs service areas. Based on their result, they have concluded that a step-wise improvement scheme for wastewater treatment systems should be planned together with the current situations, advanced on-site treatment systems and comprehensive pollutant discharges estimations to the ambient water and WWTPs.

Developing best estimates for CSO control volumes to meet NPDES requirements was studied by a group (Lee et al., 2012) in Seattle, US. Their study focused to control untreated sewer overflows at each combined sewer overflow (CSO) outfall to an average of no more than one annually and to establish a performance standard in the City's CSO NPDES permit. Their paper also describes the process established to identify the overflow control levels using a continuous long term simulation (LTS). Base on their result it was concluded that if the city decided to control CSOs with 90% confidence, storage for 2.203 MG would be needed. This would less the risk that the city would violate its NPDES permit for a larger cost than controlling the best estimate of 1.858 MG.

Dry weather channel impacts on wet weather combined sewer overflow pollution rates was studied by a group (McDonnell et al., 2014) in Cincinnati, Ohio. This paper describes how they developed a first order solids transport model from to represent the settling and washoff rates within the wastewater collection system in conjunction with the P8 urban catchment model from to model the influent mass rate

from overland flow. The model was advanced to fit in the concept of uniform settling on the soaked surfaces within the wastewater collection system. Based on their result, it was concluded that using the hydraulic data from the collection system hydraulic model as an input to the water quality model process described in this paper, the modeled results suggest that the inclusion of a DWC could provide a reduction in solids during the first flush portion of wet weather events between 26.5% and ~59%.

The development, implementation and communication of wastewater collection networks in the City of Niagara Falls suggested outline affords a united gateway for effective and efficient management of sewer systems. Based on actual data presents the use of business intelligence tools to monitor, implement, and report various components of the suggested outline. The outline developed into account four strategic perspectives –financial, socio-political, technical/operational, and regulatory – and devised four considerations for sustainable sewer systems (Younis & Knight, 2014).

In a recently reported study, using low-cost sensors, data could be collected on the event and period of overflows in each CSO structure in a combined sewer system in La Garriga, Spain over the course of 11 months (from July 2011 through May 2012). The breaking point of rain volume from which CSO structures started to overflow ranged from 0.6 mm to 2.8 mm. The structures with the best and worst performance in terms of overflow (overflow probability, order, duration and CSO ranking) were characterized and predicted overflows from rain data had accuracies ranging from 70% to 83%. The collection and analysis of real data can be used to assess, improve, and maintain CSSs in order to reduce the number and impact of overflows (Montserrat et al., 2015).

2.7.2 Past Studies on Wastewater Collection System using Mathematical Modelling

A group of researcher (Mailhot et al., 1999) was used SWIFT model to define optimal regulator operations in order to minimize total overflow volume and it has been calibrated and applied to the sewer network at Quebec, Canada. The main objective of the SWIFT model is to minimize the volumes of wastewater released by optimizing wastewater volumes stored in the network, while respecting the calculation

time constraint associated with real time control. The SWIFT simulation results are similar to those obtained with the SWMM modeJ, calibrated using observations from the same network. Based on their result they have concluded that the results of a performance study of the model indicate a wastewater overflow volume reduction ranging from 30% to 100% depending on the rain event, and an overflow frequency reduction ranging from 54% to 73% depending on the concerned site.

Modelling the impacts of CSO from Nashville using Environmental Protection Agency's demonstration approach was studied by a group (Adams et al., 1997) at Cheatham Lake on the Cumberland River below Nashville in Tennessee, US. They used the water quality model, CE-QUAL-W2, to do the clarification and description what the real effects of CSOs are and to predict the different results of CSOs achieved by various control scenarios. Base on their result, it was concluded that the water quality dynamics in Cheatham Lake are primarily driven by the water quality and quantity of releases from the headwaters at Old Hickory Dam. As a model simulation results, Nashville's CSO Control Plan is being reviewed to eliminate unnecessary and unproductive storage basins and to incorporate the new findings.

In one study, the researchers used SWMM RUNOFF with the unit hydrograph approach has been successfully applied to address rainfall dependent inflow and infiltration (RDII) related problems in a sewershed in Cincinnati. It was essential to understand the seasonal variation of groundwater infiltration (GWI) and its impact on the sewer flows. The researchers described that reliable flow and rainfall monitoring data and GWI rates were essential for proper hydraulic model calibration and validation (i.e. EXTRAN) whichever approach (physical or empirical) was used to generate RDII hydrographs (Vallabhaneni et al., 2002).

Modeling surface runoff, groundwater flow and their interaction with PCSWMM and MODFLOW was studied by a group (Rivard at al., 2004) in the City of Rostov, Russia. The paper describes the complex conditions that were analyzed, and different approaches to use the results from the surface runoff model (PCSWMM) as input to the groundwater model (MODFLOW). Based on their results, it was concluded that many types of projects in urban drainage are categorized by this relations of groundwater and surface water systems, where variations in one system have a significant effect on the other.

Modeling Approach using PCSWMM to Support Infiltration/Inflow Remediation Area Studies was studied by a group (McGill et al., 2007) in Ohio, US. They argue the lessons learned and the solutions that the project team developed, consisting of the development of new PCSWMM routines and several SWMM code revisions. Each of these solutions represents valuable developments theoretically applicable to other PCSWMM modeling plans. By pausing to carefully examine the project goals and approach, the project team was able to develop a set of modeling tools and application approaches designed to streamline the City's I/I models and provide a consistent approach for this and future City of Columbus I/I project teams to build upon.

In this research, the system-wide computer model (SWMM) was used to execute a comprehensive hydraulic capacity assessment to classify system deficiencies of the wastewater collection system under dry and wet weather conditions and it has been used to find solutions to hydraulic shortages in order to make available adequate system volume under current and upcoming situations. This process used to develop a solution to hydraulic capacity deficiencies in the Mill Creek Basin of the Metropolitan Sewer District of Greater Cincinnati (MSDGC) using SWMM modelling techniques to display options and define cost-effective solutions are discussed, with a creature made to read SWMM output files and produce planning level costs. The updated SWMM5 software (U.S. EPA, 2002) was found valued in precisely and efficiently modeling the large collection system (about 24,000 nodes) of the Mill Creek Basin (Wride et al., 2007).

Modelling the impacts of Combined Sewer Overflows on the river Seine water quality was studied by a group (Even et al., 2007) in river Seine at Paris, French. The PROSE model was used in their research to run simulation to investigate the impact on the river Seine of both permanent dry-weather effluents and of very much transient CSO and the model also was used to represent the impact of Paris at large spatial and temporal scales by using the data from laboratory, site samplings, modelling studies and experiments. Based on the result of the model, 56% of the oxygen consumption was caused by the benthic oxygen demand; CSOs clarified 32% of this demand for a typical summer month and the D90 rises by $1 \text{ mgO}_3 \text{ L}^{-1}$ when they are excluded. When simplified and classical modeling approaches applied in the

Seine mainly used re-calibration to adjust models results to the observations and simply have miss the CSOs phenomena, the interest of a completely deterministic approach is illustrated.

Using SWMM as a tool for hydrologic impact assessment was studied by a group (Jang et al., 2007) in South Korea. They also used SWMM modelling to evaluate the hydrologic impact of urbanization was recommended as an enhancement to the official role of synthetic hydrograph-urban hydrology model combination for pre- and post-development conditions respectively. Based on their result, the suggested approach can be used as a more responsible way of evaluating the urbanization effect and the product can be used with the design of detention pond for water quality and quantity control of urban runoff.

In another study, a group of researcher prepared combined sewer overflow CSO discharge monitoring reports DMRs for the City of Indianapolis, Indiana by applying the calibrated sewer system hydraulic model on a continuous basis. Wide variations are observed in year-to-year precipitation patterns and associated CSO discharges from the combined sewer systems. Long-term CSO DMR data would provide a sound and consistent approach in evaluating overflow characteristics in relation to precipitation conditions and assessing the performance and effectiveness of the projects. Efficient model simulations and data processing were expected to keep the cost for continuous modeling affordable, and justifies its used to support important decision-making related to expensive sewer system wet-weather overflow control programs (Vallabhaneni et al., 2007)

A study of a group of researcher (Chen et al., 2010) used PCSWMM with the U.S for updating the system wide sewer model in the City of Columbus. SWMM 5 provided a number of advantages for modeling the operating strategies versus previous models of the Columbus system that used SWMM 4.4. In particular, the ability wrote control rules directly in SWMM 5 offers a significant advantage for modeling complex hydraulic structures and real time control (RTC) strategies. Preliminary operating model simulations demonstrated the feasibility of implementing real time controls in SWMM 5 and that it could be used to find optimal solutions in operation of complex collection systems.

In recent research, the management of sewer systems of the City of Dresden (Germany), for every flow section in sewer networks, an individual model method was expressed whose parameters were optimized by least squares approach (Christian and Peter, 2011). As a result of the application of mechanistic methods, determined parameters can be interpreted in relation to structural data. In the test case, a relationship between pipe condition and infiltration potential was detected. The determination of the infiltration coefficient along with the pipe condition is consistent. The groundwater influence and the year of implementation were recognized as meaningful indicators to calculate the infiltration potential of sewer pipes. The multiple model and the parameters can be used for further hydrodynamic modelling and the study of present, past and future hydrological circumstances.

A group of researcher in 2012 was researched that Inflow and Infiltration (I/I) into sewer systems is generally unwanted because it reduce the performance of WWTP and increases CSOs. It is very expensive to reduce I/I in sewer rehabilitation, water managers not only need methods to precisely measure I/I, but also they need sound approaches to evaluate the real performance of applied rehabilitation measures. The researchers were successfully demonstrated that the effectiveness of the method in case study of “Development of a systematic approach to reduce inflow and infiltration in rural areas” funded by the Ministry for the Environment, Agriculture and consumers protection of the state of Northrhine-Westphalia. The rehabilitation reduced groundwater infiltration by 23.9%. A stormwater inflow reduction of 35.7%, however, was statistically insignificant. Investigations into the experimental design of monitoring campaigns confirmed that the variability of the data as well as the number of observations collected before the rehabilitation impact the detection limit of the effect. This implies that it is difficult to improve the data quality after the rehabilitation has been implemented (Staufer et al., 2012).

An approach for estimating groundwater infiltration(GWI) rates into wastewater collection systems under typical year conditions was studied by a group of researcher (Zhang et al., 2014) in the City of Columbus in Ohio, US. Their study investigates the relationship of GWI and precipitation, and develops an approach to estimating GWI under typical year conditions using long term wastewater treatment plant (WWTP) effluent data and long term precipitation data, as part of the Sewer

System Capacity Model (SSCM) Update 2006 Project, Columbus, Ohio. The SSCM 2006 model is the City of Columbus's current version of the system wide sewer model developed using the PCSWMM modeling platform with the USEPA's SWMM5 as the computational engine. Based on their results, significant positive linear relationships were found between GWI and precipitation both annually and monthly.

One project, 'Dynamic Adaptation of Urban Water Infrastructure for a Sustainable City Development in an Alpine Environment (DynAlp) was presented a sensitivity analysis to compare impact of increased rainfall intensities and pavement of urban areas. The first results of a climate change and land-use change impacted study for an Alpine case study. Based on the stimulation results, the researchers mentioned that simulations of pluvial flooding and its associated risk of damages and combined sewer overflow discharges would help to develop effective adaption strategies with taking into account the temporal dynamics of a growing city and its water infrastructure (Kleidorfer et al., 2014).

Table. 2.7 Past Studies on Wastewater Collection System

| Author Name and Year | Title of Work | Summary |
|---------------------------------|---|---|
| Tafari and Selvakumar (2002) | Wastewater collection system infrastructure research needs in the USA | Focus on three major areas (1) Assessment of system integrity; (2) operation, maintenance, and rehabilitation; and (3) new construction. -Existing programs should be utilized and new approaches must be established that address both technology and management innovation. |

Table. 2.7 Past Studies on Wastewater Collection System (cont.)

| Author Name and Year | Title of Work | Summary |
|---------------------------------|---|---|
| Tsuzuki et al. (2009) | On-site treatment systems in the wastewater treatment plants (WWTPs) service areas in Thailand: scenario based pollutant loads estimation | <p>Their research focused on the important of assessment of the presence of on-site treatment facilities in WWTPs service area.</p> <p>They have concluded that a step-wise improvement system for wastewater treatment systems should be planned together with the current conditions, advanced on-site treatment systems and inclusive contaminant discharges assessments to the ambient water and WWTPs.</p> |
| Lee et al. (2012) | Developing best estimates for CSO control volumes to meet NPDES requirements | Their study focused to limit untreated overflows at each CSO outlet to an average of no more than one annually and to establish a performance standard in the City's CSO NPDES permit. |
| McDonnell et al. (2014) | Dry weather channel impacts on wet weather combined sewer overflow pollution rates | <p>They developed a first order solids transport model to represent the washoff and settling rates within the wastewater collection system.</p> <p>The modeled results suggest that the inclusion of a DWC could provide a reduction in solids during the first flush portion of wet weather events</p> |

Table. 2.7 Past Studies on Wastewater Collection System (cont.)

| Author Name and Year | Title of Work | Summary |
|---------------------------------|---|--|
| Younis and Knight (2014) | Development and implementation of an asset management framework for wastewater collection networks | <p>Proposed framework affords an integrated access for effective and efficient management of wastewater collection systems.</p> <p>The outline developed into account four strategic perspectives – financial, socio-political, operational/technical, and regulatory – for wastewater collection systems</p> |
| Montserrat et al. (2015) | Using data from monitoring combined sewer overflows to assess, improve, and maintain combined sewer systems | <p>Using low-cost sensors, data could be gathered on the incidence and period of overflows in every combined sewer overflow structure in a combined sewer system.</p> <p>The gathering and examination of real data can be used to improve, assess, and keep CSSs in order to decrease the amount and effect of overflows.</p> |

Table 2.8 Past Studies on Wastewater Collection System using Mathematical Modelling

| Author Name and Year | Title of Work | Summary |
|-----------------------------|---|---|
| Mailhot et al. (1999) | Real Time Control of Combined Sewer Overflows: the SWIFT Model | They was used SWIFT model to define optimal regulator operations in order to minimize total overflow volume and it has been calibrated and applied to the sewer network at Quebec, Canada. The SWIFT simulation results are similar to those obtained with the SWMM modeJ, calibrated using observations from the same network. |
| Adams et al. (1997) | Modelling CSO impacts from Nashville using EPA's demonstration approach | They used the water quality model, CE-QUAL-W2, to do clarification and description what the real effects of CSOs are and to make predictions of results likely to be accomplished by various CSO control scenarios. |
| Vallabhaneni et al. (2002) | SSO Evaluations: Infiltration and Inflow using SWMM RUNOFF and EXTRAN | Their research presents methodology to develop improved sanitary sewer models which can be used to cost-effectively address wet-weather problems such as excessive RDII and resulting SSOs and basement backups. |
| Rivard at al. (2004) | Modeling surface runoff, groundwater flow and their interaction with PCSWMM and MODFLOW | The paper describes different approaches to use the results from the surface runoff model (PCSWMM) as input to the groundwater model (MODFLOW) to know interaction of surface water and groundwater systems |

Table 2.8 Past Studies on Wastewater Collection System using Mathematical Modelling (cont.)

| Author Name and Year | Title of Work | Summary |
|-----------------------------|--|--|
| McGill et al. (2007) | Modeling Approach using PCSWMM to Support Infiltration/Inflow Remediation Area Studies | They discuss quite a lot of SWMM code revisions and the development of new PCSWMM routines for valuable developments potentially applicable to other PCSWMM modeling projects. |
| Wride et al. (2007) | Finding Solutions to Sanitary Sewer System Capacity Deficiencies | SWM was used to execute a inclusive hydraulic capacity assessment to classify system deficiencies of the wastewater collection system under both dry- and wet-weather flow conditions. |
| Even et al. (2007) | Modelling the impacts of Combined Sewer Overflows on the river Seine water quality | The PROSE model was used to simulate the effect on the river Seine of both permanent dry-weather discharges and of highly transient CSO and it was also used to represent the impact of Paris at large temporal and spatial scales by using the data from laboratory experiments, spot samplings, and modelling studies. |

Table 2.8 Past Studies on Wastewater Collection System using Mathematical Modelling (cont.)

| Author Name and Year | Title of Work | Summary |
|-----------------------------|--|---|
| Jang et al. (2007) | Using SWMM as a tool for hydrologic impact assessment | They also used SWMM modelling to evaluate the hydrologic effect of urbanization was suggested as an development to the official role of synthetic hydrograph-urban hydrology model combination for before and future development conditions respectively. |
| Vallabhaneni et al. (2007) | CSO Discharge Reporting using a Continuous Modeling Approach | <p>Their study presents a case study based on broad knowledge in preparing CSO DMRs for the City of Indianapolis, Indiana by applying the calibrated sewer system hydraulic model on a continuous basis.</p> <p>As a result, the protocol for model application for the 6-month DMR has been developed and refined with each successive application of the model.</p> |
| Chen et al. (2010) | Using SWMM 5 to Develop Wet Weather Operating Strategies in a Large Sewer System | <p>In the study, SWMM 5 was applied as a fully dynamic hydraulic model with 1200 pipes, 11 pump stations, 28 orifices and 48 storage or wet wells.</p> <p>This research focuses on the effectiveness of SWMM 5 to perform the large scale complex modeling simulations through evaluation of the model representation and model verification.</p> |

Table 2.8 Past Studies on Wastewater Collection System using Mathematical Modelling (cont.)

| Author Name and Year | Title of Work | Summary |
|-----------------------------|---|--|
| Christian and Peter (2011) | Quantification of groundwater infiltration and surface water inflows in urban sewer networks based on a multiple model approach | This paper presents a methodology to identify I/I and estimate its quantity. |
| Staufer et al. (2012) | Assessing the performance of sewer rehabilitation on the reduction of infiltration and inflow | In this paper, they statistically assess the performance of rehabilitation measures to reduce I/I. They successfully make evident the effectiveness of the method in a case study, where rehabilitation reduced groundwater infiltration by 23.9%. A reduction of stormwater inflow of 35.7%, however, was statistically insignificant. |
| Zhang et al. (2014) | Approach for Estimating Groundwater Infiltration Rates into Wastewater Collection Systems under Typical Year Conditions | Their study investigates the relationship of GWI and precipitation. Based on their results, significant positive linear relationships were found between GWI and precipitation both annually and monthly. |

Table 2.8 Past Studies on Wastewater Collection System using Mathematical Modelling (cont.)

| Author Name and Year | Title of Work | Summary |
|---------------------------------|---|---|
| Kleidorfer et al. (2014) | Impact of a changing environment on drainage system performance | This paper presents a sensitivity analysis to compare impact of increased rainfall intensities and pavement of urban areas. This paper presents first results of a climate change and land-use change impact study for an Alpine case study. |

CHAPTER III

RESEARCH METHODOLOGY

3.1 Study Site

Cha-Am is located at 12.8 [latitude in decimal degrees], 99.9667 [longitude in decimal degrees] at an elevation/altitude of meters (Fig 3.1). The Land of the city is generally flat with the average elevation of 5m. Cha-Am is serviced by a combined sewer system and the flow is pumped to an aerated lagoon, centralized wastewater treatment system, before it discharges to the ocean via a small stream. The combined sewer system has been in operation at Cha-Am since 2001 with the size of the pipes between 1.2 m to 1.5 m diameter. The total length of the main line and lateral lines in the collection system are approximately 11590 m and 4541 m, respectively. There are three pump stations in the collection system including the main pumping station at the wastewater treatment plant, emergency pumping station, and one lifting pump station that pumps the wastewater from the beach front area to the wastewater treatment plant.

The wastewater collection system of Cha-Am collects the wastewater from the area around the municipality office and along the beach front area. The wastewater from the area around the municipality is conveyed to the WWTP by gravity while the wastewater from the beach front area is conveyed to the lifting pump station before pumping to the WWTP. The lifting pump station, called Jaolai pump station, has three pumps which are rated between 40.5-970 m³/hr/pump, approximately 1200 to 1500 m³/day. The end point of the wastewater collection system is the WWTP which has a pumping station that includes four pumps of 3.66 m in diameter and the pump capacity is approximately 280 m³/hr/pump. The pumping operation of the station was controlled by an automatic float switch level. The locations of wastewater treatment plant and main lines of wastewater collection system are presented in Fig 3.2.



Figure 3.1 Location of Cha-Am

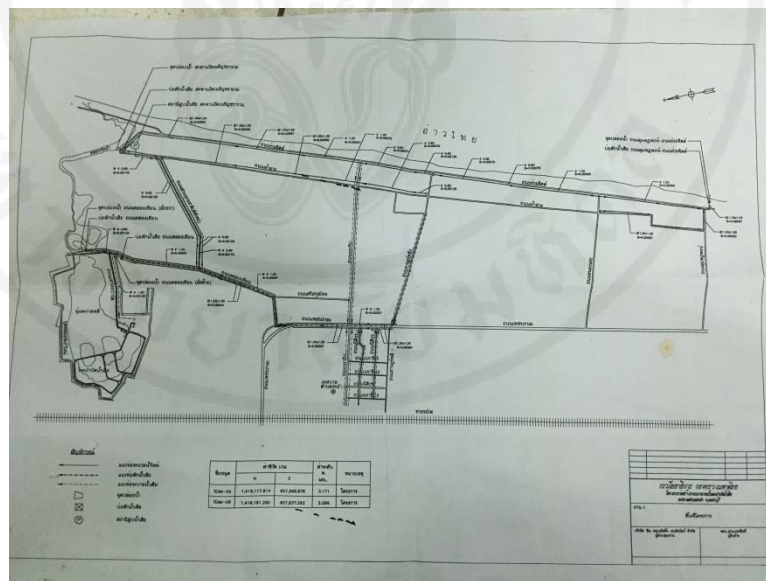


Figure 3.2 Wastewater Collection System & Wastewater Treatment Pond

3.2 Methodology

As described previously, the main objective of the research is to investigate quantity of flow in the current wastewater collection system in the Cha Am municipality area as well as to simulate the flow of wastewater collection system by using PCSWMM modelling software. The study would be started by the reviewing the

information of current wastewater collection system in Cha-Am municipality area. Required information will be collected from Cha-Am municipal office and by interviewing the local people. The methodological approach for this study is schematically presented in Figure 3.3 below.

3.2.1 Defining Data Requirement

Models need both spatial and temporal data that cover the expected range for which the system is to be evaluated (Walski et al., 2007). The model is being developed to simulate and estimate the flow of current wastewater collection. The input data for the model set up includes: physical design parameters of the current system (pipe sizes, lengths, manhole locations), and existing and expected hydraulic design parameters (slope, flow conditions, etc).

In order to organize the data-collection process, data requirements are classified into the five categories as shown in Table 3.1.

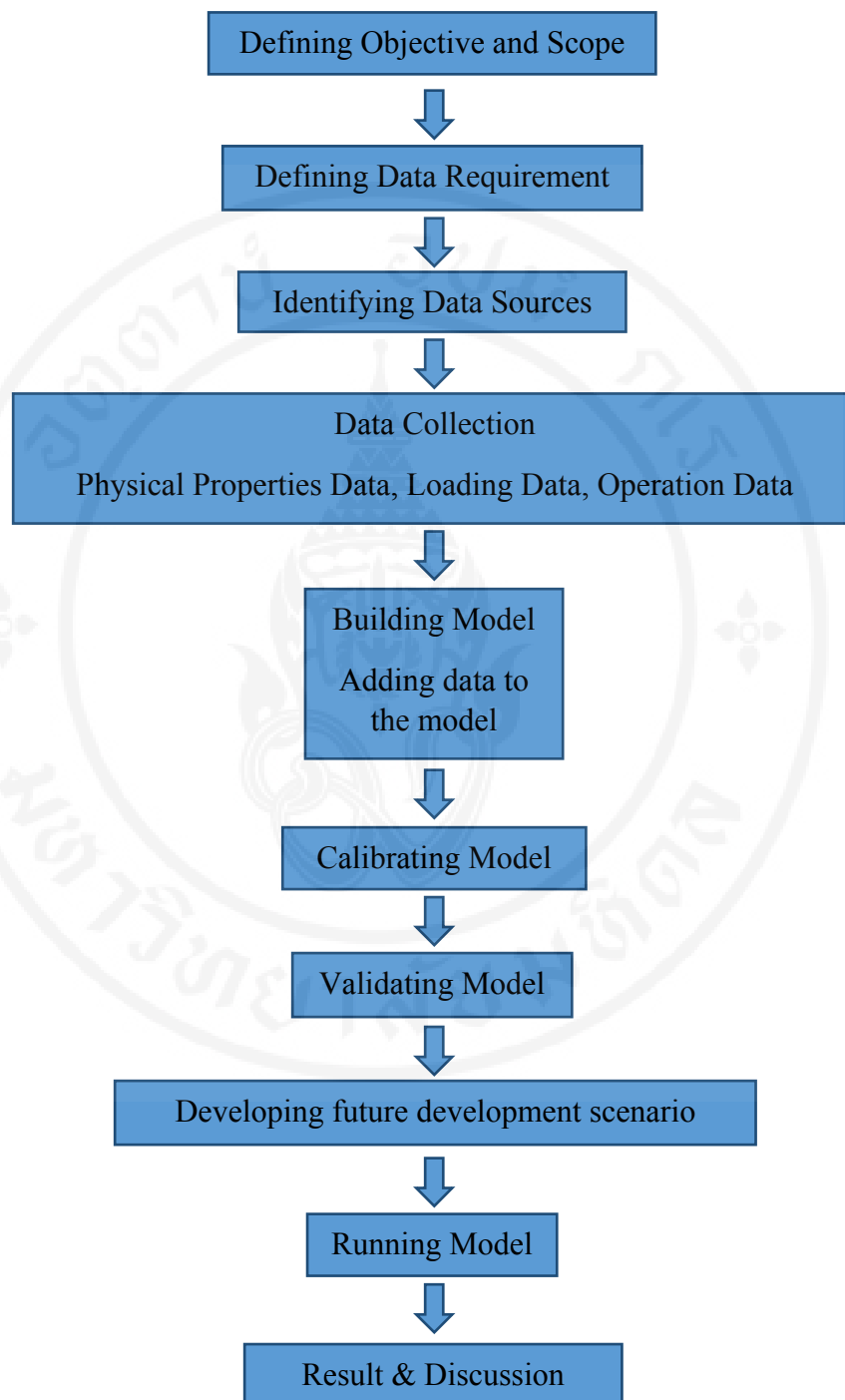


Figure 3.3 Schematic diagram of the methodology steps

Table 3.1 Data Requirement and Sources

| Data Requirement | | Sources |
|---|---|--|
| Category | Data | |
| Network Layout | x and y coordinates of manhole Locations of overflow structure, wet well and pump station Pipe lengths and connectivity Pipe materials and diameters Pipe slopes and invert levels Elevation of manholes | Construction/record drawings Field measurements Google Earth |
| Sanitary flow (domestic, commercial and industrial) | Location of each source Min, max, mean daily flows Diurnal patterns | Construction/record drawings Maps, aerial photos Census data Land-use data Inflow data to WWTP |
| Wet Weather flow | Infiltration rate for each sub basin or pipe section Inflow locations Inflow quantity Location, dates and quantities of overflows | Field measurements Field inspection Flow analysis of treatment plant Hydrologic analysis |
| Operation Data | Pump operation's settings Flow-control structures' setting Control strategies Flows to treatment plants Pumped quantities | Personal interviews with operators Operations manuals and records Field inspection |

Table 3.1 Data Requirement and Sources

| Data Requirement | | Sources |
|-------------------------|--|---|
| Category | Data | |
| Calibration data | Flow rate and Recorded depth Location and Frequency of overflows Precipitation Rain gauge locations | Field inspection Field measurements Operations records Weather records |

3.2.2 Identifying Data Sources

System Maps and Record Drawings. The system maps and record drawings provide most of the information about the physical layout of an existing wastewater collection system. The physical features, site, and the slope of pipes; location and elevation of other system components such as manholes, pumping stations, and outfalls; and the sewer system boundaries are often provided on maps.

Field Surveys. Field surveys offer the most-accurate three-dimensional coordinates of sewer network characteristics. However, survey data typically cost more than data from other sources. Surveys can be used to fill in data gaps and to verify data from construction drawings.

Field Inspections. Field inspections are used to spot-check written records and to fill in missing information. Visits to pump stations can show if any equipment has been replaced since the original construction. Operators may install modified impellers or switch out pumps altogether; hence, it is important to know the actual pumps in the pumping station.

Other Data Sources. It is probable that we will require to identify other data sources to produce a perfect model that reflects the sewer system and matches the objective requirements. The required data depend upon the model's objective. The following are some of the potential sources of additional data:

- Manufacturers of sewer pipe and ancillary structures
- Hydrologic reports and surveys
- Land-use, cover, and building-location maps
- Census and planning projection data

- Water-consumption data, particularly for industrial/commercial sites
- Customer complaint / flooding records
- Records of major contributors to wastewater loads
- Local government agencies

3.2.3 Data Collection (Physical Properties, Loading data, Operational data)

The physical data were gathered from the system maps obtained from the municipality office (Fig 3.4), record documents and include the following:

- Sewer pipe length, diameter, and material
- Invert and ground elevations
- Pump types and number
- Wet well dimensions

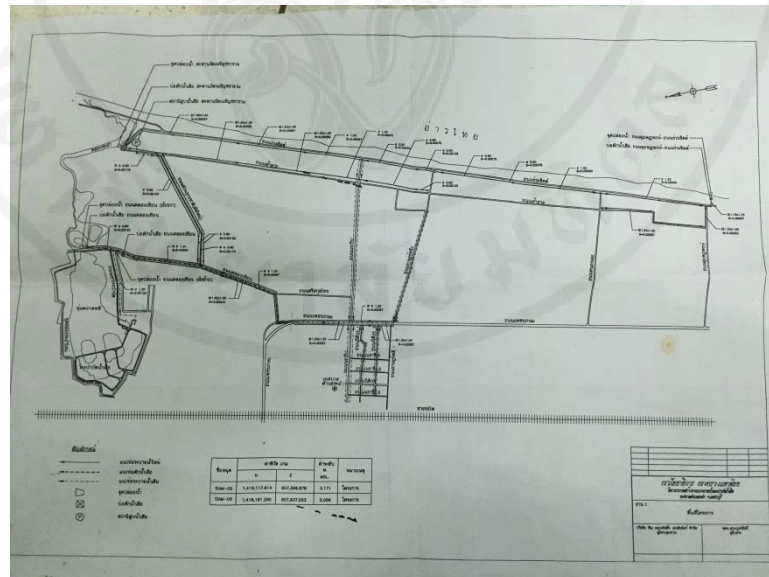


Figure 3.4 The system map of the wastewater collection system

Once located in the field, the coordinates of each manhole were recorded using GPS on an iPhone 6 as shown in figure 3.5. During these field visits, the condition of each sewer segment was checked, and information on design modifications was used to update the draft layout. One of the design modification found during the field visit, it was one of the sewer outfall on the southern part of the

city that discharge to the ocean was shut down by the municipality. Attribute information, such as pipe diameter, elevations, slope of the pipe, and pipe materials, was previously created by the Cha-Am municipality as construction drawings. Basic checks of this database were made and field inspections were used when questionable information was found.



Figure 3.5 Coordinate of manhole recorded by iPhone 6

Walski et al., 2007 said that a wastewater collection system model must be able to simulate the flow in the sewer network at all locations and times. The pragmatic approach is to load the model with the best information available, using measurements of the sewage flow at selected points in the system to calibrate. The continuous daily flow data for the year 2015 were collected from the WWTP officer, Mr. Anant Bootengchan (Fig 3.6). Spot measurements of flow and depth were done in three places, which are at the inlet of WWTP, manhole near emergency pump station, and the inlet of lifting pump station, by manually using a velocity meter as shown in Figure 3.7.

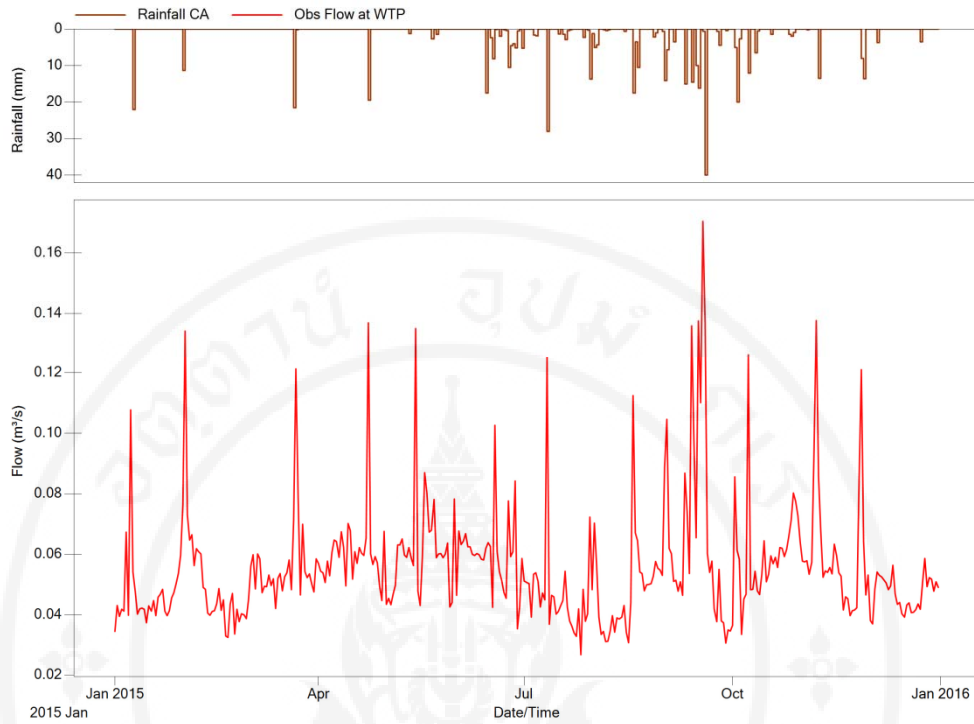


Figure 3.6 Rainfall and WWTP inflow data



Figure 3.7 Spot measurement of flow and depth

The calibration of model under wet weather condition is also important because these conditions are usually the most critical situation for sewer modelling, Precipitation values in one form or another also are needed. In Thailand, the Thailand

Meteorological Department (TMD) is responsible for the collection of precipitation data throughout the country. These data are available on an hourly, daily, and monthly frequency for some stations and can be requested in electronic format but there are only daily rainfall data for a small town like Cha-Am. The rainfall data for the year 2015 (Fig 3.6) was requested from TMD with the daily interval in millimeter at the location which is approximately at the center of the whole catchment.

The final requirement is the operational data for a sewage system that include information such as pump controls and regulator settings. In addition, system operators may have knowledge of these data. Interviewing the operators is important because operators can often provide insights different from those of the engineers and managers.

3.2.4 Model Building

One of the initial project tasks was to collect, verify, organize, and digitize information on the geographic layout and physical attributes of the entire wastewater collection system. The data were used to prepare a draft layout and physical attributes of the wastewater collection system on Google Earth Pro (version 7.1.5.1557). Google Earth Pro was used to draw the draft layout of the wastewater collection system that included the location of the manholes, subcatchments, outfalls, and the pump stations as shown in Figure 3.8. The coordinates of the manholes, subcatchments, outfalls and pump stations were imported manually to the Google Earth Pro for the purpose of getting KML (Keyhole Markup Language) file format that can be easily imported to PCSWMM.

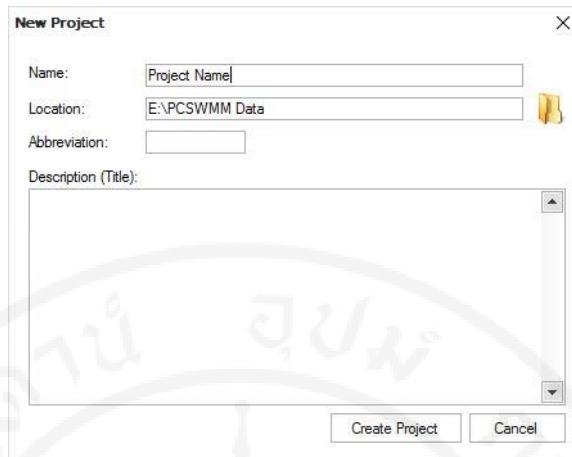


Figure 3.9 Creating new project in PCSWMM software

- A number of project options can be set directly from the simulation Options (Fig 3.10) section of the Project dialog such as flow unit, routing method, infiltration Model, offsets, Auto-length, etc. When starting a new project, the flow units, map units, auto-length switch and coordinate system should be considered and set as required.
- Based on the objective of the research, the following simulation option were selected.

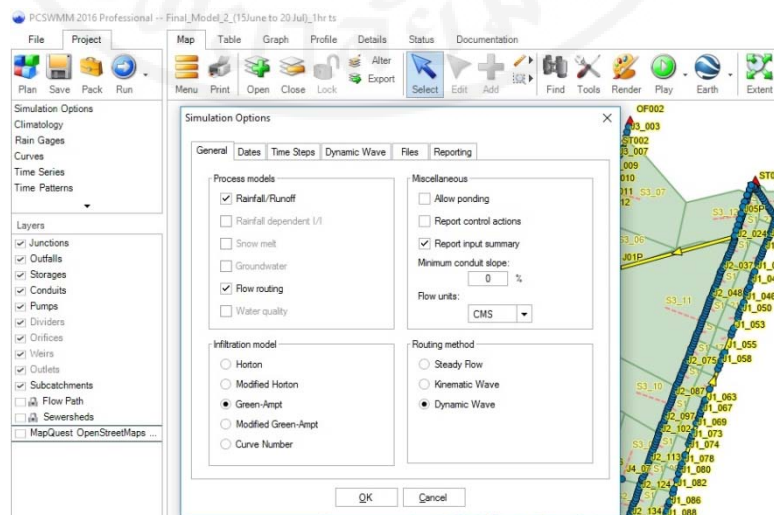


Figure 3.10 Simulation options dialog box

2. Loading a background layer

- Click the Map panel.

- Click the OSM Map button to open the Open Street Map as shown in Figure 3.11.
- Locate the project area.



Figure 3.11 Loading background layer in Open Street Map

3. Adding an outfall node

The outfall is a terminal point in the wastewater collection system where water is discharged to a treatment plant or a receiving water body (such as stream, lake, and river) with known water surface elevation.

This step is adding physical model entities to the project in the Map Panel.

- Click the Outfalls item in the Layers panel and click the Add Button.
- Click on the map in the center of the road, as shown in Fig 3.12. OF 1 will be created. The data of outfall can be inserted in attributes panel.

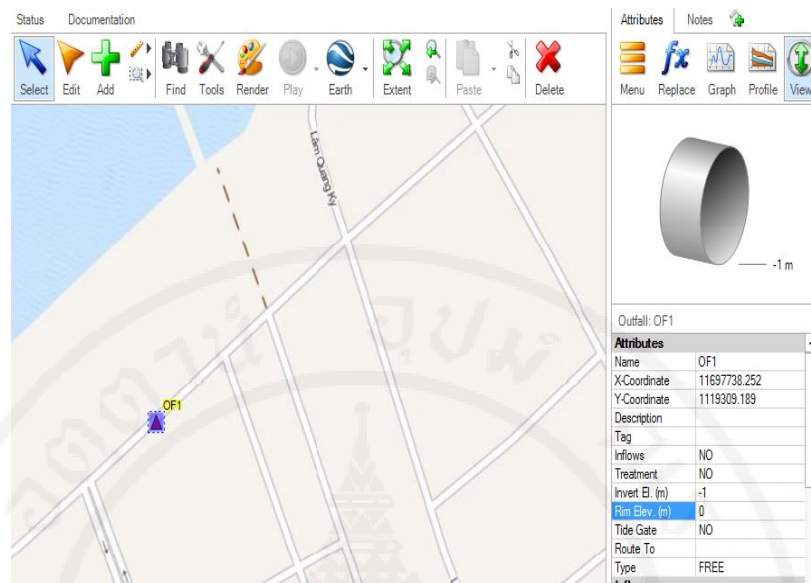


Figure 3.12 Adding outfall node and its attributes

- The Properties of the Layer (e.g. style and label) can manage by clicking the Layer Properties (Render) button (Fig 3.13).

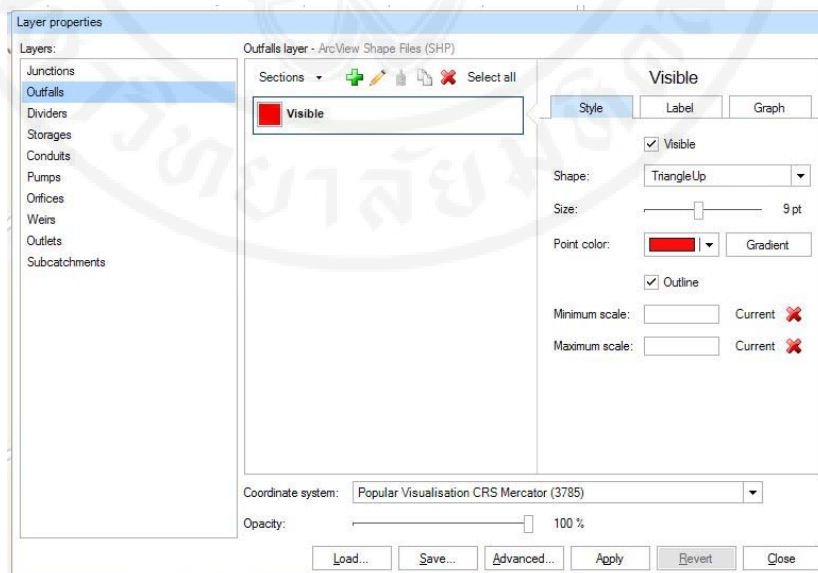


Figure 3.13 Layer properties

4. Importing Subcatchment

A subcatchment is a land plot that collects rainfall related with a rain gage and produces runoff that runs into a drainage system node or to additional

subcatchment. In this step, the subcatchments are created by importing data file previously created by Google Earth Pro (Fig 3.14).

- Click the File panel. Select Import and click on GIS/CAD under Import to Map option. The import data box will be appeared.
- In the import data box, select subcatchment tab and browse the subcatchment data file.
- After browsing the data file, Tip update coordinate under import option. Press the Finish button to commit the subcatchment created.

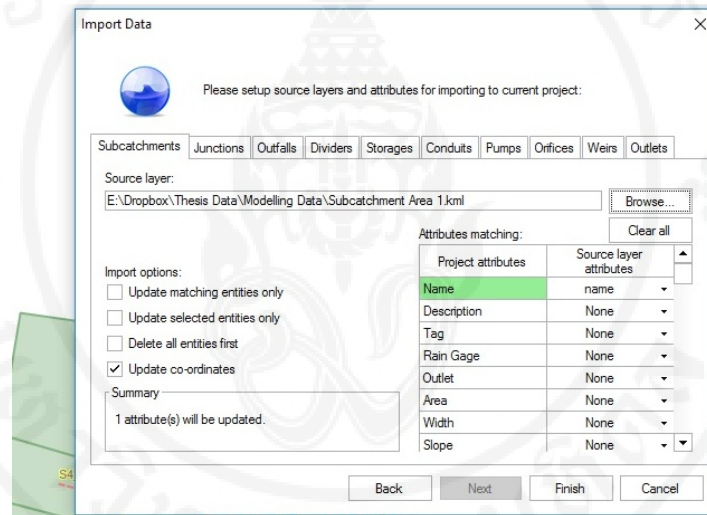


Figure 3.14 Importing Subcatchment

- The Attributes panel will display by selecting one subcatchment it include the name, computed area, and default values for the rest of the SWMM attributes for this subcatchment. The data collected for the subcatchment were added manually (e.g. slope %, impervious %, infiltration parameter)

5. Importing junction nodes

Junction nodes in this section represent the manholes in the real collection system. It is a point in the wastewater collection system where pipes connect to one another with minor storage capacity (e.g. pipe fittings, manholes, or river junction). The steps of importing junction to PCSWMM software are same with the steps of importing subcatchment as described in previous section (see Fig 3.14).

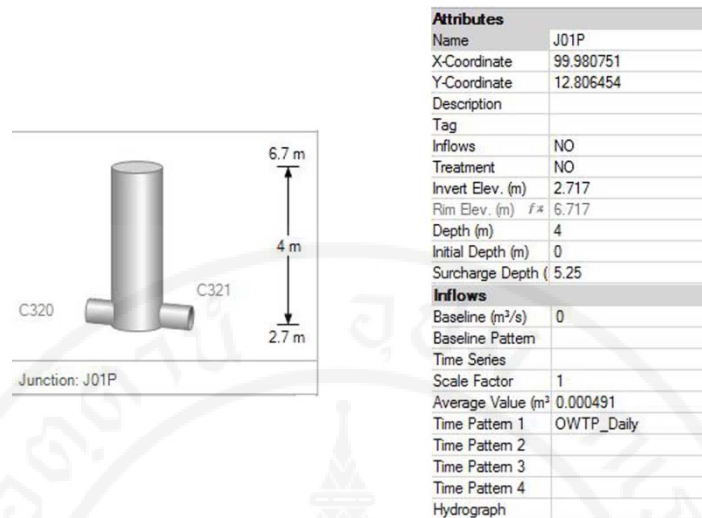


Figure 3.15 Junction Nodes and it's attributes

In PCSWMM the the depth of the junction can be defined by explicitly setting the Junction depth (ft or m) or optionally by setting the Rim Elevation from which the Junction depth is automatically calculated. The Elevation data of the Junction Nodes can insert at the Table panel in the Table tab. The Rim Elevation and Invert Elevation values can be input to the table as shown in Figure 3.16.

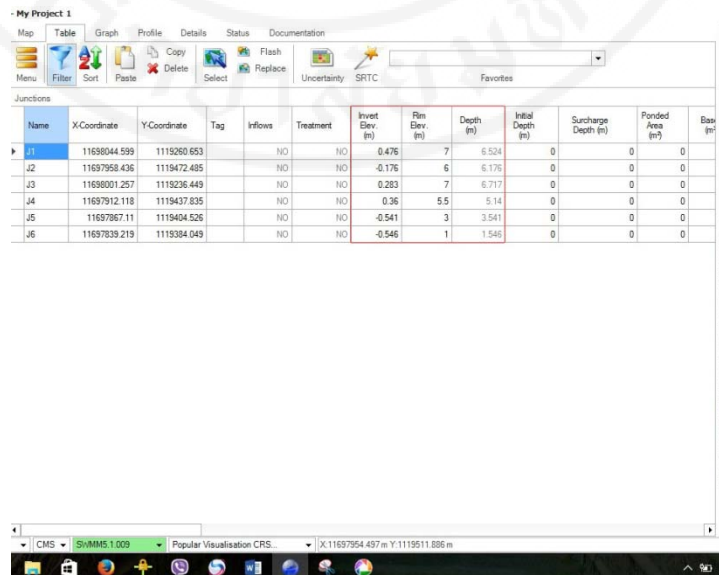


Figure 3.16 Table panel for Junction

6. Adding Conduits

It is a pipe or channel that transports water from one delivery system node to another. Sewer lines for the model input were drawn based on the existing sewer network lines. The existing sewer network lines were constructed using 0.6 m, 0.8 m, 1 m and 1.2 m diameter concrete circular pipes and 1.2x1.2 m, 1.2x1.5 m and 1.5x1.5 m concrete rectangular box, respectively. The steps of adding conduits to the PCSWMM software were explained in the following.

The step of adding conduits:

- Click on the Map tab at the top of the screen.
- Click the Conduits item in the Layers panel and click the Add button in the toolbar of the Map panel.
- Click on the upstream Junction node and then click on the downstream Junction node to finish creating the conduit (Fig 3.17). The attributes will appear and the Name textbox will display the conduit name.
- Click the Select button in the toolbar of the Map panel to exit the Add shape mode.
- Ensure Show link arrows. If it is not shown, go to the Menu button in the Map toolbar then select Preferences to open the Preferences editor to edit as shown in Figure 3.18.
- The data of the conduit can be input in the Attribute toolbox at the right hand side of the screen.

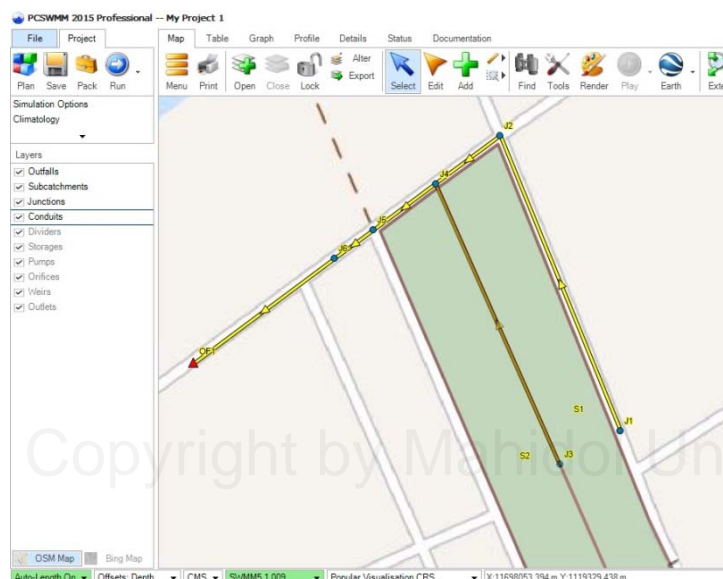
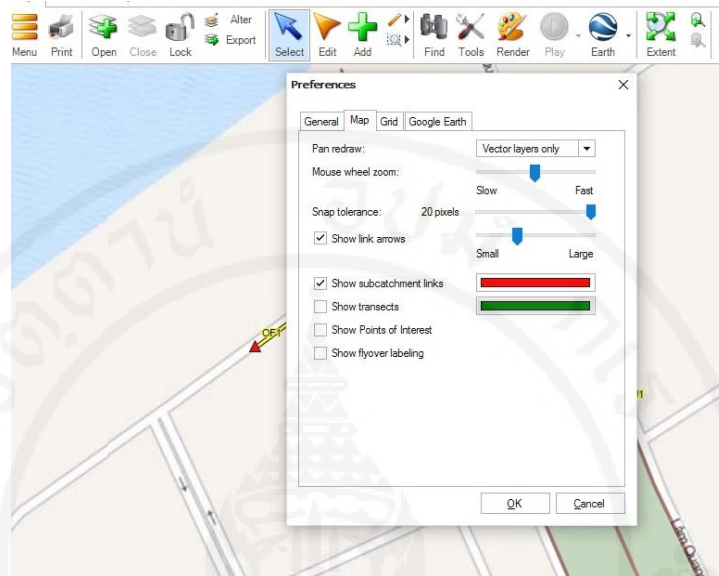


Figure 3.17 Adding Conduits**Figure 3.18** Preference toolbox for editing preferences

7. Linking Subcatchments to associated outlet Junctions

Default attributes are assigned by PCSWMM after adding map entities to a new project. To change the value of a specific attribute for an entity, select the entity and enter the new values in the Attribute panel.

Subcatchments require two connecting attributes to be set:

- The rain gage that generates rainfall data for the subcatchment.
- The node of the drainage system that receives runoff from the subcatchment. The outlet junctions will be assigned in this step and the rain gage object will be assigned when we create the design storm.

Assigning outlets for the subcatchments:

- Click on the Select button to ensure the Select mode is activated.
- Select one of the subcatchment by clicking on its polygon in the map.

The attributes of the subcatchment will be displayed in the Attributes panel at the right hand side of the screen.

- In the Outlet attribute, choose Junction from the dropdown list of nodes as shown in figure 3.19. A dotted line will be displayed after connecting the subcatchment to the outlet node.

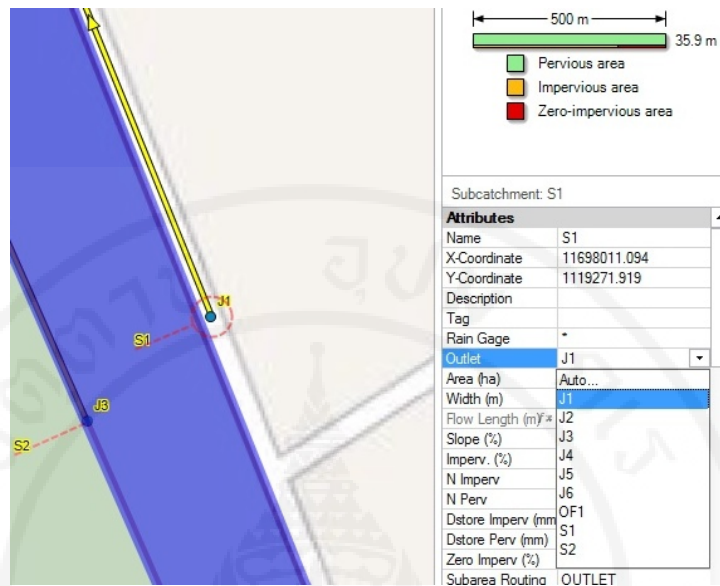


Figure 3.19 Linking subcatchment to outlet junction

8. Assigning subcatchment attributes

Although the Area attributes of a PCSWMM subcatchment and the Length attribute of a PCSWMM conduit are updated by editing the conduit shape or the subcatchments polygon shape, other attributes of the subcatchment are not automatically computed. However, many attributes can be calculated by the GIS capabilities of PCSWMM using background layers that contain relevant data.

An overland flow path for each subcatchment would be defined to compute an initial estimate of the subcatchment width attributes. In most cases, the flow path should represent the average maximum length of overland sheet flow for the subcatchment. A first estimate of the Width parameter can be obtained by dividing the subcatchment Area by the length of the overland flow path. Firstly, a shape file would be created to compute the length of the overland flow path and to use the Set Flow Length/Width tool to calculate the subcatchment widths;

- Ensure the subcatchments layer is active.
- Click on the Tools button and click on the Set Flow Length/Width tool in the subcatchment section.
- In the Set Flow Length/Width tool, click on the New button to create a line shape file for drawing the overland flow paths.

- In the Create Flow Lengths Layer dialog, browse to the destination Folder to save the layer as Flow Path.shp as shown in Figure 3.20. The Set Flow Length/Width tool will close and the new layer will be created and added to the project.

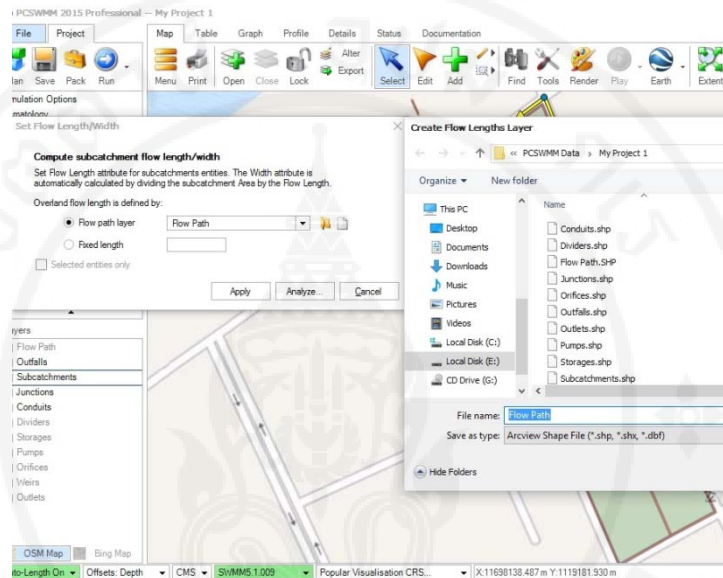


Figure 3.20 Creating flow length layer

- Check the Layers Panel in the Map panel to view the new layer. Ensure it is selected.
- Click the Add button in the toolbar of the Map panel.
- Draw the overland flow path by first clicking the western boundary of the polygon of subcatchment and then click at a point on the eastern boundary that is nearly perpendicular to the first point.
 - Press Enter Key to finish drawing the flow path line.

Now flow paths can be used to defined the Flow Length attributes for the subcatchments

- Ensure the subcatchment layer is active.
- Click on the Tools button and click one the Set Flow Length/Width tool.

- Under Overland flow length is defined by: choose the Flow path layer option and ensure the Flow Path layer is selected in the drop down list as shown in Figure 3.21.
- Ensure that Selected entities only box is not checked.

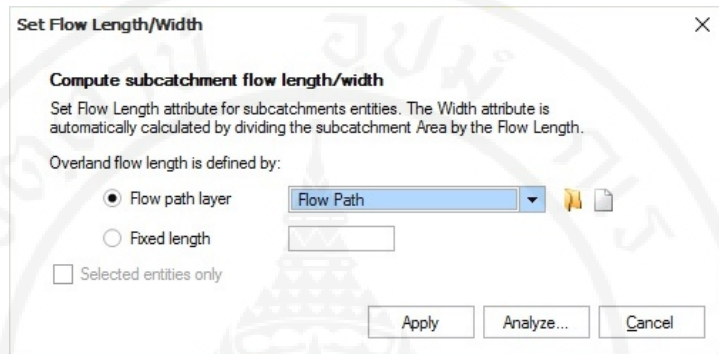


Figure 3.21 Choosing flow path layer option

- Click on the Analyze button to execute the computation and preview the results.

In Figure 3.22, the table will present the flow lengths and widths calculated for each subcatchment.

| Name | Area (ha) | Length (m) | Old Width (m) | New Width (m) |
|-------|------------|------------|---------------|---------------|
| S4_01 | 25.4561 | 651.4451 | 390.764 | 390.7636 |
| S4_03 | 21.0549 | 671.8996 | 313.364 | 313.3638 |
| S4_04 | 44.2529 | 695.3185 | 636.441 | 636.4407 |
| S2_01 | 6.3125 | 189.678 | 332.801 | 332.8008 |
| S2_03 | 5.5781 | 340.3212 | 163.907 | 163.9069 |
| S2_04 | 6.2137 | 311.3706 | 199.56 | 199.5596 |
| S2_02 | 7.1269 | 376.3586 | 189.365 | 189.3646 |
| S2_05 | 2.0412 | 146.5731 | 139.262 | 139.2616 |
| S2_06 | 8.5116 | 386.8226 | 220.039 | 220.0389 |
| S2_15 | 2.4036 | 153.8003 | 156.28 | 156.2805 |
| S2_08 | 6.3793 | 159.1655 | 400.797 | 400.7967 |
| S2_07 | 7.2998 | 193.8257 | 376.617 | 376.6167 |
| S2_10 | 3.2488 | 272.6639 | 119.15 | 119.1504 |
| S2_13 | 7.918 | 251.6003 | 314.706 | 314.7055 |
| S2_11 | 3.6018 | 278.8833 | 129.151 | 129.1508 |
| S2_09 | 4.2519 | 268.2033 | 158.533 | 158.5328 |
| S2_12 | 3.4546 | 285.2722 | 121.098 | 121.0984 |
| S2_14 | 4.9829 | 280.9275 | 177.373 | 177.3732 |

Figure 3.22 Flow lengths and widths calculated

- Review the table proposed changes and click Apply to effect the changes to the subcatchment Width parameters.

- Click Close to exit the Set Flow Length/Width tool.

The rest of the subcatchment attributes would be set, such as Manning's n values for impervious/pervious areas, percent of impervious area, effective surface slope, and infiltration parameter, after this step was done. The percentage of pervious/impervious areas were calculated manually by measuring the roof areas and the pavement area in Google Earth Pro.

- Ensure the Map panel is being displayed and the Subcatchments layer is selected from the Layers panel.
- Select individual subcatchment and add the attributes data manually.
- Enter the values in the Attributes panel as shown in the Figure 3.23 (from the previously computed data).

2 selected Subcatchments

| Attributes | |
|---------------------------------|--------|
| Name | |
| X-Coordinate | |
| Y-Coordinate | |
| Description | |
| Tag | |
| Rain Gage | * |
| Outlet | |
| Area (ha) | |
| Width (m) | |
| Flow Length (m)* | |
| Slope (%) | 0.5 |
| Imperv. (%) | 25 |
| N Imperv | 0.01 |
| N Perv | 0.1 |
| Dstore Imperv (mm) | 0.05 |
| Dstore Perv (mm) | 0.05 |
| Zero Imperv (%) | 25 |
| Subarea Routing | OUTLET |
| Percent Routed (%) | 100 |
| Curb Length | 0 |
| Snow Pack | |
| LID Controls | 0 |
| Groundwater | NO |
| Erosion | NO |
| Infiltration: Green-Ampt | |
| Suction Head (mm) | 3.5 |
| Conductivity (mm/d) | 0.5 |
| Initial Deficit (frac.) | 0.25 |

Figure 3.23 Attributes panel of the selected subcatchment

9. Dry weather flow calculation

In this model, a top-down approach was chosen to calculate the average wastewater generation rate of each sewersheds base on the impervious percentage of each sewersheds. Three distinct dry weather periods were selected to compute the average dry weather flow of the wastewater collection system. The total average dry

weather flow of the whole area was distributed to each subcatchment by the following equation.

$$\text{Wastewater Generation rate} = \frac{\text{Average DWF} \times \text{Impervious Area of Subcatchment}}{\text{Total Impervious area of the whole area}}$$

After the calculation was done, the wastewater generation rate for each subcatchment was assigned to respective junction node.

10. Assigning junction attributes

The main pipeline in the system conveying wastewater from south to north direction exists parallel along the beach and has variable slope from 0.0005 to 0.0017. PCSWMM can calculate the required invert elevation of the junctions in the drainage network by adding slope value of each sewer line using Set Slope Tool :

- Click on the Tools button to display the Tools browser (Fig 3.24).
- Click on the Set Slope tool in the node section.
- Select Set slope to: and enter the value for slope (e.g. 0.25%).
- Insure that Preserve node rim elevations and Raise upstream nodes invert elevation are both selected and Apply to flatter conduits only box is not selected.
- Click on the Analyze button.

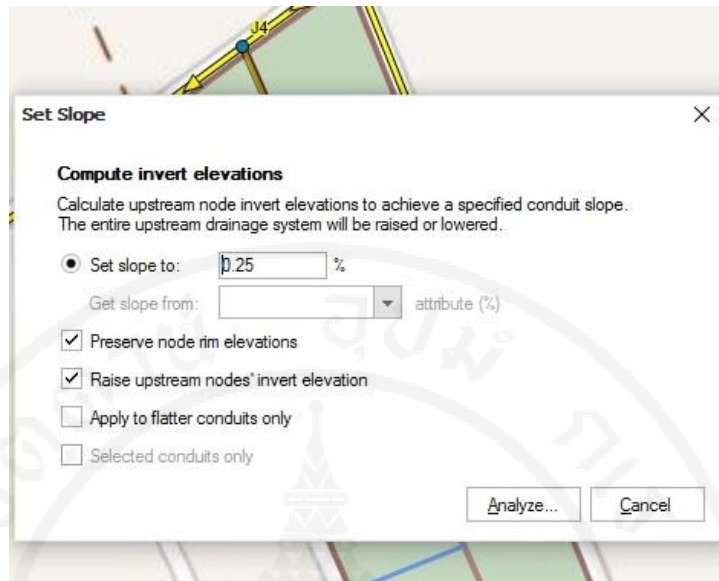


Figure 3.24 Set Slope toolbox

A table presenting the calculated changes appears (see Fig 3.25). Review the proposed changes and click the Apply button to implement them and then click on the Close button.

| Node Name | Node Type | Old Invert Elev. (m) | New Invert Elev. (m) | Change in Invert Elev. (m) | Old Depth (m) | New Depth (m) | Comments |
|-----------|-----------|----------------------|----------------------|----------------------------|---------------|---------------|----------|
| J1 | Junction | 0.476 | 0.183 | -0.293 | 6.524 | 6.817 | |
| J3 | Junction | 0.283 | 0.043 | -0.24 | 6.717 | 6.957 | |
| J2 | Junction | -0.176 | -0.323 | -0.147 | 6.176 | 6.323 | |
| J4 | Junction | 0.36 | -0.467 | -0.827 | 5.14 | 5.967 | |
| J5 | Junction | -0.541 | -0.604 | -0.063 | 3.541 | 3.604 | |
| J6 | Junction | -0.546 | -0.69 | -0.144 | 1.546 | 1.69 | |

Figure 3.25 Calculated result of elevation data for each junction

11. Creating a Rain Gauge

The last step before running the simulation is creating the rainfall input to the model. Firstly, the selected rainfall data in excel file will be imported to the

PCSWMM to create time series data using time series project tool as shown in Figure 3.26.

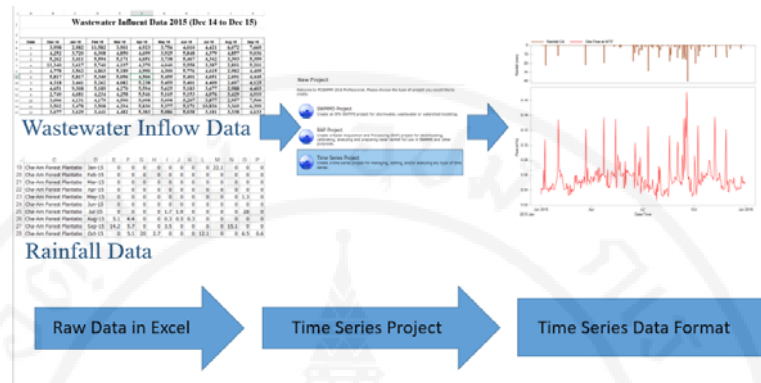


Figure 3.26 Creation of time series data

- Click on the Open button in the Graph panel and open the Microsoft Excel file.
- In the Open Custom Time Series Format dialog, set the Skip first drop down list to 3 (i.e. skip first three rows).
- In the first column of the table, set the header (first row) drop down list to Date/Time.
- In the second column of the table, set the header drop down list to Value.
- Also in the second column, in the second header row (below Value), select rain fall, and in the third header row, select m or in on the next row.
- Click on the OK button to import and display the time series in the Graph panel.
- Click Save to save the timeseries file.

After creating rainfall time series data, the rain gage can now be created by using this data.



Figure 3.27 Raingage editor toolbox

- Click the Menu button and select the Add to Time Series Editor
- Select the Time Series Data
- After selecting the time series data, Click on the Option and select Create Rain Gage. Now assign this rain gage to the subcatchments.
 - Click on the Subcatchments item in the Layers panel.
 - Press the Ctrl+A buttons to select all of the subcatchments.
 - In the Attributes panel, use the drop down list to set the Rain Gage attribute.

12. Running a simulation

Before analyzing the performance of the drainage system, we need to set some simulation options:

- Click Simulation Option in the Project panel at the left hand side of the screen.
- In the General tab of the Simulation Options dialog, the flow routing should already be set to Dynamic Wave. Also, the Infiltration Model is set to Green Ampt.
- Duration of the simulation can be set under the Dates tab.
- Reporting time can be set under the Time Steps tab. This time step controls the time resolution of the computed output time series.
- Click and close the Simulation Options dialog.
- Click the Run button in the Project Panel.

After running the model, a pop up message box indicates whether the run was successful or unsuccessful. If successful, the message relays continuity errors for surface runoff, flow routing and quality routing.

For a successful run, review the run statistics on the bottom right hand side of the screen. They are rendered based on their value. If the continuity error is less than 1% the error percentages will be shown in Green (Fig 3.28) and that mean the model is successfully run.

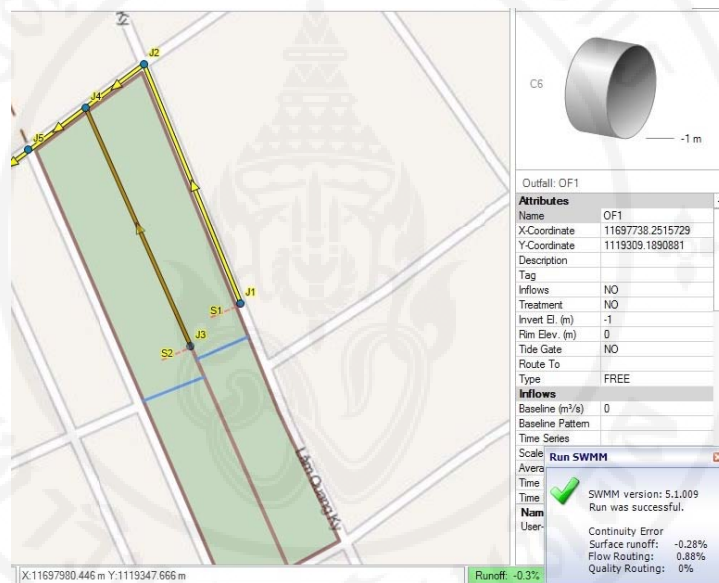


Figure 3.28 Successful running of Model

If unsuccessful, check the source of the error and try to fix it as follows:

- Select the Status tab and review the error messages carefully.
- Select the Details panel and review the input data in detail.
- Go back to the Map Panel, check whether all required attributes of each entity are entered and whether the entities are correctly linked.

To generate profile plots:

- Return to the map panel and select junction at one end of the pathway.
- Hold the Shift key down and click outfall at the far end of the pathway.

The path of connecting entities is selected.

- Click Profile button in the toolbar of the main menu to view the profiles as shown in Figure 3.29.

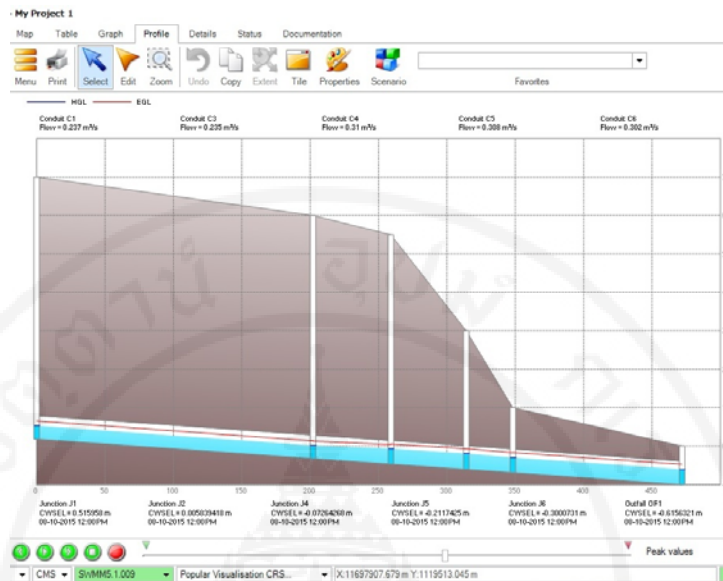


Figure 3.29 Profile of the selected pathway

- Click the Menu button in the Profile panel and select Show Peak Values to check surcharging nodes or conduits.

- Surcharging conditions will be signaled by red dots at the top of the junctions. If it is surcharging, the model can be used to resize the pipe diameters.

To generate a time series plot of the results:

- Open the Graph panel by selecting the Graph tab.
- In the Time series manager tree list, expand Links >> Flow group.
- Right-click on the Flow group item and choose Select All from the pop-up menu. The result will be shown by Graph as shown in Figure 3.30.
- Appearance of the result can be customized at the Graph properties editor.

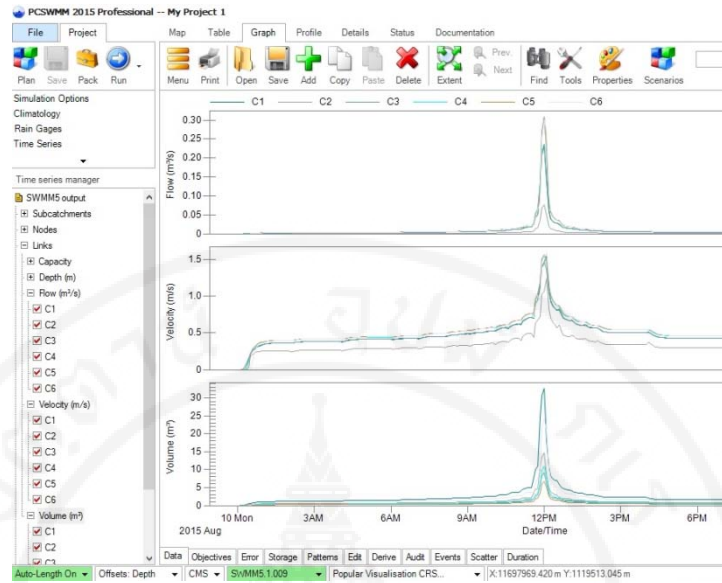


Figure 3.30 Time series plot of the results

3.2.5 Model Calibration

The process of running a model by a set of input data and then adjusting suitable model parameters to get a reasonable match between observed data and model predicted result is known as model calibration (US EPA, 1999). Models of existing systems should be calibrated and verified before they can be properly applied. The calibration checks generally contain velocity, depth, volume and flow for wastewater collection system modelling.

Model calibration consists of adjusting the sewer system attributes within reasonable limits to achieve model simulated results that closely replicate actual field-observed depths and flow and operator observations. The calibration of wet weather conditions was done by comparing the simulated and recorded flow, volume and the peak flow for the individual storm event (see section 4.4 of this report). The volumes comparison were made on a daily storm event within the period between 15 June 2015 and 20 July 2015. The calibration of existing wastewater collection system is provided in section 4.4 of this report. Sensitivity of surface runoff volume and peak flow estimates to key surface runoff parameters are listed in Table 4.1 in section 4.1.

3.2.6 Model Validation

Model validation is a process of comparing model results to monitoring data not used for calibration (i.e. different wet weather events and different periods of dry weather flow) with no changes to the model and its parameters. The model should be capable to meet the prescribed validation accuracy levels with no adjustments. If the model fails this test, the modeler needs to understand the cause of this failure and repeat calibration steps as required to address the problems.

3.2.7 Model Runs

Once the model has been created, it can be used for a variety of analyses. The value of the model lies in being able to examine various “what if” scenarios. The modeler should have some idea of the kinds of scenarios that will be simulated using the model. It is usually a good idea to develop a range of scenarios in conjunction with management, engineering, and operations personnel from the utility. In this research, the model was used to examine the proposed future development scenario in Cha-Am.

3.2.8 Developing Proposed Future Development Scenarios

A simple plan of layout of buildings and other structures were prepared from the primary information obtained during field visit as well as secondary data obtained from the internet as well as from the literature and past studies. The main idea of the proposed future development scenario was taken from the AIT students’ report that was submitted to Professor Kim Irvine on August, 2016.

3.2.8.1 Design of development in the proposed area

The first step was to determine the total area of the proposed development site. Google Earth Pro was used to draw a polygon representing the development area and the measurement tool in Google Earth Pro was used to calculate the area of polygon occupied by the proposed site. The total area of the development site is 1237650 m² as shown in Figure 3.31. Each zone contain only one building type as shown in Table 3.2.



Figure 3.31 Zoning of the proposed development area

Table 3.2 Area of each zone and the type of building

| Zone | Area (m ²) | Building type | No. of building | Area of building | Total building Area |
|------|------------------------|------------------------------|-----------------|------------------|---------------------|
| 1 | 140316 | Detached houses | 99 | 414.00 | 40986 |
| 2 | 258005 | Condo | 11 | 6821.30 | 75034 |
| 3 | 59857 | Twin houses | 30 | 525.97 | 15779 |
| 4 | 59125 | Low-cost Resort | 150 | 327.28 | 49092 |
| 5 | 178825 | Park | - | - | - |
| 6 | 113561 | Apartment | 11 | 7527.00 | 82797 |
| 7 | 206305 | Luxury Resort | 200 | 382.50 | 76500 |
| 8 | 116582 | Commercial and Shopping mall | 5 | 6276.61 | 31383 |
| 9 | 105074 | Luxury Condominium | 4 | 9697.60 | 38790 |

The data related with area of buildings were obtained from the previous study (Suwal et al., 2016)

The proposed development area was divided into nine zones and each zone is designed to contain only one type of building structure for simplicity. Zoning of the area was done considering factors such as aesthetic value, distance from other structures, proximity to the beach, convenience of the residents etc.

The area of building structure with associated parking space and appropriate spacing from adjacent structure was calculated as shown Table 3.2.

The number of building in each zone was determined based on this data and total area of each zone.

The population of each subcatchment and the wastewater generation rate was determined in order to calculate the dry weather flow as shown in Table 3.3. The dry weather flow was calculated based on the population and the typical flow rate of each building type (see Table 3.4).

Table 3.3 Total population of the area

| Zone | Building type | No. of building | No. of Floor | No. of flat/floor | Resident/ Flat* | Total Resident |
|------|------------------------------|-----------------|--------------|-------------------|-----------------|----------------|
| 1 | Detached houses | 99 | 1 | 1 | 3.6 | 356 |
| 2 | Condo | 11 | 8 | 34 | 3.6 | 10771 |
| 3 | Twin houses | 30 | 1 | 2 | 3.6 | 216 |
| 4 | Low-cost Resort | 150 | 1 | 2 | 2.0 | 600 |
| 5 | Park | - | - | - | - | - |
| 6 | Apartment | 11 | 5 | 34 | 2.0 | 3740 |
| 7 | Luxury Resort | 200 | 1 | 1 | 3.6 | 720 |
| 8 | Commercial and Shopping mall | 5 | - | - | - | - |
| 9 | Luxury Condominium | 4 | 8 | 34 | 3.6 | 3917 |
| | | | | | | 20320 |

*Data from (Census, 2010)

Table 3.4 Quantity of wastewater generation

| Zone | Building type | No. of building | Population | Typical flow rate (m ³ /unit/day)* | Dry weather flow(m ³ /day) |
|-----------------------------|----------------------------|-----------------|------------|---|---------------------------------------|
| 1 | Detached houses | 99 | 356.4 | 0.265 | 94.45 |
| | Convenience shop | 2 | 8 | 0.038 | 0.30 |
| | | | | | 94.75 |
| 2 | Condo | 11 | 10771.2 | 0.189 | 2035.76 |
| | Convenience shop | 2 | 8 | 0.038 | 0.30 |
| | | | | | 2036.06 |
| 3 | Twin houses | 30 | 216 | 0.580 | 125.28 |
| | Convenience shop | 2 | 8 | 0.038 | 0.30 |
| | | | | | 125.58 |
| 4 | Low-cost Resort | 150 | 600 | 0.580 | 348.00 |
| | Convenience shop | 2 | 8 | 0.038 | 0.30 |
| | | | | | 348.30 |
| 5 | Park | - | - | - | |
| 6 | Apartment | 11 | 3740 | 0.227 | 848.98 |
| | Convenience shop | 2 | 8 | 0.038 | 0.30 |
| | | | | | 849.28 |
| 7 | Luxury Resort | 200 | 720 | 0.568 | 408.96 |
| | Convenience shop | 2 | 8 | 0.038 | 0.30 |
| | | | | | 409.26 |
| 8 | Commercial & shopping mall | 5 | 250 | 0.038 | 9.50 |
| 9 | Luxury Condominium | 4 | 3916.8 | 0.580 | 2271.74 |
| | Convenience shop | 2 | 8 | 0.038 | 0.30 |
| | | | | | 2272.05 |
| Total Wastewater Generation | | | | | 6144.79 |

*From (Robert et al., 2006), (Walski et al., 2007)

3.2.8.2 PCSWMM Model Application

The wastewater collection system for the development area was designed as combined sewer system. For the combined sewer system, the wastewater and stormwater collected from the proposed development site was discharged into the old system at the point near the emergency pumping station. The proposed development area was divided into nine subcatchments to generate surface runoff as well as sanitary flow (see Figure 3.32). The impervious percentage was calculated for the subcatchment from the total area of each subcatchment and the area of the building Table 3.5. The junction nodes were provided to receive the inflow from

each subcatchment and the circular conduits with 1 m diameter were placed to route the wastewater flow toward the wastewater treatment plant and the required data were added (see Table 3.5 and 3.36). The largest storm event that used during the calibration period with 24 mm depth was used to run the simulation.



Figure 3.32 Design layout of the new wastewater collection system

Table 3.5 Assigned subcatchment attribute

| Name | Outlet | Area (ha) | Width (m) | Flow Length (m) | Slope (%) | Imperv. (%) |
|--------|--------|-----------|-----------|-----------------|-----------|-------------|
| Zone_1 | J8 | 14.032 | 371.383 | 377.8 | 0.5 | 29 |
| Zone_2 | J6 | 25.801 | 798.579 | 323.1 | 0.5 | 29 |
| Zone_3 | J5 | 10.507 | 248.173 | 423.4 | 0.5 | 26 |
| Zone_4 | J3 | 11.658 | 416.335 | 280.0 | 0.5 | 83 |
| Zone_5 | J4 | 11.356 | 451.176 | 251.7 | 0.5 | 0 |
| Zone_6 | J2 | 17.883 | 616.893 | 289.9 | 0.5 | 72 |
| Zone_7 | J2 | 20.631 | 870.779 | 236.9 | 0.5 | 37 |
| Zone_8 | J1 | 5.986 | 280.111 | 213.7 | 0.5 | 27 |
| Zone_9 | J1 | 5.913 | 289.403 | 204.3 | 0.5 | 37 |

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Surface Runoff Calculation

Since PCSWMM is running EPA SWMM5 engine, this section describes how SWMM5 converts precipitation excess (evaporation, rainfall less infiltration, and initial abstraction) into surface runoff (overland flow). Runoff generation of SWMM5 on a subcatchment is computed by subcatchment basis. A nonlinear reservoir was used to calculate rainfall producing surface runoff over a subcatchment.

Governing Equation

SWMM5 conceptualizes a subcatchment as a rectangular surface that has a uniform slope S and a width W that flows to a particular exit as shown in Figure 4.1. Overland flow is produced by the process of modelling the subcatchment as a nonlinear reservoir, as sketched in Figure 4.2.

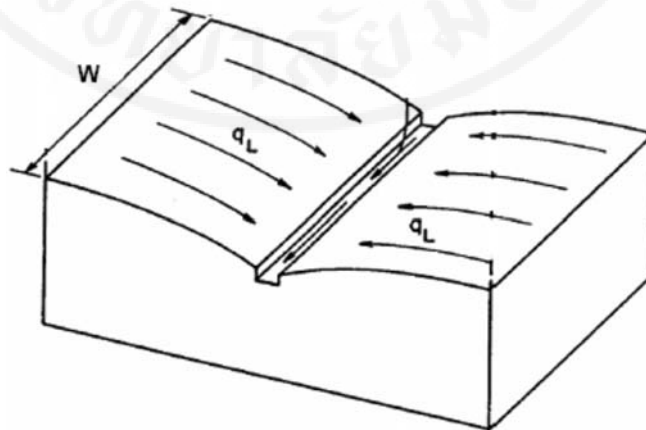


Figure 4.1 Idealized representation of a subcatchment.

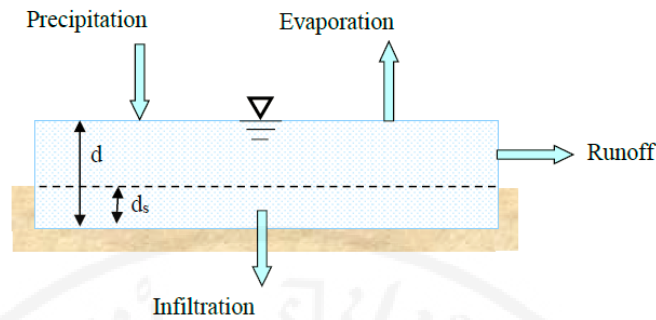


Figure 4.2 Nonlinear reservoir model of a subcatchment.

As shown in the Figure 4.2, the subcatchment receives inflow from precipitation and losses from evaporation and infiltration. The remaining extra water ponds on the subcatchment surface to a depth d . Pondered water directly above the depression storage depth ds can convert into runoff outflow q . Depression storage accounts for primary rainfall abstractions such as interception by flat roofs, and vegetation, surface ponding, and surface wetting.

From conservation of mass, the net change in depth d per unit of time t is simply the difference between inflow and outflow rates over the subcatchment:

$$\frac{\partial d}{\partial t} = i - e - f - q \tag{4.1}$$

where:

- i = rate of rainfall + snowmelt (m/s)
- e = surface evaporation rate (m/s)
- f = infiltration rate (m/s)
- q = runoff rate (m/s).

Note that the fluxes i , e , f , and q are expressed as flow rates per unit area ($\text{cms/m}^2 = \text{m/s}$).

Assuming that flow across the surface of the subcatchment acts as if it were uniform flow within a rectangular channel of height $d-ds$, width W (m), and slope S , the runoff's volumetric flow rate Q (cms) can be express by using the Manning equation as:

$$Q = \frac{1.49}{n} S^{1/2} R_x^{2/3} A_x \quad (4.2)$$

where:

- n = surface roughness coefficient
 S = average subcatchment slope (m/m)
 A_x = area across the width of the subcatchment (m²)
 R_x = the hydraulic radius (m).

Referring to Figures 4.1 and 4.2, A_x is a rectangular area with height $d-d_s$ and width W . Because W will be much larger every time than d it follows that $A_x = (d-d_s)W$ and $R_x = d-d_s$. Substituting these expressions into Equation 4.2 gives:

$$Q = \frac{1.49}{n} WS^{1/2} (d - d_s)^{5/3} \quad (4.3)$$

To obtain q which is a runoff flow rate per unit of surface area, Equation 4.3 is divided by the subcatchment's surface area, A :

$$q = \frac{Q}{A} = \frac{1.49WS^{1/2}}{An} (d - d_s)^{5/3} \quad (4.4)$$

Substitution Equation (4.4) into original mass balance relation (4.1) results in:

$$\frac{\partial d}{\partial t} = i - e - f - \alpha (d - d_s)^{5/3} \quad (4.5)$$

where α is defined as:

$$\alpha = \frac{1.49WS^{1/2}}{An} \quad (4.6)$$

When $d \leq d_s$, q is zero and the mass balance equation becomes simply:

$$\frac{\partial d}{\partial t} = i - e - f \tag{4.7}$$

Partitioning of the subcatchment

The surface runoff equation was developed on idealized rectangular subcatchment area basis. The subcatchment in the urban area can contain both pervious surfaces, which permit rainwater to penetrate into the impervious surfaces, and nearby soil. Moreover, it is usual for impervious surfaces to start producing runoff more or less, instantly after a storm incident occurs, well before its depression storage depth fills up. To model this manner, a subcatchment's the impervious area should be delineated into two subareas: one without depression storage and one with depression storage. In general, a subcatchment might contain three types of subareas as provided in Figure 4.3.

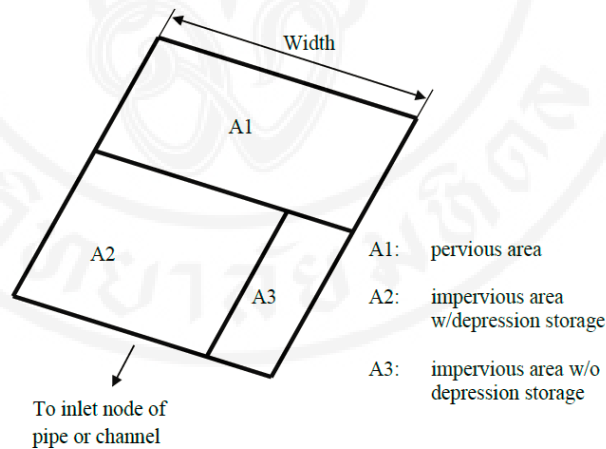


Figure 4.3 Idealized subcatchment partitioning for overland flow.

The α -terms to be used in Equation (4.5) for each subarea based on Figure 4.3 are:

$$\alpha_p = \frac{1.49WS^{1/2}}{A_1 n_p} \quad \text{for the pervious subarea A1} \tag{4.7}$$

$$\alpha_p = \frac{1.49WS^{1/2}}{(A_2 + A_3)n_l} \quad \text{for impervious subareas A2 and A3 (4.8)}$$

where:

- n_p = the pervious area's roughness
- n_l = the roughness of both impervious areas
- A_i = the surface area (m^2)

Parameter Estimates

Imperviousness

A subcatchment's percent imperviousness is a parameter that can be measured accurately from aerial photos or land use maps. The Google Earth Pro was used to measure the impervious area in this research. The percent imperviousness was calculated as:

$$\text{Impervious Percent} = (\text{Impervious Area} / \text{Subcatchment Area}) \times 100$$

The results of the calculated impervious percent of each subcatchment was shown in Table 4.2.

Subcatchment Width

Runoff calculation requires a modelling parameter width to indicate the shape or flow path of the subcatchment. The width of the direct connection subcatchment was calculated as:

$$\text{Width} = \text{Area} / \text{Flow Length}$$

The flow length can be calculated using flow length/width tools as previously described in section 3.2.5. The calculated results of the width and flow length are shown in Table 4.2.

Slope

The slope of all subcatchment was assumed to be 0.5%, being a combination of commercial and single-family roof slopes and parking lot slopes. The slope can be adjust after model calibration if necessary.

Manning’s Roughness Coefficient, n

The manning’s roughness coefficient also was assumed as 0.01 before the model calibration.

Depression Storage

Depression storage is a volume that must be filled prior to the existence of runoff on both pervious and impervious areas (Viessman and Lewis, 2003). Depression storage for pervious and impervious areas was primarily assumed to be 0.05 mm.

Parameter Sensitivity

Sensitivity of surface runoff volume and peak flow estimates to key surface runoff parameters is listed in Table 4.1.

Table 4.1 Sensitivity of runoff volume and peak flow to surface runoff parameters

| Parameter | Typical effect on hydrograph | Effect of <u>increase</u> on runoff volume | Effect of <u>increase</u> on runoff peak | Comments |
|--------------------|------------------------------|--|--|--|
| Area | Significant | Increase | Increase | Less effect for a highly porous catchment |
| Imperviousness | Significant | Increase | Increase | Less effect when pervious areas have low infiltration capacity. |
| Width | Affects shape | Decrease | Increase | For storms of varying intensity, increasing the width tends to produce higher and earlier hydrograph peaks, a generally faster response. Only affects volume to the extent that reduced width on pervious areas provides more time for infiltration. |
| Slope | Affects shape | Decrease | Increase | Same as for width, but less sensitive, since flow is proportional to square root of slope. |
| Roughness | Affects shape | Increase | Decrease | Inverse effect as for width. |
| Depression storage | Moderate | Decrease | Decrease | Significant effect only for low-depth storms. |

Calculated results of surface runoff

Table 4.2 Results of infiltration and surface runoff for each subcatchment

| Name | Area (ha) | Width (m) | Flow Length (m) | Slope (%) | Imperv. (%) | N Imperv | N Perv | Dstore Imperv (mm) | Dstore Perv (mm) | Zero Imperv (%) | Percent Routed (%) | Suction Head (mm) | Conductivity (mm/hr) | Initial Deficit (frac.) | Precipitation (mm) | Infiltration (mm) | Runoff Depth (mm) | Runoff Volume (ML) | Peak Runoff (m ³ /s) | Runoff Coefficient |
|-------|-----------|-----------|-----------------|-----------|-------------|----------|--------|--------------------|------------------|-----------------|--------------------|-------------------|----------------------|-------------------------|--------------------|-------------------|-------------------|--------------------|---------------------------------|--------------------|
| S1_01 | 1.031 | 106.7 | 96.6 | 0.5 | 54 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.77 | 0.89 | 0.01 | 0.00 | 0.53 |
| S1_02 | 1.072 | 105.8 | 101.3 | 0.5 | 79 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.35 | 1.3 | 0.01 | 0.00 | 0.774 |
| S1_03 | 1.562 | 153.0 | 102.0 | 0.5 | 71 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.48 | 1.16 | 0.02 | 0.00 | 0.696 |
| S1_04 | 1.477 | 149.1 | 99.0 | 0.5 | 89 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.18 | 1.46 | 0.02 | 0.00 | 0.871 |
| S1_05 | 1.463 | 139.5 | 104.8 | 0.5 | 55 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.75 | 0.9 | 0.01 | 0.00 | 0.539 |
| S1_06 | 1.367 | 140.7 | 97.2 | 0.5 | 54 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.77 | 0.89 | 0.01 | 0.00 | 0.53 |
| S1_07 | 2.001 | 195.5 | 102.4 | 0.5 | 66 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.57 | 1.08 | 0.02 | 0.00 | 0.647 |
| S1_08 | 1.958 | 201.8 | 97.0 | 0.5 | 77 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.38 | 1.26 | 0.02 | 0.00 | 0.754 |
| S1_09 | 1.412 | 140.0 | 100.9 | 0.5 | 19 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.36 | 0.31 | 0 | 0.00 | 0.188 |
| S1_10 | 1.258 | 132.6 | 94.9 | 0.5 | 44 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.94 | 0.72 | 0.01 | 0.00 | 0.432 |
| S1_11 | 2.094 | 204.4 | 102.5 | 0.5 | 45 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.92 | 0.74 | 0.02 | 0.00 | 0.442 |
| S1_12 | 1.870 | 196.6 | 95.1 | 0.5 | 73 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.45 | 1.2 | 0.02 | 0.00 | 0.715 |
| S1_13 | 2.627 | 265.6 | 98.9 | 0.5 | 31 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.15 | 0.51 | 0.01 | 0.00 | 0.305 |
| S1_14 | 2.558 | 264.0 | 96.9 | 0.5 | 50 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.84 | 0.82 | 0.02 | 0.00 | 0.491 |
| S1_15 | 1.411 | 140.9 | 100.1 | 0.5 | 96 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.07 | 1.57 | 0.02 | 0.00 | 0.939 |
| S1_16 | 1.347 | 143.2 | 94.1 | 0.5 | 98 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.03 | 1.61 | 0.02 | 0.00 | 0.959 |
| S1_17 | 1.548 | 159.3 | 97.1 | 0.5 | 25 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.26 | 0.41 | 0.01 | 0.00 | 0.247 |
| S1_18 | 1.450 | 155.5 | 93.2 | 0.5 | 75 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.42 | 1.23 | 0.02 | 0.00 | 0.735 |
| S1_19 | 1.178 | 122.3 | 96.3 | 0.5 | 96 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.07 | 1.57 | 0.02 | 0.00 | 0.939 |
| S1_20 | 1.207 | 120.1 | 100.5 | 0.5 | 99 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.02 | 1.62 | 0.02 | 0.00 | 0.968 |
| S1_21 | 1.394 | 144.8 | 96.2 | 0.5 | 80 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.33 | 1.31 | 0.02 | 0.00 | 0.783 |
| S1_22 | 1.392 | 141.6 | 98.3 | 0.5 | 98 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.03 | 1.61 | 0.02 | 0.00 | 0.959 |
| S1_23 | 2.144 | 223.4 | 96.0 | 0.5 | 69 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.52 | 1.13 | 0.02 | 0.00 | 0.676 |
| S1_24 | 2.177 | 228.8 | 95.2 | 0.5 | 72 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.47 | 1.18 | 0.03 | 0.00 | 0.706 |
| S1_25 | 1.628 | 171.2 | 95.1 | 0.5 | 50 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.84 | 0.82 | 0.01 | 0.00 | 0.491 |
| S1_26 | 1.593 | 167.9 | 94.9 | 0.5 | 65 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.59 | 1.07 | 0.02 | 0.00 | 0.637 |
| S1_27 | 1.383 | 138.6 | 99.8 | 0.5 | 42 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.97 | 0.69 | 0.01 | 0.00 | 0.413 |
| S1_28 | 1.358 | 140.5 | 96.6 | 0.5 | 65 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.59 | 1.07 | 0.01 | 0.00 | 0.637 |
| S1_29 | 0.472 | 134.2 | 35.2 | 0.5 | 75 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.42 | 1.24 | 0.01 | 0.00 | 0.739 |
| S1_30 | 1.031 | 132.5 | 77.8 | 0.5 | 50 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.84 | 0.82 | 0.01 | 0.00 | 0.492 |
| S1_31 | 1.284 | 213.5 | 60.1 | 0.5 | 60 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.67 | 0.99 | 0.01 | 0.00 | 0.59 |
| S1_32 | 2.183 | 122.2 | 178.7 | 0.5 | 80 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.33 | 1.31 | 0.03 | 0.00 | 0.781 |
| S2_01 | 6.313 | 332.8 | 189.7 | 0.5 | 66 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.57 | 1.08 | 0.07 | 0.01 | 0.645 |
| S2_02 | 7.127 | 189.4 | 376.4 | 0.5 | 27 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.22 | 0.44 | 0.03 | 0.00 | 0.264 |
| S2_03 | 5.578 | 163.9 | 340.3 | 0.5 | 12 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.47 | 0.2 | 0.01 | 0.00 | 0.118 |
| S2_04 | 6.214 | 199.6 | 311.4 | 0.5 | 17 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.39 | 0.28 | 0.02 | 0.00 | 0.167 |
| S2_05 | 2.041 | 139.3 | 146.6 | 0.5 | 20 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.34 | 0.33 | 0.01 | 0.00 | 0.197 |
| S2_06 | 8.512 | 220.0 | 386.8 | 0.5 | 47 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.89 | 0.77 | 0.07 | 0.00 | 0.458 |

Table 4.2 Results of infiltration and surface runoff for each subcatchment (cont.)

| Name | Area (ha) | Width (m) | Flow Length (m) | Slope (%) | Imperv. (%) | N Imperv | N Perv | Dstore Imperv (mm) | Dstore Perv (mm) | Zero Imperv (%) | Percent Routed (%) | Suction Head (mm) | Conductivity (mm/hr) | Initial Deficit (frac.) | Precipitation (mm) | Infiltration (mm) | Runoff Depth (mm) | Runoff Volume (ML) | Peak Runoff (m ³ /s) | Runoff Coefficient |
|-------|-----------|-----------|-----------------|-----------|-------------|----------|--------|--------------------|------------------|-----------------|--------------------|-------------------|----------------------|-------------------------|--------------------|-------------------|-------------------|--------------------|---------------------------------|--------------------|
| S2_07 | 7.300 | 376.6 | 193.8 | 0.5 | 67 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.55 | 1.1 | 0.08 | 0.01 | 0.655 |
| S2_08 | 6.379 | 400.8 | 159.2 | 0.5 | 17 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.39 | 0.28 | 0.02 | 0.01 | 0.168 |
| S2_09 | 4.252 | 158.5 | 268.2 | 0.5 | 19 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.36 | 0.31 | 0.01 | 0.00 | 0.186 |
| S2_10 | 3.249 | 119.2 | 272.7 | 0.5 | 63 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.62 | 1.03 | 0.03 | 0.00 | 0.615 |
| S2_11 | 3.602 | 129.2 | 278.9 | 0.5 | 19 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.36 | 0.31 | 0.01 | 0.00 | 0.186 |
| S2_12 | 3.455 | 121.1 | 285.3 | 0.5 | 16 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.41 | 0.26 | 0.01 | 0.00 | 0.157 |
| S2_13 | 7.918 | 314.7 | 251.6 | 0.5 | 19 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.36 | 0.31 | 0.02 | 0.00 | 0.187 |
| S2_14 | 4.983 | 177.4 | 280.9 | 0.5 | 47 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.89 | 0.77 | 0.04 | 0.00 | 0.459 |
| S2_15 | 2.404 | 156.3 | 153.8 | 0.5 | 69 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.52 | 1.13 | 0.03 | 0.00 | 0.675 |
| S2_16 | 2.640 | 136.4 | 193.5 | 0.5 | 56 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.74 | 0.92 | 0.02 | 0.00 | 0.548 |
| S2_17 | 5.743 | 289.0 | 198.7 | 0.5 | 51 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.82 | 0.84 | 0.05 | 0.00 | 0.499 |
| S3_01 | 3.387 | 187.6 | 180.6 | 0.5 | 51 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.82 | 0.84 | 0.03 | 0.00 | 0.499 |
| S3_02 | 8.949 | 432.3 | 207.0 | 0.5 | 43 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.95 | 0.7 | 0.06 | 0.01 | 0.421 |
| S3_03 | 8.073 | 306.1 | 263.7 | 0.5 | 27 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.22 | 0.44 | 0.04 | 0.00 | 0.265 |
| S3_04 | 20.019 | 501.7 | 399.0 | 0.5 | 29 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.19 | 0.47 | 0.1 | 0.01 | 0.283 |
| S3_05 | 19.243 | 517.3 | 372.0 | 0.5 | 11 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.49 | 0.18 | 0.03 | 0.01 | 0.108 |
| S3_06 | 9.424 | 239.1 | 394.2 | 0.5 | 20 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.34 | 0.33 | 0.03 | 0.00 | 0.196 |
| S3_07 | 20.493 | 400.3 | 511.9 | 0.5 | 12 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.47 | 0.2 | 0.04 | 0.01 | 0.118 |
| S3_08 | 19.074 | 426.5 | 447.2 | 0.5 | 6 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.57 | 0.1 | 0.02 | 0.01 | 0.059 |
| S3_09 | 7.771 | 225.8 | 344.1 | 0.5 | 7 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.56 | 0.12 | 0.01 | 0.00 | 0.069 |
| S3_10 | 11.899 | 284.6 | 418.1 | 0.5 | 7 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.56 | 0.12 | 0.01 | 0.00 | 0.069 |
| S3_11 | 38.024 | 672.4 | 565.5 | 0.5 | 0 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.67 | 0 | 0 | 0.00 | 0 |
| S3_12 | 9.812 | 295.4 | 332.2 | 0.5 | 4 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.61 | 0.07 | 0.01 | 0.00 | 0.04 |
| S4_01 | 25.456 | 390.8 | 651.4 | 0.5 | 82 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.3 | 1.33 | 0.34 | 0.01 | 0.793 |
| S4_03 | 21.055 | 313.4 | 671.9 | 0.5 | 75 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.42 | 1.22 | 0.26 | 0.01 | 0.725 |
| S4_04 | 44.253 | 636.4 | 695.3 | 0.5 | 67 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.55 | 1.09 | 0.48 | 0.01 | 0.649 |
| S5_01 | 14.616 | 286.5 | 510.2 | 0.5 | 32 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 1.14 | 0.52 | 0.08 | 0.00 | 0.312 |
| S5_02 | 2.628 | 117.3 | 224.0 | 0.5 | 84 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.27 | 1.37 | 0.04 | 0.00 | 0.819 |
| S5_03 | 2.910 | 98.7 | 294.9 | 0.5 | 48 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.87 | 0.79 | 0.02 | 0.00 | 0.469 |
| S5_04 | 8.071 | 222.2 | 363.3 | 0.5 | 13 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 1.46 | 0.21 | 0.02 | 0.00 | 0.128 |
| S5_05 | 8.608 | 116.3 | 740.2 | 0.5 | 47 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.89 | 0.76 | 0.07 | 0.00 | 0.456 |
| S5_06 | 14.808 | 288.3 | 513.6 | 0.5 | 65 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.67 | 0.59 | 1.06 | 0.16 | 0.00 | 0.631 |
| S5_07 | 9.053 | 175.3 | 516.4 | 0.5 | 47 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.89 | 0.77 | 0.07 | 0.00 | 0.457 |
| S5_08 | 8.015 | 189.0 | 424.1 | 0.5 | 78 | 0.01 | 0.1 | 0.05 | 0.05 | 25 | 100 | 3.5 | 0.5 | 0.25 | 1.68 | 0.37 | 1.27 | 0.1 | 0.00 | 0.757 |

4.2 Infiltration Calculation

The process of rainfall penetration into the soil and fills the pores of the underlying soil is called Infiltration (Akan and Houghtalen, 2003). The biggest loss of rainwater usually occur with infiltration. PCSWMM provides a choice of five different approaches for calculating soil infiltration rates – the Horton, Modified Horton, Green-Ampt, Modified Green-Ampt, and Curve Number models. The Green-Ampt method

was selected to use in this model since it is based on physical parameters that can be associated to the site's soil type.

Governing Equations

The concept of the Green-Ampt infiltration process is one in which infiltrated water moves vertically downward in a saturated layer, beginning at the surface (Figure 4.4) (Green and Ampt, 1991). In the wetted zone the moisture content θ is at saturation θ_s while the moisture content in the un-wetted zone is at some known initial level θ_i .

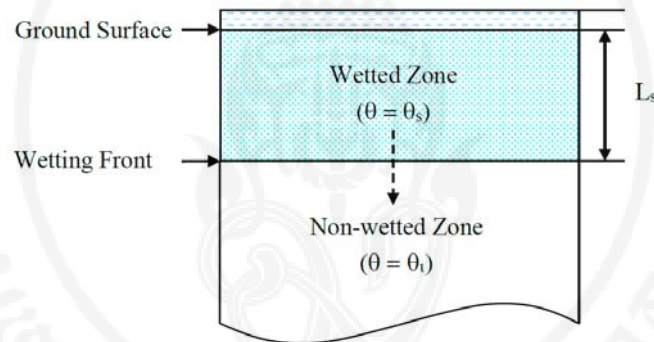


Figure 4.4 Two-zone representation of the Green-Ampt infiltration model (Nicklow et al., 2006)

$$f_p = K_s \left[1 + \frac{\psi_s \theta_d}{F} \right] \quad (4.9)$$

where:

- K_s = saturated hydraulic conductivity (m/s)
- ψ_s = suction head along the wetting front (m)
- θ_d = initial moisture deficit (m)
- F = cumulative infiltration (m/s).

Parameter Estimate

The soil parameters that need to supply for each subcatchment for the Green-Ampt infiltration method are:

- K_s = the saturated hydraulic conductivity (m/s or mm/hr),

- ψ_s = suction head along the wetting front (m or mm)
- θ_d = the maximum moisture deficit available (volume of dry voids per volume of soil)

Saturated Hydraulic Conductivity (K_s)

Possibly the greatest only source to approximate the saturated hydraulic conductivity (K_s) and suction head (ψ_s) for a wide range of soils – and one that makes use of the Green-Ampt method relatively attractive – is the data by Rawls et al. (1983), shown in Table 4.3.

Table 4.3 Green-Ampt parameters for different soil classes (Rawls et al., 1983)

| Soil Class | Porosity, ϕ | Effective Porosity, ϕ_e^* | Wetting Front Suction Head, ψ_s (in) | Saturated Hydraulic Conductivity, K_s (in/hr) |
|-----------------|------------------------|--------------------------------|---|---|
| Sand | 0.437 (0.374–0.500) | 0.417 (0.354–0.480) | 1.95 (0.38–9.98) | 4.74 |
| Loamy sand | 0.437 (0.363–0.506) | 0.401 (0.329–0.473) | 2.41 (0.53–11.00) | 1.18 |
| Sandy loam | 0.453 (0.351–0.555) | 0.412 (0.283–0.541) | 4.33 (1.05–17.90) | 0.43 |
| Loam | 0.463 (0.375–0.551) | 0.434 (0.334–0.534) | 3.50 (0.52–23.38) | 0.13 |
| Silt loam | 0.501 (0.420–0.582) | 0.486 (0.394–0.578) | 6.57 (1.15–37.56) | 0.26 |
| Sandy clay loam | 0.398 (0.332–0.464) | 0.330 (0.235–0.425) | 8.60 (1.74–42.52) | 0.06 |
| Clay loam | 0.464 (0.409–0.519) | 0.309 (0.279–0.501) | 8.22 (1.89–35.87) | 0.04 |
| Silty clay loam | 0.471 (0.418–0.524) | 0.432 (0.347–0.517) | 10.75 (2.23–51.77) | 0.04 |
| Sandy clay | 0.430 (0.370–0.490) | 0.321 (0.207–0.435) | 9.41 (1.61–55.20) | 0.02 |
| Silty clay | 0.479 (0.425–0.533) | 0.423 (0.334–0.512) | 11.50 (2.41–54.88) | 0.02 |
| Clay | 0.475 (0.427–0.523) | 0.385 (0.269–0.501) | 12.45 (2.52–61.61) | 0.01 |

*Effective porosity is the difference between the porosity and the residual moisture content that remains after a saturated soil is allowed to drain thoroughly

Suction Head (ψ_s)

The suction head is the most difficult parameter to measure and the detailed data are rare for most soils. Luckily, the results gotten for Green-Ampt infiltration are not very sensitive to the estimate of ψ_s (Brakensiek and Onstad, 1977). Brakensiek et al. (1981) noted that ψ_s was very much interrelated with hydraulic conductivity over all soil classes. Using nonlinear regression on the average values for these two variables listed in Table 4.4 produces the following relationship for K_s in in/hr and ψ_s in inches:

$$\psi_s = 3.237K_s^{-0.328} (R^2 = 0.9) \quad (4.10)$$

Maximum Moisture Deficit (θ_{dmax})

The maximum moisture deficit, θ_{dmax} is defined as the difference between the moisture content at saturation and at the start of the simulation. Because this parameter is the most sensitive of the three parameters for estimates of runoff from pervious areas (Brakensiek and Onstad, 1977), some care should be taken in determining the best θ_{dmax} value to use. Table 4.4, derived from Clapp and Hornberger (1973), is the source of θ_{dmax} values for various soil types.

Table 4.4 Typical values of θ_{dmax} for various soil types.

| Soil Texture | Typical θ_{dmax} at Soil Wilting Point |
|-----------------|---|
| Sand | 0.34 |
| Sandy Loam | 0.33 |
| Silt Loam | 0.32 |
| Loam | 0.31 |
| Sandy Clay Loam | 0.26 |
| Clay Loam | 0.24 |
| Clay | 0.21 |

The calculated infiltration values for each subcatchment are shown in Figure 4.2. The require parameter to use in the Equation 4.9 were obtained from the literature and previous studies as described in perivious section.

4.3 Flow Routing Equation

Flow routing within a conduit link in SWMM 5 is ran by the conservation of mass and momentum equations for gradually varied, unsteady flow (i.e., the Saint-Venant flow equations). The PCSWMM provide three options used to solve these equations:

- Steady Flow Routing;
- Kinematic Wave Routing; and
- Dynamic Wave Routing.

The dynamic wave routing option was chosen to reduce flow continuity error. Dynamic wave routing solves the complete one-dimensional Saint Venant flow equations that consist of the continuity and momentum equations for conduits and a volume continuity equation at nodes, and therefore produces the most theoretically accurate results for pumping and surcharging conditions. PCSWMM routing calculations were done in 5 second time intervals, with output reporting done every 30 minutes as well as averaging over an entire simulation period.

Governing Equation

SWMM 5 solve the conservation of mass and momentum equations that govern the unsteady flow of water through a drainage network of pipes and channels. These equations, known as the Saint-Venant equations, can be expressed in the following form for flow along an individual conduit:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad \text{Continuity (4.11)}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(Q^2 / A)}{\partial x} + gA \frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \quad \text{Momentum (4.12)}$$

where:

- x = distance along the conduit,
- t = time,
- A = cross-sectional area,
- Q = flow rate,
- H = the hydraulic head of water in the conduit (elevation head plus any possible pressure head),
- S_f = the friction slope (head loss per unit length),
- h_L = the local energy loss per unit length of conduit, and
- g = the acceleration of gravity.

The friction slope S_f can be expressed in terms of the Manning equation as:

$$S_f = \frac{n^2 V |V|}{k^2 R^{4/3}}$$

where:

- n = the Manning roughness coefficient,
- V = the flow velocity (equal to Q/A),
- R = the hydraulic radius of the flow's cross-section, and
- k = 1.49 for US units or 1.0 for metric units.

The local energy loss per unit length of conduit h_L can be expressed as:

$$h_L = \frac{KV^2}{2gL}$$

where:

- K = a local loss coefficient at location x and
- L = the conduit length.

When analyzing a single conduit with the equations 4.11 and 4.12, one needs a set of initial conditions for H and Q at time 0 as well as boundary conditions at $x = 0$ and $x = L$ for all times t .

When analyzing a network of conduits, an additional continuity relationship is required for the junction nodes that connect two or more conduits together (see Figure 4.5). In SWMM a continuous water surface is assumed to exist between the water elevation at the node and in the conduits that enter and leave the node (with the exception of free fall drops should they occur). The change in hydraulic head H at the node with respect to time can be expressed as:

$$\frac{\partial H}{\partial t} = \frac{\Sigma Q}{A_{store} + \Sigma A_s} \tag{4.13}$$

where:

- A_{store} = the surface area of the node itself,
- ΣA_s = the surface area contributed by the conduits connected to the node,
- ΣQ = the net flow into the node (inflow – outflow for all node)

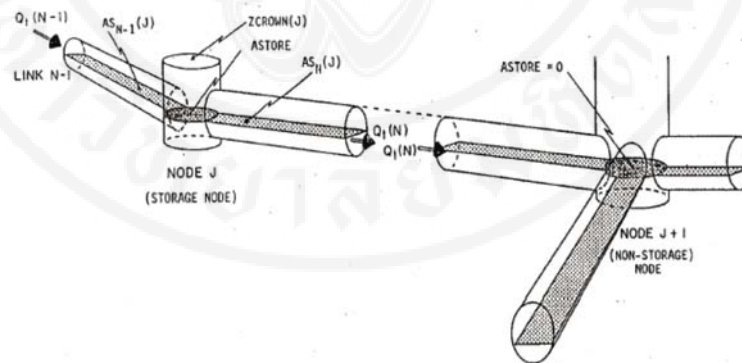


Figure 4.5 Node-link representation of a drainage system in SWMM (Roesner et al, 1992).

General solution for conduits

Equations 4.11, 4.12, and 4.13 are solved in SWMM by converting them into an explicit set of finite difference formulas that compute the flow in each conduit and head at each node for time $t + \Delta t$ as functions of known values at time t . The equation solved for the flow in each conduit is:

$$Q_{t+\Delta t} = \frac{Q_t + \Delta Q_{gravity} + \Delta Q_{inertial}}{1 + \Delta Q_{friction} + \Delta Q_{losses}} \quad (4.14)$$

The individual ΔQ terms have been named for the type of force they represent and are given by the following expressions:

$$Q_{gravity} = g\bar{A}(H_1 - H_2)\Delta t / L$$

$$Q_{inertial} = 2\bar{V}(\bar{A} - A_t) + \bar{V}^2(A_2 - A_1)\Delta t / L$$

$$\Delta Q_{friction} = \frac{gn^2|\bar{V}|\Delta t}{k^2\bar{R}^{4/3}}$$

$$\Delta Q_{losses} = \frac{\sum_i K_i |V_i| \Delta t}{2L}$$

where:

\bar{A} = average cross-sectional flow area in the conduit,

\bar{R} = average hydraulic radius in the conduit,

\bar{V} = average flow velocity in the conduit,

V_i = local flow velocity at location i along the conduit,

K_i = local loss coefficient at location i along the conduit,

H_1 = head at upstream node of conduit,

H_2 = head at downstream node of conduit,

A_1 = cross-sectional area at the upstream end of the conduit,

A_2 = cross-sectional area at the downstream end of the conduit.

The equation solved for the head at each node is:

$$H_{t+\Delta t} = H_t \frac{\Delta Vol}{(A_{store} + \sum A_s)_{t+\Delta t}} \quad (4.15)$$

where ΔVol is the net volume flowing through the node over the time step as given by:

$$\Delta Vol = 0.5 \left[(\sum Q)_t + (\sum Q)_{t+\Delta t} \right] \Delta t$$

4.4 Model Calibration

Model calibration began with the selection of storm events that would help refine model parameters. The period between 15 June 2015 and 20 July 2015 was selected as a model calibration period because the correlation between the rainfall data and the observed inflow to WWTP were reasonably match in this period. PCSWMM was calibrated using observed WWTP inflow data and daily rainfall data for the period 15 June to 20 July 2015 (Figure 4.6). The location of rain gage and calibration point are shown in Figure 4.7. PCSWMM routing calculations were done in 5-second time intervals, with output reporting done every 30 minutes as well as averaging over an entire simulation period. Figure 4.8 shows the analysis option of calibration period in PCSWMM. The model assumes that all pumps included operate at a constant rate. Pumps at the WWTP were not modeled. Instead, the downstream boundary condition was set as a free discharge from a single conduit representing the inlet to the WWTP. The calibration goals for volume were set at 10% and peak flows at 20% as provided in the previous study of Stonehouse et al., 2006 .

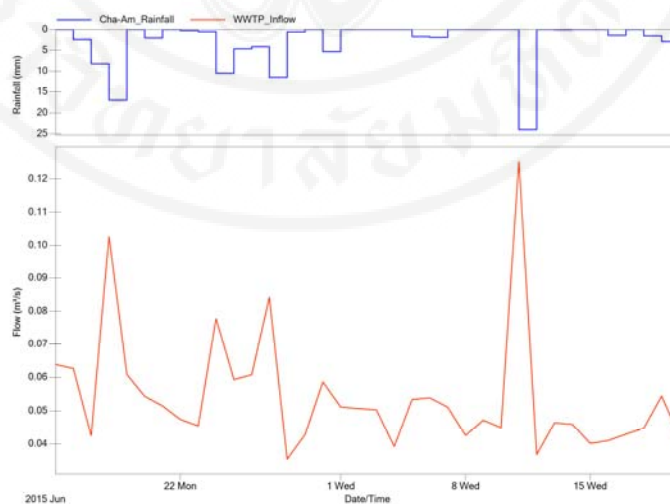


Figure 4.6 Observed WWTP inflow and daily rainfall data

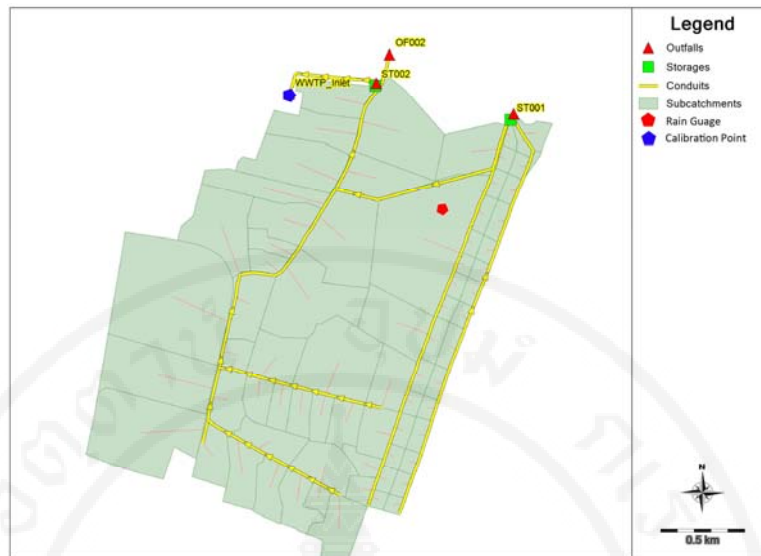


Figure 4.7 The location of rain gage and calibration point

```

*****
Analysis Options
*****
Flow Units ..... CMS
Process Models:
  Rainfall/Runoff ..... YES
  RDII ..... NO
  Snowmelt ..... NO
  Groundwater ..... NO
  Flow Routing ..... YES
  Ponding Allowed ..... NO
  Water Quality ..... NO
Infiltration Method ..... GREEN_AMPT
Flow Routing Method ..... DYNWAVE
Starting Date ..... JUN-15-2015 00:00:00
Ending Date ..... JUL-20-2015 00:00:00
Antecedent Dry Days ..... 0.0
Report Time Step ..... 00:30:00
Wet Time Step ..... 00:01:00
Dry Time Step ..... 00:30:00
Routing Time Step ..... 5.00 sec
Variable Time Step ..... YES
Maximum Trials ..... 8
Number of Threads ..... 2
Head Tolerance ..... 0.001500 m
    
```

Figure 4.8 Analysis option of calibration period

Model results for the period 15 June to 20 July 2015 are shown in Figure 4.9. The modelled flows are compared to the observed inflow to the WWTP, based on the PCSWMM model result. In the figure, the model accurately predicted the peak values for the three storm events. Also, the calibration was very good for all storms used to calibrate the model, which indicates that the rainfall is being distributed correctly within the subcatchment, even for smaller storm events. The total flow volume for these three storms collectively also was similar between the model result

and the observed with the value of 158800 m³ and 158400 m³, respectively. The comparison between the maximum flow, minimum flow, mean flow, and total flow during the calibration period were shown good results as shown in Table 4.5.

Table 4.5 Flow comparison between model predicted and observed

| Objective function | predicted | Observed |
|--------------------|-----------|----------|
| Maximum flow | 0.1175 | 0.1253 |
| Minimum flow | 0.05177 | 0.03542 |
| Mean flow | 0.0542 | 0.05404 |
| Total flow | 158800 | 158400 |

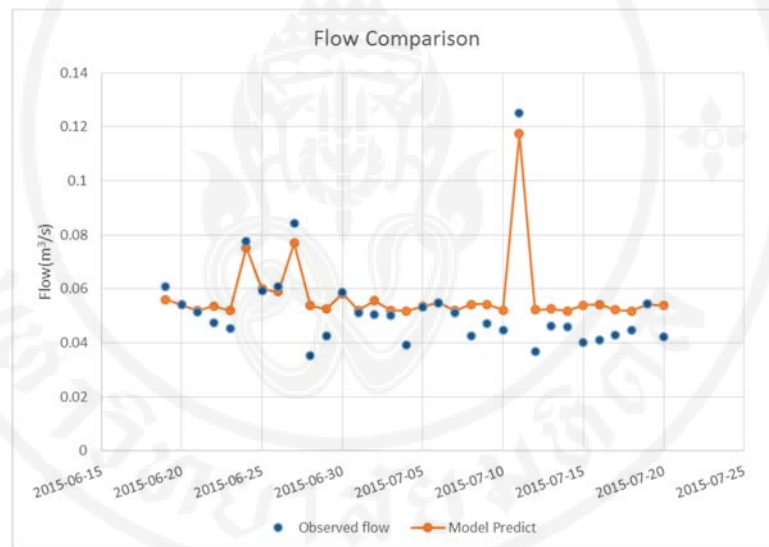


Figure 4.9 Flow comparison between model predict and observed

The observed peak flow for ten storm events were selected to compare with the model predicted peak flow during calibration period. A comparison between the modelled and observed peak flow for ten storm events showed good correspondence with the r² value of 0.99 (Figure 4.10).

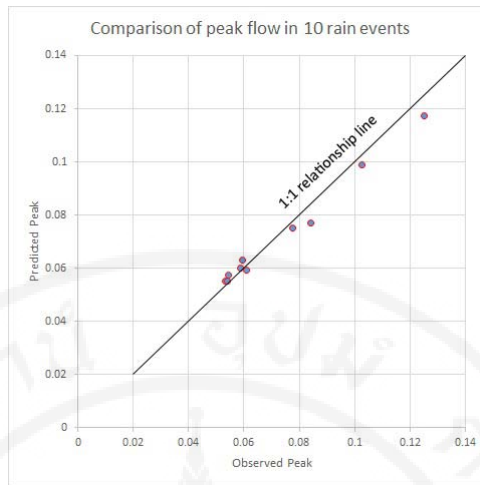


Figure 4.10 Comparison of modelled and observed peak flow in 10 rain events

A comparison of the modelled and observed event volume that entered the WWTP between 15 June and 20 July 2015 also showed good correspondence with the r^2 value of 0.89 (Figure 4.11). There was a slight bias towards model underestimation for the smaller events.

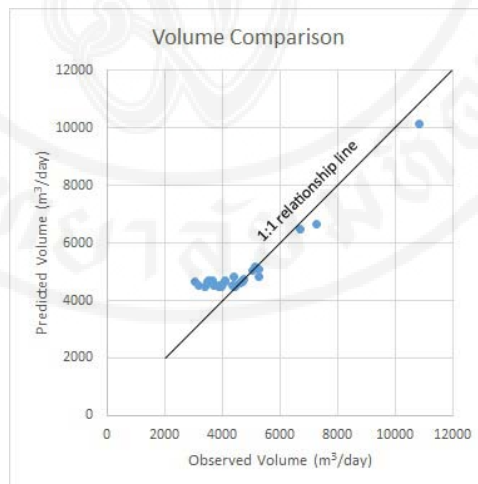


Figure 4.11 Volume comparison between model predict and observed

The model calibration results indicate that the modeled flow and volumes are close to the measured flow and volumes at the inlet of the wastewater treatment within 10 significant storm events during the calibration period as shown in Table 4.6. The simulated peak flow also matches reasonably well the observed peak flow in terms of the 10 storm events. The calibration goals for volume and peak flows were set at 10% and 20%, respectively. These goals were met.

Table 4.6 Model calibration results for 10 significant storm events

| | Event 1 | Event 2 | Event 3 | Event 4 | Event 5 | Event 6 | Event 7 | Event 8 | Event 9 | Event 10 |
|------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|
| Rainfall (mm) | 17 | 10.5 | 4.6 | 4.1 | 11.5 | 5.3 | 1.7 | 1.9 | 24 | 2.9 |
| Observed Peak Flow (cu.m/s) | 0.1026 | 0.0777 | 0.0593 | 0.0608 | 0.0842 | 0.0587 | 0.0534 | 0.0538 | 0.1253 | 0.0544 |
| Predicted Peak Flow (cu.m/s) | 0.0988 | 0.0753 | 0.0630 | 0.0591 | 0.0770 | 0.0601 | 0.0552 | 0.0550 | 0.1175 | 0.0574 |
| Peak Flow difference(%) | -3.68 | -3.09 | 6.33 | -2.79 | -8.52 | 2.47 | 3.30 | 2.14 | -6.24 | 5.46 |
| Observed Volume (cu.m) | 8866 | 6713 | 5123 | 5256 | 7276 | 5068 | 4615 | 4651 | 10826 | 4700 |
| Predicted Volume (cu.m) | 8540 | 6505 | 5447 | 5109 | 6655 | 5193 | 4767 | 4751 | 10151 | 4956 |
| Volume difference | -3.68 | -3.10 | 6.32 | -2.80 | -8.53 | 2.47 | 3.29 | 2.15 | -6.23 | 5.45 |

4.5 Model Validation

After the model was calibrated, one additional recorded rainfall events were simulated to further verify the model results. The periods 19 July to 20 October 2015 was selected as a model validation period. The largest ten storm events during the first period were chosen for the purpose of model validation. A good correlation and comparison was achieved for the validation events as shown in Table 4.7. The simulated peak flow also matches reasonably well the observed peak flow although some discrepancies were found.

Table 4.7 Model validation result for 10 significant storm event during first period

| | Event 1 | Event 2 | Event 3 | Event 4 | Event 5 | Event 6 | Event 7 | Event 8 | Event 9 | Event 10 |
|------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|
| Rainfall (mm) | 7.7 | 6.1 | 17.5 | 14.2 | 15.1 | 24.6 | 25.1 | 35.3 | 14 | 30.1 |
| Observed Peak Flow (cu.m/s) | 0.069 | 0.0620 | 0.0953 | 0.1486 | 0.0862 | 0.1214 | 0.1252 | 0.1651 | 0.0849 | 0.1417 |
| Predicted Peak Flow (cu.m/s) | 0.0722 | 0.0703 | 0.1125 | 0.1046 | 0.0868 | 0.1359 | 0.1375 | 0.1704 | 0.0855 | 0.1263 |
| Peak Flow difference(%) | 4.18 | 13.39 | 18.05 | -29.61 | 0.70 | 11.94 | 9.82 | 3.21 | 0.71 | -10.87 |
| Observed Volume (cu.m) | 6242 | 6072 | 9719 | 9036 | 7500 | 11739 | 10817 | 14721 | 7390 | 10910 |
| Predicted Volume (cu.m) | 6238 | 6074 | 9720 | 9037 | 7500 | 11742 | 11880 | 14723 | 7387 | 10912 |
| Volume difference (%) | -0.06 | 0.03 | 0.01 | 0.02 | -0.01 | 0.02 | 9.82 | 0.01 | -0.04 | 0.02 |

4.6 Results of Proposed Future Development Scenario

The capacity of the wastewater treatment plant at Cha-Am municipality is 17000 m³/day and the average wastewater generated at present ranges from (3500 to 5000) m³/day with a peak discharge of 6000 m³/day. The modeled daily inflow to the wastewater treatment plant before implementing new collection system was 4534

m³/day during the simulation with 24 mm rainfall data. The inflow was increase to 10470 m³/day after implementing new collection system for the proposed development area in the model as provided in Figure 4.12. The quantity of wastewater discharged by the development area combined with the old system capacity into the wastewater treatment plant did not exceed the capacity of the plant.

The model was also run using the rainfall data during the calibration period, 15 June 2015 to 20 July 2015, to know the model response on the various rainfall event. Figure 4.13 show the comparison of inflow to WWTP between current wastewater collection system and the whole wastewater collection system including proposed development area. The total flows during the period of simulation are 16110 and 37350, respectively.

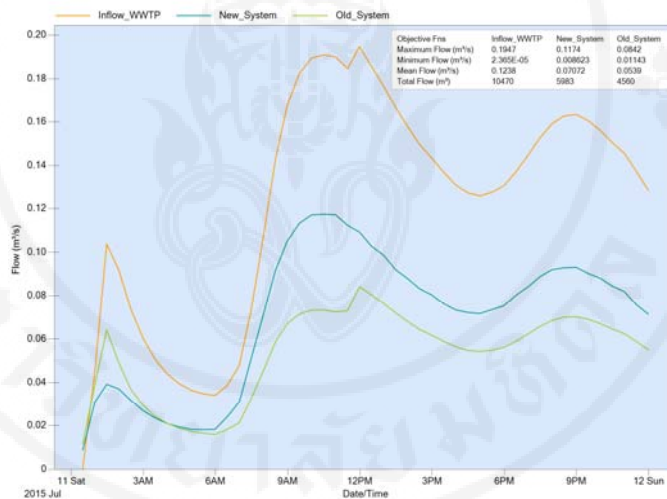


Figure 4.12 Comparison between the flow before and after development

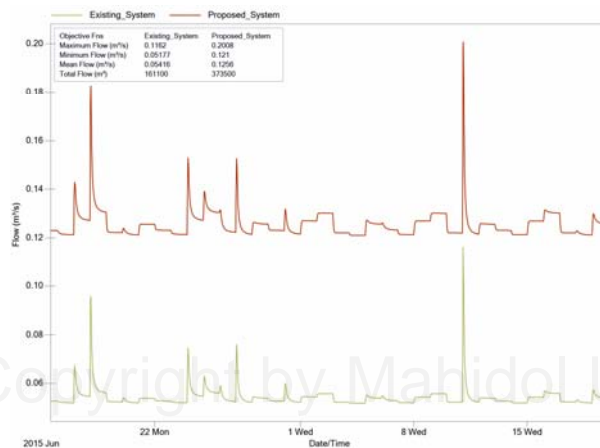


Figure 4.13 Comparison between the flow in current and proposed systems

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

PCSWMM has been developed to investigate the quantity of combined sewage flow associated with the current wastewater collection for Cha-Am, Thailand. The model results were similar to the observed flow data. The model was calibrated using the observed WWTP inflow data and daily rainfall data for the period 15 June to 20 July 2015. The 1:1 lines between modeled and observed peak flow and event volume for the calibration events qualitatively showed good correspondence. The r^2 values between modeled and observed peak flow (99%) and event volume (89%) also were strong. After the model was calibrated, one additional recorded rainfall events were simulated to further verify the model results during the periods 19 July to 20 October 2015. A good correlation and comparison of peak flow and volume was achieved. The calibrated model can now be used with some confidence to obtain additional information about the quantity of wastewater flow in the collection system and fluctuations in the inflow to the Cha-Am municipality wastewater treatment system that may be useful to town planners and designers.

The model can also help to evaluate future expansion of the sewer network by analyzing available capacity and identifying locations for new drainage construction to offset new development. The calibrated model was used to examine the quantity of wastewater discharged by the proposed future development scenario in Cha-Am. Based on the model results, the quantity of wastewater discharged by proposed development area combined with old wastewater collection system did not exceed the capacity of the treatment plant. The next step in this research will be to link the collection system with the ALTS system that has been modelled separately in PCSWMM and explore the impact of future development scenarios on treatment efficiency.

5.2 Recommendations

- Only daily inflow data and rainfall data were used to calibrate the model due to insufficient resource. The calibration and validation should be done with more accurate time series data in the future.
- There is only one rain gauge in Cha-Am municipality. It would be better if Cha-Am Wastewater Treatment Plant authority maintains more rain gauge. Then the rainfall data used in modeling will be more accurate.
- The separate sewer system is recommended for the future expansion of the wastewater collection system because the stormwater runoff can be easily discharged into the canal.
- There was no chance to get information from the municipality about the cleaning schedule of the wastewater collection system. Therefore, sediment buildup in the collection pipeline was not considered in the current model because of lack of information. It should be carefully considered in the future work.
- A strong recommendation is given to the city to plan for both a wastewater collection system and a wastewater treatment system. The two components should not stand alone.
- The future research is recommended to develop an integrated model that can simulate for both quantity and quality of flow in wastewater collection system as well as the treatment plant efficiency.

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