Aalborg University

Model Predictive Control of a Sewer System

Control and Automation:
Master Thesis

Group:
CA10-1030

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STUDENT REPORT

Title:

Model predictive control of flow and concentration of sewage in a sewer system

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Preface

NEW PREFACE !!!!

Sources are indicated by [name,year], and can be found in the bibliography list at the given [name,year].

Jacob Naundrup Pedersen

Contents

Nomenclature

Abbreviation

Abbreviation	Definition
GIS	Geographically Information System
WATS	Wastewater of Aerobic/Anaerobic Transformations in Sewers
WWTP	Wastewater Treatment Plant

Symbols

Symbol	Description	Units
A	Area	m^2
Q	Water flow	m^3/s
q	Inflow of water m^2/s	
D	Diameter meter	m
r	Radius	m
F	Force	N
θ	Angle	rad
v	Velocity	m/s
m	Mass	kg
V	Volume	m^3
ρ	Density	kg/m^3
l	Length	m
g	Gravitational acceleration	m/s^2
T	Temperature	$°C$
m_n	Mass flow	kg/s

Introduction 1

Sewers were created to solve the seemingly simple problem of removal of wastewater. The first sewers, registered, dates back to 7000 B.C. in urban settlements and were created to remove wastewater from houses and surface runoff created by precipitation. To avoid clogging and wear of the sewers grit chambers was constructed. They work by slowing the flow of sewage in long narrow channels making the solids, such as sand, end up as sediments in the channels due to gravity. Complexity of sewers increased in ancient Rome where large underground systems were created leading to the main sewer system called "Cloaca Maxima" making it possible to have latrines with running water within households, though mostly made available for the rich.

Waste were still thrown onto streets as the population, without immediate access to a latrine in their household, during night time did not want to put in the effort to properly dispose of the waste. Because of this the ancient Rome suffered from illnesses related to waste lying in the streets. The hygienic aspect of proper disposal of wastewater in relation to drinking water were not considered until the 19th century, where several European cities saw large outbreak of cholera causing the deaths of millions.

The growth in waste furthermore caused the expansion of 26 km. sewer network in Paris to 600 km. during the 19th century. But it is not until the start of the 20th century that the chemical and microbial processes in sewers are considered. The microbial cause of cholera were identified by the German doctor Robert Koch in 1883, a discovery for which he in 1905 received the Nobel Prize in physiology and medicine. The growing industries and technological progress in the 20th century meant that more chemicals were disposed into the sewers having severe consequences for the organic life downstream of the receiving waters. Wastewater treatment plants were introduced to reduce the pollution, but several countries did not have any wastewater treatment plants before after World War II. Today disposal of sewage and setup of wastewater treatment plants is a given part of construction of new settlements, even in poor regions of the world [Hvitved-Jacobsen et al., 2013].

1.1 General sewer construction

This section will elaborate on the general contruction of sewers. Furthermore a brief explanation, of input into the sewer to output from the wastewater treatment plant (WWTP), is given.

Generally sewer construction can be put into two categories which are gravity and pressure sewers. Gravity sewers utilize the topographic advantages of the area in which they are built. But in places where the level of the surface does not accommodate a slope of the sewer pipe such that wastewater flow in the desired direction, wells with pumps are used to transport the wastewater to an elevated level, which can be seen in figure 1.1.

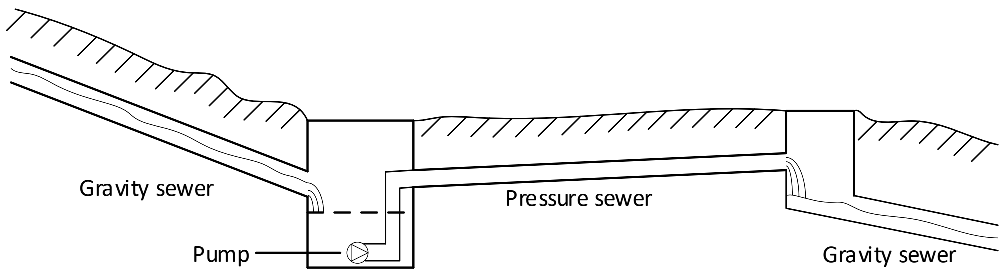

Figure 1.1: Illustrate different methods for transportation of wastewater.

Design of sewer systems involves careful considerations such that as much of the systems utilize the gravity for transport of wastewater to minimize the energy consumption. For this reason the WWTP is typically located in a low topographic area near a river, fjord or the sea. The design process also involves the dimensioning of the pipes to avoid overflow and the depth in which they are placed in the ground such that subzero temperatures does not prevent the flow in the sewers at any time. Furthermore the slope of the pipes must be chosen such that a high enough flow is created to avoid clogging. The material used to create the pipes gives different amount of friction e.g. a concrete surface will be more rough than polyethylene and thereby have a higher friction. This means that a larger slope of a concrete pipe is needed to avoid clogging in the pipes. Typically gravity sewer pipes is made of concrete and pressure sewer pipes of polyethylene.

In figure 1.2 a block diagram of the flow of wastewater is seen.

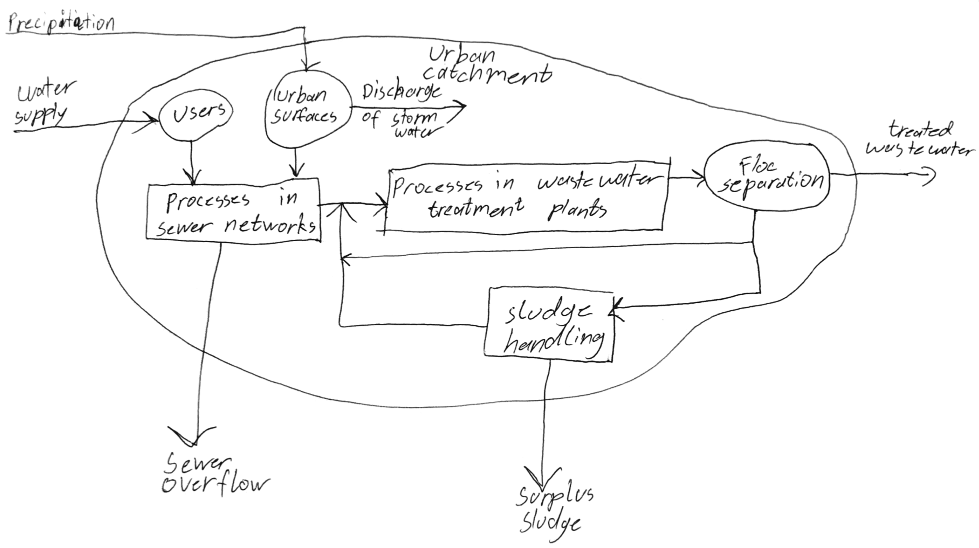

Figure 1.2: General overview of the flow of wastewater from users and surface runoff to the treated water is released into receiving waters. Arbejdsblad billede, inspiration er taget fra hvitved. Fjern sludge handling of floc separation og forklar det nede ved afsnittet.

In the left side of the figure precipitation from urban surfaces and roads are collected in the sewer by inlets placed at the gutter. In recent times separate sewer systems for surface runoff are constructed, which are also called storm water sewers. The water in these sewers are typically led in to storm water basins, rivers or the sea. In areas with older sewer constructions storm water is let into the sewers where it is mixed with wastewater. The wastewater comes from households or industry disposing of substances of varying consistency. Heavy precipitation can cause the sewers to be filled, and to avoid overflow into household or on roads the wastewater is let into rivers or the sea during such events. The reason for designing storm water sewers is partly to avoid letting untreated sewage into the nature, but also to better be able to control the cleaning process in the WWTP. It is desirable to have a steady flow of wastewater with a certain level of chemical concentration flowing into the WWTP. The chemical and microbial reaction happening in the sewer lines is discussed in subsection 1.2.1. When wastewater is received in the treatment plant several processes occurs to separate the unwanted substances from the received wastewater before the clean water is released into nearby rivers or the sea. The processes which the wastewater undergoes at the plant is discussed in subsection 1.2.2.

1.2 Chemical and biological processes

This section will describe the chemical and biological processes that wastewater undergoes from the water is used to it is cleaned at the water treatment plant. The processes in a wastewater treatment plant will be investigated to get an understanding of the different processes.

Within wastewater there is an infinite number of living organisms before entering the WWTP. It contains from around 100.000 to 1.000.000 microorganisms per millimeter. Theses organisms originates from sanitary waste and soil. They are a natural living part of the organic matter and they are an important part of the cleansing, of the wastewater, at the WWTP. To be able to obtain a high water quality at the output of the WWTP it is necessary to have a thorough understanding of these microorganisms [College, 2018].

Nearly all of the microorganisms found in wastewater are not harmful and therefore does not cause a disease for mankind. However a small group of the microorganisms can cause diseases and these are of a great concern in wastewater treatment. The most known diseases are typhoid fever, dysentery, cholera, and hepatitis [College, 2018].

The microorganisms in WWTP have a specific role in the decomposition of the waste. The three most notable microorganisms in the biological treatment process are bacteria, fungi and protozoa. Where the bacteria have the primary role of degrading the wastewater compounds, thereby producing settable soils. Bacteria is a single cell organism and is capable of reproducing rapidly when in contact with water. They consume the food by taking it through the cell wall [College, 2018]. Fungi like bacteria decomposes the organic waste, however they also pose a significant problem for the wastewater treatment as the fungi can proliferate to an extent such that it has detrimental consequences for the effluent quality [AquaEnviro, 2018]. Lastly protozoa acts as predators toward the present bacterial population such that it can be controlled [College, 2018].

In figure 1.3 an illustration is shown of the processes that wastewater undergoes within the sewer.

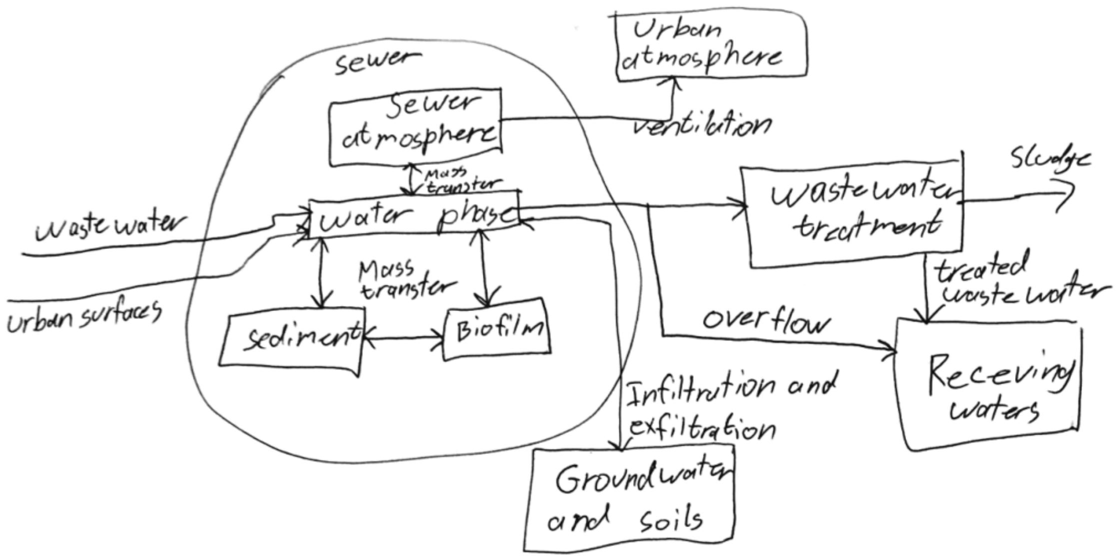

Figure 1.3: General overview of a sewer where the potential processes are illustrated. arbejdsblad billede. [1]

Wastewater are subject to a variety of mass changes in a sewer. One is due to free electrons in the wastewater, where different kinds of chemical reactions occurs. This results in different compounds being created which will be elaborated in subsection 1.2.1. The concentration level and the chemical compounds, which exists at the inlet of the sewer, undergoes reactions in the sewer before reaching the WWTP. These reactions has the possibility to create gases which are released into the urban atmosphere, which is not ideal as it is typically malodorous. Microorganisms are reproducing on the biofilm that is created on the surface of the pipe. Furthermore the wastewater in the pipes can sink into the groundwater and the soils due to small leaks in the construction of the sewer. The wastewater ends up at the wastewater treatment plant, this process will be explained in subsection 1.2.2. And as previous mentioned in case of heavy precipitation to avoid flooding, the wastewater will be lead into receiving waters.

1.2.1 Chemical reactions in a sewer

A wastewater treatment plant does not only receive what is discharged into the sewer from the industry and households but also the chemical and biological reactions that occurs in a sewer. The chemical reactions occur as redox reactions between the different compounds. Redox reaction is the transfer of electrons between two compounds at a atomic or molecular scale. By transferring electrons from one compound to another new compounds will arise, such as hydrogen sulfide which is know for its malodorous smell of rotten eggs. These reactions are determined by the electron acceptors that are present in the wastewater. The electron acceptor is the compound that receives electrons in a redox reaction. Examples of dissolved acceptors are oxygen (O_2), nitrate (NO_3^-) and sulfate (SO_4^{2-}), which determines whether aerobic, anoxic or anaerobic processes may occur. The redox reaction reduces these three compounds in the wastewater by changing them to new compounds such as water H_2O, molecular nitrogen (N_2) and hydrogen sulfide (H_2S) [Hvitved-Jacobsen et al., 2013].

Where redox reactions happens are to a great extend determined by the design of the sewer.

Different conditions such as aerobic, anaerobic and anoxic conditions exist where the last only occurs if nitrate is artificially added to the wastewater. If the sewer is in an aerobic state then the typical characteristics for the sewer are either partly filled gravity sewer or an aerated pressure sewer. This means that there are free oxygen (O^+) molecules, and these will be connected with hydrogen to create water. If the sewer is in an anoxic state, which occurs in pressure sewers, then the addition of nitrate to the wastewater results in molecular nitrogen. If the sewer is in an anaerobic state the characteristic of the sewer is either a pressure sewer or a full flowing gravity sewer, then the reaction will result in hydrogen sulfide as the sulfate will bind with the hydrogen molecules. With the knowledge of these condition sewers can actively be designed to achieve a specific state [Hvitved-Jacobsen et al., 2013]. The two desired states in the sewers are aerobic in gravity sewers and anoxic in pressure sewers to avoid malodorous dissipation into the urban atmosphere.

This knowledge is used to construct a simulation that is able to express the chemical and biological reaction which occur in wastewater. To model these chemical and biological reactions in sewers a model concept, Wastewater Aerobic/Anaerobic Transformation in Sewers (WATS), is used. The WATS model is expressed as differential mass balances equations that is suitable for numerical computation and can therefore be include in simulations for a specific objective e.g. model of water, biofilm and gas phase transformations. The WATS model can be applied to variety of different sewers as long as a fundamental understanding of the sewer process is available, whether it is aerobic, anoxic or anaerobic processes that dominate the sewer, the soil composition and the pH concentration of the wastewater must also be included in the WATS model for a sewer [Hvitved-Jacobsen et al., 2013].

1.2.2 Wastewater treatment plant

[2] Wasterwater from households and industry contains organic and inorganic matter and if it is release into the water environment it will result in polluted environment and cause oxygen depletion and thereby kill the wildlife in the water environment. Therefore the wastewater is lead to a WWTP to purify it from these substance that are harmful to the environment. In the following section the process that wasterwater undergoes in the WWTP will be elaborated.

In figure 1.4 the process wastewater undergoes is illustrated.

[2] FiXme Note: Noget specifikt for hvordan det ser ud i Fredericia

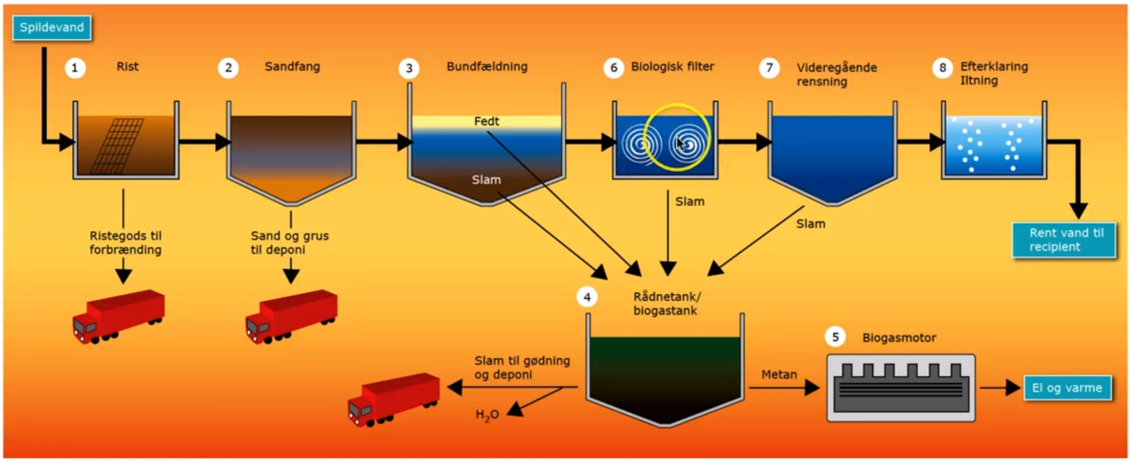

Figure 1.4: General overview of a wastewater treatment plant. arbejdsblad billede. [3]

At the WWTP the wastewater undergoes several process before the organic and inorganic matter are removed. The first stage of purifying the wastewater is screening. Here larger objects are removed from the wastewater which would either block the flow or damage the equipment. Examples of objects that are filtered from the wastewater are bottles, plastic bags and diapers. These objects transported to a combustion facility.

The water is lead into the primary treatment where the wastewater first will enter a grit chamber where objects as sand or stones will settle to the bottom of the tank. These grit chambers are crucial in WWTP that are connected with combined sewer systems, which means that the storm water from urbane surfaces is discharged into the same sewer as the human waste. The storm water may wash sand, stones, and gravel into the sewer and these objects will therefore be sorted out in this process. These objects are collected and disposed at a waste disposal site.

After the screening and the removal of grit the wastewater contains organic and inorganic matter. By leading the wastewater into a large settlement tank where the flow of the wastewater is reduced and thereby some the organic matter will sink to the bottom of the tank, while the fat will accumulated at the top of the tank. Here there fat will be scrapped into the digester tank. The matter that have sedimented is now called sludge or raw primary biosolids. At the bottom of the tank large scrappers are scrapping the floor moving the sludge to the center of the tank where it is pumped into the digester tank. From here the separated water floats or is pumped into the secondary treatment.

In this stage the water is lead into a aeration tank. By aeration the wastewater the bacteria gain optimal conditions for respiration and thereby speeding up the process of breaking down the leftovers of the organic matter from the primary treatment process. By breaking down the organic matter the bacterias will produce CO_2 that will evaporate into the atmosphere. When the bacteria have consumed the organic matter it will start to sediment at the bottom of the tank. In figure 1.5 this process is illustrated.

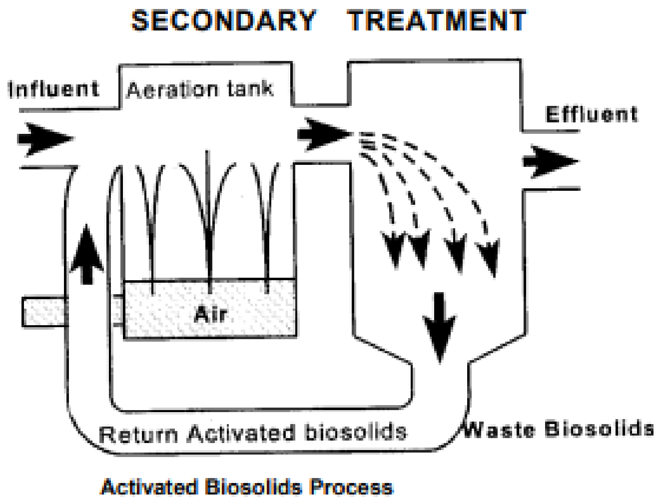

Figure 1.5: Illustration of the secondary treatment process. arbejdsblad billede. [4]

This is called the activated sludge process, due to when the sludge sediment some of it is reused in the aeration phase, thereby keeping a high bacteria population. The sludge that have sedimented is pumped to the digester tank.

Hereafter a chemical purification is done to remove the inorganic matter that is left in the wastewater. This will create chemical reactions and thereby create new compounds that will sediment in the tank, which will be pumped into the digester tank. The chemical added to the process does not cause any damage to the environment.

After these treatment processes there are still some diseases in the water. It is disinfected in tanks where a mixture of chemicals are used to cleanse the remaining water before leading it into the environment. Hereafter it is passed through a settlement tank where the remaining particles will sediment creating more sludge. Hereafter the water is lead into the environment.

The sludge that is collected in the digester tank undergoes further treatment, where the remaining water in the sludge is separated from it. The water is lead back to the wastewater treatment process where it will undergo the same process again. The sludge is collected and used as fertilizer or disposed in a landfill and the gas from it is used at a biogas facility to produce electricity and heat.

1.3 Afsnit om konstant vandflow og stofmængde ind til WWTP

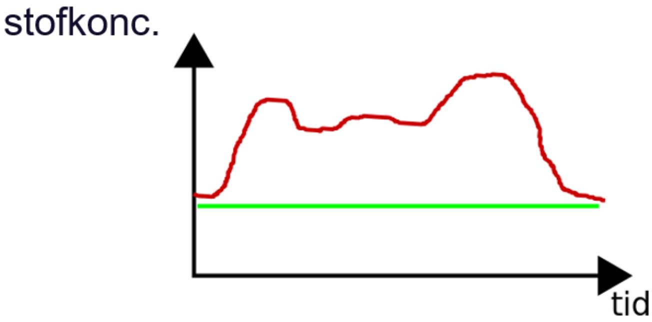

Figure 1.6: Input to the WWTP over a day, where the red line is showing the current input to the WWTP and the green is that wanted input. arbejdsblad billede. [5]

beskrive at vi gerne vil have et konstant indflow ind til WWTP, da selve iltningsprocessen så kan køres mere konstant, hvilket vil betyde energi besparelse. Kilde fra de to hoveder på Byggeri. Beskrive at industrierne bare smider deres affald ud uden at tænke over, hvad det har af indflydelse på resten af systemet.

2 System description

This section will go into details of the structure of the sewer network for which the further work of this project will be based upon.

As mentioned in section 1.2 a steady flow of sewage with a fixed level of contaminants is desired such that an optimal utilization of the wastewater treatment plant can be obtained. An area of interest is Fredericia with a sizable population of approximately 40.000 people and industries where some of the largest consists of a brewery, bottling plant, refinery and a dairy plant [Statistics-Denmark, 2018]. All of these industries is placed in the outskirts of the city, meaning that the wastewater discharged into the sewer goes through populated areas creating an uneven flow of sewage to the wastewater treatment plant. Two main sewer lines separates the northern and southern part of the city. To limit the project only the northern main sewer line is considered, which covers the largest part of the households and the industry located in the city. In figure 2.1 a simplified overview of the northern main sewer line with the various areas of population and industry in Fredericia attached to it. The placement of the sewers shown in 2.1 is obtained from a Geographically Information System (GIS) map publicly available by the municipal of Fredericia [Fredericia-Spildevand, 2018]. The red and the green lines indicate sewers with flows of wastewater and combined wastewater and surface runoff respectively. The populated areas are indicated by two different transparent blue colors, for easier to distinguish between the different parts of the sewer network. The red transparent areas indicate small to medium sized industry. Only the sewer lines out of or between the separate areas are shown. Furthermore the areas connected by a red line has a separate sewer system for surface runoff, which is lead into various ponds or the sea, minimizing the load on the wastewater treatment plant. The bottling plant, refinery and the brewery is marked by the purple, brown and black rings respectively. Several inlets for surface runoff connected directly to the main sewer line exists. The added disturbance from these inlets is neglected on the assumption that the disturbances from the connected areas will be considerable larger.

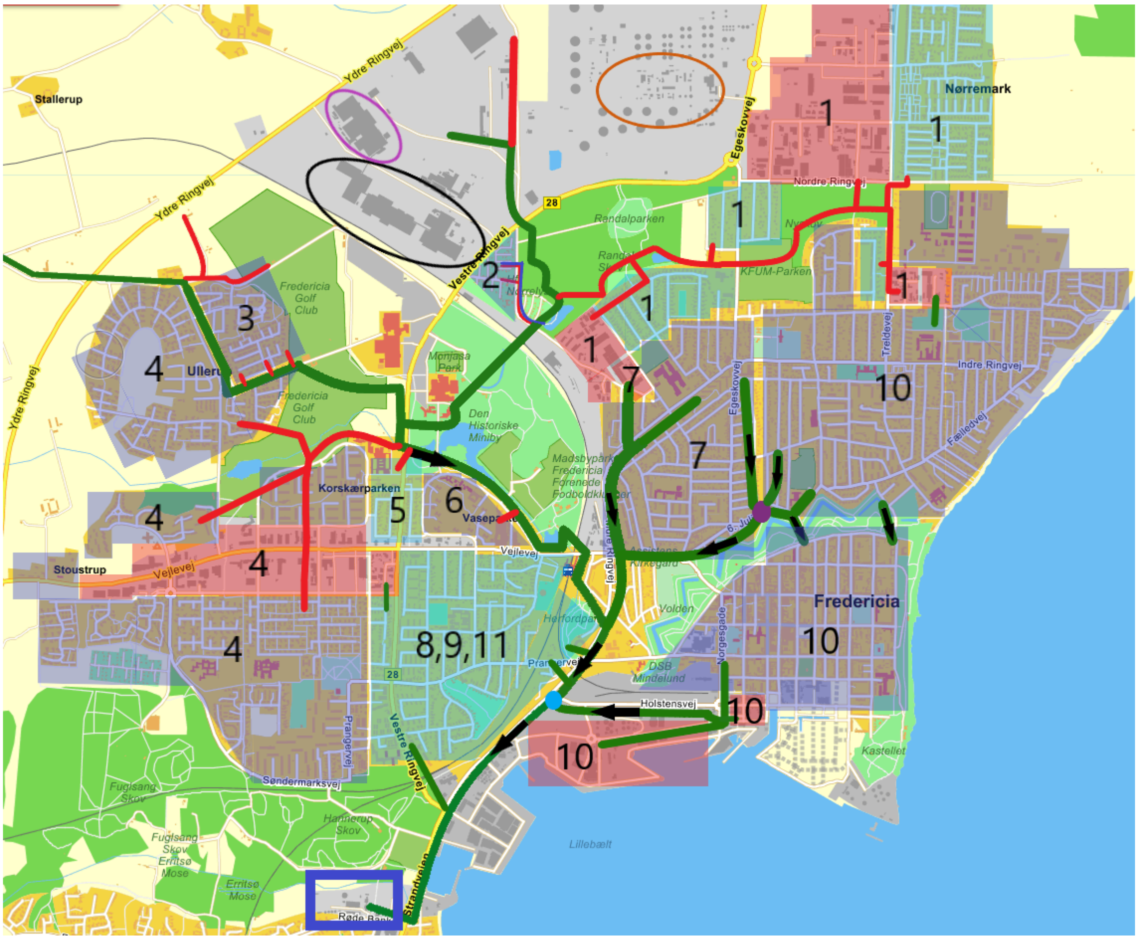

Figure 2.1: Simplified mapping of the northern part of the sewer network in Fredericia. The two blue transparent colors indicate populated areas and the red transparent area indicate industry. Red and green lines is sewers with flows of wastewater and combined wastewater and surface runoff respectively. Bottling plant, refinery and brewery is marked by purple, brown and black circles respectively. The purple dot is a connecting point with two incoming and two outgoing sewer lines. Blue dot is a wastewater reservoir. Blue rectangle marks the location of the wastewater treatment plant. [Eniro, 2018]

[1]

The various enumerated parts in figure 2.1 is shown by order of attachment to the main sewer line, together with distance between each attachment, in figure 2.2.

[1] FiXme Note: (The blue dot is a sewer reservoir)this is a guess pt. so might need to be corrected

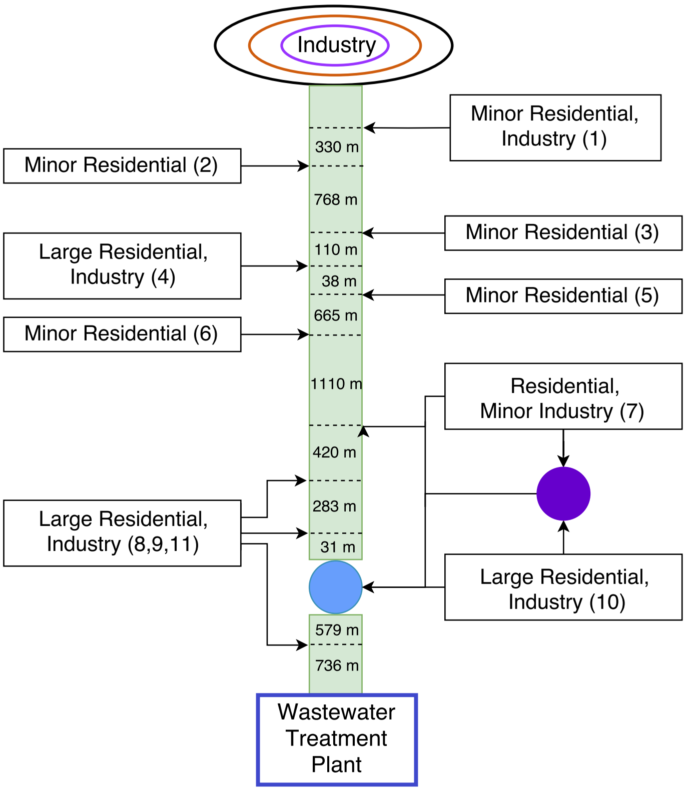

Figure 2.2: Simplification of the attachments to the main sewer line shown in figure 2.1. The numbers correspond to which area is connected to the main sewer line farthest from the wastewater treatment plant, with the distance between them.

Furthermore the different sections consist of pipe of varying diameters as can be seen in table 2.1.

Pipe section	Pipe length (meter)	Inner pipe diameter (millimeter)
$1 \rightarrow 2$	303 27	900 1000
$2 \rightarrow 3$	155 295 318	1000 800 900
$3 \rightarrow 4$	110	900
$4 \rightarrow 5$	38	1000
$5 \rightarrow 6$	665	1000
$6 \rightarrow 7$	155 955	1000 1200
$7 \rightarrow 8$	293 11 116	1200 1300 1200
$8 \rightarrow 9$	283	1400
$9 \rightarrow 10$	31	1400
$10 \rightarrow 11$	125 94 360	1600 1500 1600
$11 \rightarrow$ WWTP	736	1600
Total length $1 \rightarrow$ WWTP	5070	

Table 2.1: Table of the various lengths and the approximate inner diameter of pipe, appearing in order, in the main sewer line. Pipe section indicate the length of pipe between the attachment of the various areas to the main sewer line.

Modeling 3

The approach for modeling a sewer system with its different components comprising of free flow gravity and pressurized sewer lines, interconnections and reservoirs. This is with the goal of obtaining a model of the main sewer line with the various areas as input disturbances, as shown in figure 2.1, such that control of the flow and concentrate into the WWTP can be performed. In the following methods to model the components, such as flow in gravity and pressurized sewer lines (section 3.1), interconnections such that disturbances can be added to the main sewer line (section 3.2), reservoirs in the sewer network (section 3.3) and the concentrate of the wastewater flowing in the main sewer line (section 3.4), is examined.

3.1 Hydraulics of sewer pipes

As mentioned in

3.1.1 Preissmann scheme

3.2 Sewer interconnection

As mentioned in

3.3 Sewer reservoir

3.4 Concentrate in sewer pipes

As mentioned in

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Appendix A

Rettelser