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IMPACT OF THERMAL USE OF WASTEWATER IN A SEWER ON THE INLET TEMPERATURE OF A WASTEWATER TREATMENT PLANT

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Submitted by:

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Abstract

Thermal use of energy contained in wastewater is a promising technology for increasing the share of renewable energies. However, if the heat is extracted from the wastewater in the sewer it can have negative influences on the cleaning capacity of the wastewater treatment plant. In order to prevent negative influences an analysis of wastewater temperature and its development in the sewer is necessary. Unfortunately little information about the development is available and only a few methods exist for predicting changes in temperature. Therefore this thesis focuses on analysing wastewater temperature development in the sewer and potential influences on wastewater temperature as well as evaluating existing methods for predicting wastewater temperature in the sewer.

For the first part of the study wastewater temperature data from 18 measuring points in one sewer main over a period of five months were used for the analysis. The evaluation of the data revealed even though wastewater enters the sewer with an average of 19.5 °C it decreases to a certain level in the main sewer. This wastewater temperature level increases by around 2 °C every month between March and July. The temperature increase over time is mainly driven by changes in soil temperature.

For the second part of the study four methods for predicting wastewater temperature in the sewer were analysed. On the one hand there are two simple methods, an alligation alternate and taking measurements. On the other hand wastewater temperature can also be predicted with two more complicated models, the model described by Abdel-Aal et al. (2013, 2014) or the model behind the Tempest software tool. After evaluating their individual advantages and disadvantages it was concluded that using measurements for a first evaluation of the situation in the sewer is the best method available and if a more detailed analysis is desired an adapted version of the model by Abdel-Aal et al. could be a promising tool in the future.

Zusammenfassung

Energie aus Abwasser ist eine vielversprechende Technologie, um den Anteil an erneuerbarer Energie zu erhöhen. Wenn die Wärmeentnahme im Kanal stattfindet, kann dies negative Auswirkungen auf die Reinigungsleistung der Kläranlage haben. Um diese zu vermeiden, ist eine Untersuchung der Abwassertemperaturverhältnisse im Kanal notwendig. Im Moment ist jedoch wenig über die Abwassertemperaturentwicklung im Kanal bekannt und es gibt nur wenige Methoden um die Entwicklung vorherzusagen. Daher beschäftigt sich diese Arbeit mit der Analyse von Abwassertemperaturentwicklungen im Kanal, mit den Einflussfaktoren auf diese und sie beurteilt vorhandene Methoden, um Abwassertemperaturen im Kanal vorhersagen zu können.

Für den ersten Teil der Arbeit wurden Abwassertemperaturdaten von 18 Messstellen ausgewertet, welche über einen Zeitraum von fünf Monaten in einem Hauptsammelkanal aufgenommen wurden. Die Analyse zeigte, dass obwohl Abwasser mit einer Durchschnittstemperatur von 19,5 °C in den Kanal eintritt, sich die Abwassertemperatur auf ein konstantes Level abkühlt. Dieser Level steigt von März bis Juli um durchschnittlich 2 °C an und ist hauptsächlich von der umgebenden Bodentemperatur beeinflusst.

Im zweiten Teil der Arbeit werden vier Methoden zur Vorhersage von Abwassertemperaturen im Kanal untersucht. Zum einen gibt es zwei einfache Methoden, zu welchen die Mischungsrechnung und die Auswertung von Messungen zählen. Zum anderen wurden zwei komplizierte Modelle gefunden. Das eine wird von Abdel-Aal et al. (2013, 2014) beschrieben und das andere ist die Software TEMPEST. Die Vor- und Nachteile aller Methoden wurden analysiert und es hat sich herausgestellt, dass die Auswertung von Messergebnissen die beste Methode für eine erste Abschätzung der Abwassertemperaturentwicklung im Kanal darstellt.

Falls eine detailliertere Untersuchung von möglichen Entwicklungen gewünscht ist, könnte eine erweiterte Version des Modells von Abdel-Aal et al. eine gute Möglichkeit darstellen.

Abbreviations

DWA	German Association for Water, Wastewater and Waste
PE_{60}	Population equivalent
Q	Discharge
TNb	Total bound nitrogen
WW	Wastewater
WWEA	Office of Waste, Water, Energy and Air

1. Introduction

According to the IPCC (2007) continuing with the current rate of greenhouse gas emissions will very likely result in an increase in global warming as well as other changes in the climate. Alongside many sectors that need to be addressed, a promising solution to prevent further increase of greenhouse gas emissions and to keep future negative impacts on a minimum level is changing the energy supply to renewable resources. In order to counteract climate change the European Union committed to reducing its greenhouse gas emissions by 20 % below the levels in 1990. One of the key initiatives for achieving this goal is to increase the share of renewable energy to 20 % by 2020 in the European Union, alongside an increase of energy efficiency of 20 % in the same time period (EC, 2014). As the Energy Strategy Austria points out a variety of non-fossil energy sources will be necessary to achieve this goal (BMWFJ and BMFLUW, 2010).

One technology that is being discussed in connection with this is using the thermal energy contained in wastewater as an alternative energy source for heating or cooling of buildings. This technique is already applied in Germany, Scandinavia and Switzerland and some facilities have been in use for more than 30 years. In Austria the technology is applied at only a few locations, one of them being Amstetten in Lower Austria. The thermal energy of wastewater is recovered with a heat pump and a heat exchanger installed in the sewer or in the outlet of the wastewater treatment plant (Projektteam „Energie aus Abwasser", 2012). If the heat recovery takes place in the sewer, the subsequent cooling of the wastewater can lead to decreased nitrification and nitrogen removal in the wastewater treatment plant as these processes are temperature-sensitive (AWEL, 2010). In order to prevent negative impacts from heat recovery in the sewer on the performance of the wastewater treatment plant a permit of the responsible water authority is necessary to facilitate prove that thermal use of wastewater will have no significant negative influence on the performance of the wastewater treatment plant. In Amstetten the water authority granted the permit for the existing facility without a detailed analysis, because the wastewater temperature is relatively high in the respective sewer in winter due to warm industrial discharges from a paper mill upstream and therefore it was easily predictable that the effect on the performance of the wastewater treatment plant is insignificant (Projektteam „Energie aus Abwasser", 2012). After the successful implementation of the first wastewater heat recovery system in Amstetten, installing a second plant in the sewer is discussed at the moment. For every additional plant a more detailed analysis of the impacts on the wastewater temperature on the inlet of the wastewater treatment plant and on the performance of the treatment plant has to be carried out before a permit can be granted.

However, little information about wastewater temperature conditions in the sewer is available, as only a few studies have been conducted about wastewater temperatures in sewers and even less have focused on predicting changes of the wastewater temperature in the sewer system and impacts of heat recovery. Therefore no guidelines have been developed yet for Austria on how to deal with this problem. As a result of the lack of data this thesis focuses on analysing the development of wastewater temperature in sewers, as well as determining main influences on the wastewater temperature in the first part of the study. The second part concentrates on advantages and disadvantages of available methods for describing the wastewater temperature development in the sewer system and for predicting changes of any kind of the wastewater temperature with a focus on impacts of wastewater heat recovery. At the end the evaluation of the different methods can be used by the relevant water authority to determine which methods could be used for granting a permit for thermal use of wastewater. Even though the thesis will focus on the impacts of thermal use of wastewater the considered methods can also be used to predict other influences on the wastewater temperature such as industrial discharges with a difference in temperature, sewer infiltration water or new connections.

2. Objectives

The objectives of this thesis are defining the wastewater temperature development in the sewer from house connections to the wastewater treatment plant, finding the main influences on the wastewater temperature as well as evaluating existing methods for predicting changes in wastewater temperature due to thermal use of wastewater.

The following tasks were defined in order to fulfil the overall objective of defining the wastewater temperature development in the sewer

- Analysing wastewater temperature development from the house connection to the wastewater treatment plant
- Analysing wastewater temperature development over time
- Identifying possible influences on wastewater temperature and evaluating their importance

For the evaluation of existing methods for predicting changes in wastewater temperature the following tasks were identified

- Giving an overview of existing methods for predicting wastewater temperature and their data input needed
- Identifying advantages and disadvantages of existing methods for predicting wastewater temperature

This thesis can be used as a recommendation for possible approaches for evaluating the impact of heat extraction from the sewer system on the inlet temperature of the wastewater treatment plant. In the case that the thermal use of wastewater is desired, the conditions have to be evaluated individually.

3. Fundamentals

3.1 Technical background

3.1.1 Introduction to heat extraction and heat pumps

The main components of a thermal energy recovery system without considering the different types of installation are the heat exchanger and the heat pump (Cipolla and Maglionico, 2014). The heat exchanger is overflowed by untreated or treated wastewater depending on its position and different types are available for the two situations (Projektteam „Energie aus Abwasser", 2012). The special characteristics will be discussed in the following chapters, when the various locations of installation are described. The heat pump on the other hand has no direct contact to wastewater. It uses the thermal energy contained in its surroundings, in this case heat from wastewater, to increase low temperature to a higher level by applying mechanical energy. The process is split into four stages: evaporation, compression, condensation and expansion illustrated in Figure 1.

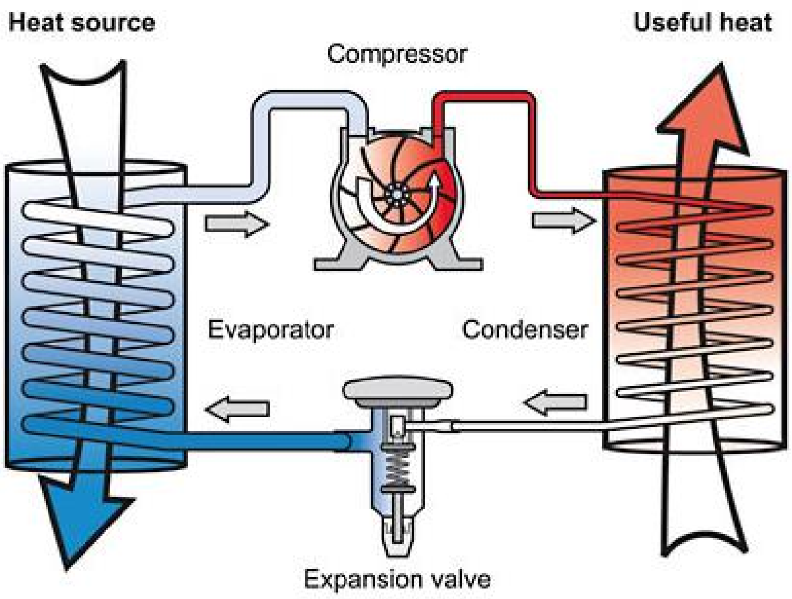


Figure 1 Schematic layout of a heat pump (Veolia, s.a.)

During the evaporation process the working fluid known as refrigerant has low pressure and its boiling temperature is lower than the surrounding temperature. Due to the temperature difference the refrigerant starts boiling and evaporates, the energy extracted for this process leads to a cooling of the surrounding medium. The gaseous refrigerant is pressurized by a compressor, which is also responsible for the constant circulation in the system, and its temperature increases. The process of condensation is following the compressor. The highly pressurized and hot vapour condensates on a heat exchanger with lower temperatures, the energy released is transferred to the heating water, which transports the heat to the heaters in the building. After the condensation the liquid refrigerant with moderate temperature and high pressure passes through a pressure-lowering device and expands on the other side with low pressure and reaches its initial state again. As an energy source for the heat pump electricity or natural gas can be used. When the cycle described above is reversed the heat pump can be used for cooling instead of heating (DWA, 2009).

3.1.2 General design parameters

The general design parameters of a thermal heat recovery system according to Cipolla and Maglionico (2014) are the flow rate and the temperature of the wastewater, the degree of wastewater temperature change before and after the heat recovery at the heat exchanger, the geometry of the sewer system, the fouling resistance at the heat exchanger, the heat exchange factor and the heat transfer surface.

When looking at the requirements regarding wastewater, a minimum discharge of 10 l/s (AWEL, 2010) to 15 l/s (Kretschmer and Ertl, 2010; DWA, 2009) on dry weather days is necessary for the system to work economically efficiently. The amount corresponds to 5000 to 10000 residents being connected upstream of the heat exchanger. For the minimum wastewater temperature only few recommendations can be found even though the efficient performance of the system depends on the wastewater temperature. Kretschmer and Ertl (2010) suggest a constant minimum wastewater temperature of 10 °C to 12 °C in winter for a reliable heating system, whereas the DWA (2009) assumes that wastewater temperatures do not decrease below 10 °C in winter in general and are therefore already higher than from other heat sources such as air, ground or groundwater.

The temperature difference between the wastewater temperature upstream and downstream of the heat exchanger depends on the wastewater temperature and the efficiency and surface of the heat exchanger, when looking at it from a technical point of view, as more heat can be extracted from higher temperatures, as well as with a more efficient technology, and a bigger exchange surface. Nevertheless, regarding the sustainable and legally permitted extraction other parameters have to be evaluated. Using energy contained in wastewater for heating or cooling can have negative effects on the performance of the wastewater treatment plant as well as on the receiving water. Therefore any negative effects from heat extraction or heat gain have to be ruled out for a sustainable performance of the system (Kretschmer and Ertl, 2010). The legal situation regarding thermal use of wastewater in Austria, Germany and Switzerland will be discussed in a following chapter. Germany and Switzerland are used for delivering insight into how other countries deal with the issue of what conditions have to be met in order for a permit for installing a heat exchanger to be granted by the relevant water authorities.

Another important design parameter is the geometry of the sewer pipe. If the heat exchanger is installed in an existing pipe a minimum diameter of 800 mm is recommended and a negative influence on the hydraulic capacity of the sewer is forbidden. The slope of the pipe has an influence on the minimum discharge. A slope in the parts-per-thousand range needs a smaller discharge than a slope in the percentage area to guarantee flooding of the heat exchanger. Furthermore, it is important that the section is suitable for maintenance work (DWA, 2009; AWEL, 2010).

The heat exchanger installed in the system has to be suitable for high pressure cleaning and needs a low susceptibility for fouling and corrosion in order for the facility to work over a longer time period (DWA, 2009).

Other important design parameters, apart from the ones related to the sewer system mentioned above, are the possibility of supplementary heating systems and the presence of potential users. If the extractable heat does not meet the temperature demand of the users the heat pump can be easily coupled with a conventional boiler or a combined heat and power plant to reach the demanded degrees. Even if the heating or cooling demand can be met with a monovalent heat pump it is recommendable to choose a bivalent system, as the space demand is five to ten times smaller. A bivalent system also increases the security of supply and the economic viability of the facility. If the heat pump is designed to cover one third of the total heat capacity demand, it will provide around three quarters of the total annual space heating demand and for one quarter fossil fuel or natural gas is needed (DWA, 2009). Regarding the potential users it is very important to extend the search for users of the generated heat from the wastewater treatment plant to other surrounding large buildings (Kind and Levy, 2012). The consumers have to be located in close proximity of the heat recovery side in order for the heat transfer to work efficiently and a minimum heating load of 100 kW is necessary to provide economic profitability (Kretschmer and Ertl, 2010; DWA, 2009).

After all, a detailed analysis of the potential site is necessary for evaluating the feasibility of the system (Kretschmer and Ertl, 2010). In general three different locations for thermal use of wastewater can be defined and are explained in the following chapters. The Figure 2 illustrates the different locations.

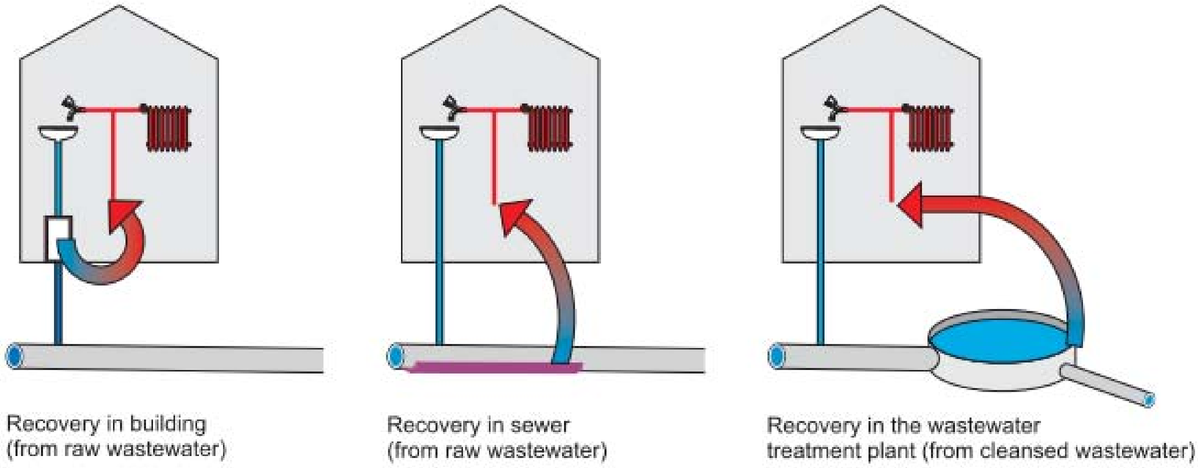


Figure 2 Locations for thermal use of wastewater (Schmid, s.a.)

3.1.3 Energy recovery in the sewer

There are two possible designs for recovering energy before the wastewater treatment plant. The heat exchanger can either be placed in the main sewer system or in a bypass. Both layouts have advantages and disadvantages and the choice depend on the local specific conditions.

Installing the heat exchanger in the existing sewer system has the advantages compared to the bypass that no additional space as well as no additional mechanical, biological or chemical treatment is needed. No mechanical moving parts are required for the system to work and also no energy has to be used to transport the wastewater to the heat exchanger. On the other hand it has also several disadvantages. The wastewater from the sewer has to be relocated during construction, which creates significant additional financial expenditures. Furthermore, the respective sewer needs a minimum diameter of 800 mm in order for an installation being permitted as it has to accessible for maintenance and repair work, which are usually more difficult than for a bypass system. In addition a permit is necessary to ensure that the heat exchanger has no significant influence on the hydraulic capacity of the sewer pipe (Projektteam „Energie aus Abwasser“, 2012; DWA, 2009). A schematic layout is illustrated in Figure 3.

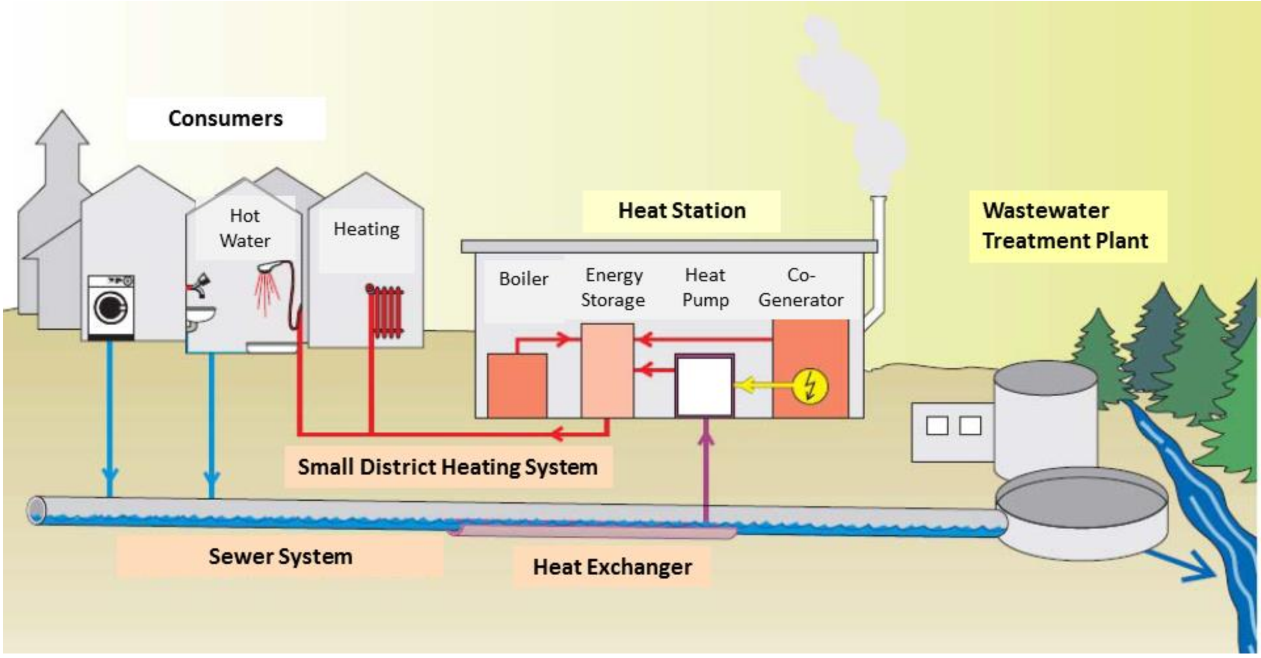


Figure 3 Basic layout of a heat recovery system (AWEL, 2010)

If the heat exchanger is located in a bypass system a partial wastewater stream is separated from the main sewer through an intake structure, the wastewater stream undergoes a screening process before being pumped to the heat exchanger and is transferred back to the main sewer after the thermal use. The deposit of suspended solids from the wastewater gets removed mechanically at most heat exchangers and is transported back to the main sewer with a screw conveyor (Projektteam „Energie aus Abwasser“, 2012). The bypass system has the advantage of being independent from the sewer operation. The separated structure is a walk-in compact unit that can be installed under dry conditions, which has the benefit that the wastewater stream from the main sewer almost does not have to be relocated during construction. Furthermore, it can also be connected to sewers with smaller diameters and the structure can be easily dismantled (DWA, 2009). However, the design is also associated with several disadvantages. The intake structure increases the energy demand of the system and wear and tear on the structures is higher due to more mechanically moving parts. Additionally mechanical and hydraulic cleaning devices are needed and more space is required (Projektteam „Energie aus Abwasser“, 2012).

Nevertheless, disregarding the design of the system several aspects have to be considered when locating the thermal use of wastewater in or connected to the main sewer ahead of the inlet of the wastewater treatment plant. The amount of discharge increases with decreasing distance to the wastewater treatment plant. In the main collector of a sewer system the wastewater quantity is usually high enough to fulfil the requirements and the distances for heat transport are reasonable as potential users are close by (DWA, 2009). When using the thermal energy of wastewater for heating or cooling upstream of the wastewater treatment plant the amount of heat recovered or put into the wastewater has an influence on the cleaning capacity of the wastewater treatment plant up to a certain degree. Considering the degree of temperature change is especially essential for wastewater treatment plants, where nitrification is mandatory all year round in Austria. Nitrification, as well as nitrogen elimination, is temperature sensitive processes. If heat is recovered from untreated wastewater, the nitrification and nitrogen elimination rate decrease at the wastewater treatment plant, which lead to a pollution increase in the effluent if no measures are taken. The negative effect can be counteract by increasing the activated sludge concentration in the activated sludge tank or by increasing the aerobe volume of the tank, which, however, should only be considered if the total tank volume can be increased as nitrogen elimination would decrease otherwise. If heat is put into the wastewater stream while using the facility for cooling in summer, the nitrification, as well as the nitrogen elimination rate, theoretically increases, but additional energy input is needed for the biological treatment as energy demand increases for the oxygen supply with rising temperatures. The surplus energy requirements are approximately 0.01 kWh per cubic meter of wastewater and temperature change of 1 °C, which is significantly lower than the energy gained from the system (AWEL, 2010). Nevertheless, the increase of the wastewater temperature can also have consequences on the ecology of the receiving water. Problems associated with the receiving waters are discussed in a subsequent chapter.

Discharge and temperature measurements in the sewer, as well as a detailed analysis of unused cleaning capacity of the wastewater treatment plant, and future developments are necessary to determine the potential energy withdrawal capacity. This is especially important if the heat balance is changed to a large degree, as temperature changes due to small interferences are usually lower than natural diurnal or seasonal fluctuations (AWEL, 2010).

Another disadvantage is that the sewer system and the wastewater treatment plant are not always operated by the same company and therefore changes in systems, as well as generated advantages and disadvantages, have to be coordinated between the different operators. This leads to additional organizational input (DWA, 2009).

3.1.4 Energy recovery after the wastewater treatment plant

The installation of a heat recovery system downstream of the wastewater treatment plant has the advantage that the discharge is relatively large and steady which results in the highest heat supply (DWA, 2009). As the wastewater overflowing the heat exchanger is treated before a wider and less expansive range of heat exchanger models is available (Projektteam „Energie aus Abwasser“, 2012). Furthermore, as a temperature decrease does not influence the cleaning capacity of the wastewater treatment plant at this point and lower effluent temperatures are desirable the amount of extractable heat is higher than in the sewer system. Therefore the amount of extractable heat is higher than in the sewer system (AWEL, 2010).

The cooling potential on the other hand is lower as higher wastewater temperatures are not acceptable (AWEL, 2010). Ecological consequences will be discussed in a following chapter. Another disadvantage is that potential users of the recovered heat are often located at a greater distance and therefore heat transport distances are larger (DWA, 2009).

3.1.5 Energy recovery on private properties

A third location for heat recovery is on private properties. The heat exchanger is installed in the pipe upstream of the house connection to the main sewer on private property. The advantages are relatively high wastewater temperatures due to short flow distances and also short heat transport distances as a result of spatial proximity. As the operator of the system is identical to the user no extra costs are added. Furthermore, the operation of the system is independent of the operation of the main sewer and rainwater does not enter the pipe (DWA, 2009). A wastewater energy recovery system is unfortunately not economically feasible for small detached buildings as minimum heating demand has to be around 150 kW. Additionally a minimum discharge of 8000 to 10000 litres per day is necessary for an economically efficient system. This corresponds to wastewater from 60 people or approximately 30 residential units (AWEL, 2010).

Even though the high average temperatures of for example 23 °C (AWEL, 2010) to around 19.5 °C increase the potential of the system, the availability varies considerably as water use is subject to daily fluctuations and therefore a constant energy supply cannot be guaranteed. Due to this and high operation costs this variation is usually the least efficient option (DWA, 2009; AWEL, 2010).

3.1.6 Heat distribution system

Two different heat distribution systems can be defined, cold and warm district heating. When cold district heating is used, the energy is transported on a low temperature level of 7 to 17 °C to one or more decentralized heating facilities. This system is commonly used if large distances between heat extraction and user have to be covered. Warm district heating describes a system, where the heat pump is located close to the heat exchanger and high temperatures of up to 80 °C are transported to the individual users. The distribution pipes have to be well insulated, which results in higher capital costs. This system is therefore only feasible for short transportation distances (AWEL, 2010).

Figure 4 illustrates the two options.

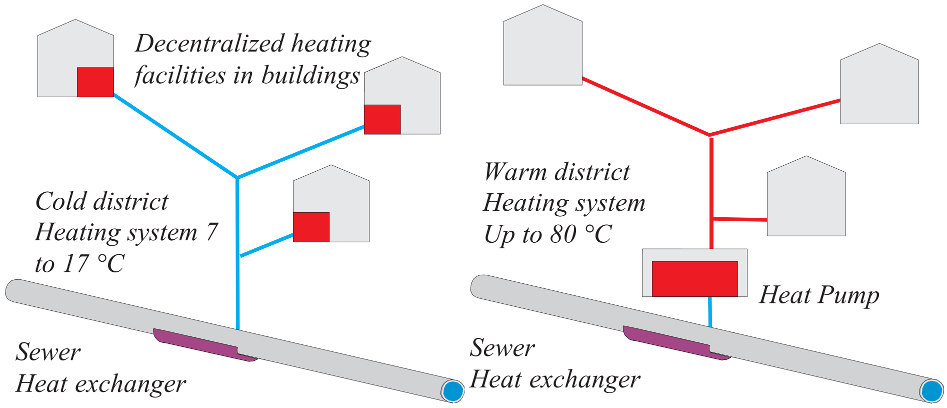


Figure 4 Cold and warm district heating (Schmid, s.a.)

3.1.7 Potential

Considerable amounts of heat are lost every day through wastewater discharge of residential houses, public facilities as well as commerce and industry. The quantity of heat that can be recovered from sewer systems with heat exchangers is very large. Around 1.2 kWh can be recovered if the temperature of 1 m³ of wastewater is changed by 1 K (AWEL, 2010). This theoretical potential is so high, that, when using all the potential of Germany, around 10 % of the total heating demand of buildings in the country could be met by energy recovered from wastewater (DWA, 2009). Even though the potential for cooling is much lower due to ecological consequences, the total energy savings that could be accomplished are significant (AWEL, 2010).

However, the actual potential still depends on many different parameters. As mentioned in the chapter 3.1.2 a minimum discharge has to be guaranteed as otherwise capital and operational costs increase in relation to recoverable energy. Industrial and commercial discharge can be beneficial to fulfil this criterion. Another important aspect is the hydraulic capacity of the sewer as well as the cleaning capacity of the wastewater treatment plant. If they are used to their capacity, a wastewater energy recovery system cannot be implemented (DWA, 2009).

The amount of energy that can be transferred by the heat exchanger is depending on the specific heat capacity of wastewater, the density of wastewater, the discharge and the amount of wastewater temperature change possible. The values of water can be taken for the specific heat capacity, as well as the density of wastewater, and are considered constant between 0 °C and 20 °C. For the discharge as well as the wastewater temperature, however, it is best to measure them for the respective heating or cooling period. The resulting temperature changes have to be estimated before the implementation of the heat exchanger and the resulting inlet temperature at the wastewater treatment plant can to be assessed, one possibility is using an alligation alternate, which is going to be explained in more detail in chapter 3.4.1 (DWA, 2009).

3.1.8 Ecological consequences

As mentioned in the previous chapters altering the temperature of wastewater can have significant consequences on the ecology of the receiving water. Reducing wastewater temperature by using the heat pump for heating can be beneficial for the water biocoenosis. On the other hand, if the temperature reduction results in a decrease of the cleaning capacity of the wastewater treatment plant, the effluent is higher polluted which has negative impacts on the ecology again. When the heat pump is used for cooling, the negative effect on the biocoenosis of the receiving water can be even worse. The resulting wastewater temperature increase stimulates the biological processes in the receiving water, which leads to an accelerated oxygen depletion in connection to lower oxygen concentrations due to the higher temperatures. In addition receiving waters tend to have lower water levels in summer, when the cooling demand is the highest. Therefore an increase wastewater temperature should be avoided unless sufficient dilution in the receiving water can be assured (DWA, 2009; AWEL, 2010).

Nevertheless, using the energy contained in wastewater for heating or cooling of buildings also has positive effects on the environment. Recovering energy from wastewater contributes significantly to reducing the greenhouse gas effect and decreases local pollution from other heating systems. When replacing gas heating with heat recovered from wastewater CO2 emissions can be reduced by 40 %. The CO2 reduction is even 20 % higher when conventional oil heating is replaced. Using this energy recovery system therefore helps counteract climate change (DWA, 2009).

3.2 Legal situation

In the following subchapters the legal situation in Austria, Germany and Switzerland is explained in order to give a basic understanding of what are the legal prerequisites for using the thermal energy contained in wastewater. Table 1 gives an overview over the current legal regulations regarding thermal use of wastewater in the respective countries. The individual regulations, however, are explained in more detail in the following parts.

Table 1 Legal requirements

	Austria	Germany	Switzerland
TNb	70 % reduction above 12 °C for more than 5000 PE60	13 - 18 mg/l above 12°C or between May 1st and October 31st depending on the size or a 70 % reduction	
Ammoniac nitrogen	5 mg/l above 8 °C for more than 5000 PE60	10 mg/l above 8 - 12°C depending on the state or between May 1st and October 31st	2 mg/l or 90 % reduction
reduction of all nitrogen entering all wastewater treatment plants	75 %		
Maximum discharge temperature into public sewer	35 °C		60 °C and maximum temperature after mixing 40 °C
Maximum discharge temperature into waterways	30 °C		25 °C
Other prerequisites for the discharge into a waterway			maximum 1.5 - 3 °C change, maximum variation of 1°C and minimum flow of 500 l/s
prerequisites in the sewer		yes	yes
possible temperature change without needing a permit		0.5 °C if temperature is not reduced below design values	0.1 °C
limit for temperature reduction at the inlet of a wastewater treatment plant			minimum inlet temperature 10 °C

3.2.1 Austria

As the use of thermal energy contained in wastewater has not been commonly applied in Austria yet, no official regulations have been introduced (Kaltenbrunner and Kretschmer, 2012). Due to the legal situation regarding wastewater and especially wastewater emissions it is not recommendable to introduce guideline values below which thermal use of wastewater does not need a permit by the relevant water authorities. In particular the Austrian regulation for wastewater emissions from municipal wastewater treatment plants (1. AEVkA), as well as the European directive 91/271/EEC, has to be considered regarding the thermal use of wastewater (Kretschmer and Ertl, 2010).

In the appendix of the 1. AEVkA (2000) it is stated that biological treatment should be preferred for the elimination of organic carbon compounds and for nitrification as well as for nitrogen and phosphorus elimination at wastewater treatment plants bigger than 5000 PE_{60}. As the processes of nitrification and nitrogen removal are temperature sensitive, the emission limitations regarding nitrogen and ammonium concentrations in the effluent are linked to the temperature of the effluent. As explained earlier, only wastewater treatment plants bigger than 5000 PE_{60} meet the requirements for thermal use of wastewater energy and therefore the legal situation will only be explained for these. The TNb (total bound nitrogen) of the influent has to be reduced by 70 % if the temperature of the effluent of the biological treatment exceeds 12 °C. Ammoniac nitrogen emission on the other hand are limited to 5 mg/l for wastewater treatment plants bigger than 5000 PE_{60} if wastewater temperature is higher than 8 °C at the outlet of the biological treatment. A temperature reduction of the wastewater in the sewer system could cause lower temperatures at the wastewater treatment plant and therefore could result in wastewater temperature falling below the discussed temperature limits of 8 °C and 12 °C and higher loads of TNb could be the consequence, which would not be the case without the thermal use of wastewater. This development, however, is not compliable with the water protection responsibilities of a wastewater treatment plant and has to be avoided (Kretschmer and Ertl, 2010).

Another important aspect considering the thermal use of wastewater is the legally maximum discharge temperature, which is not allowed to be exceeded when the heat pump is used for cooling. The general regulation for wastewater emissions (AAEV, 1996) limits the temperature of wastewater discharged into the public sewer system to 35 °C, whereas the temperature limit of wastewater discharged into waterways is 30 °C.

Alongside the Austrian law the European directive 91/217/EEC has further influence on the implementation of a heat recovery system as Austria has voluntarily identified the whole country as a sensitive area and therefore a higher reduction of nitrogen, as well as phosphorus, has to be ensured. In particular at least a 75 % reduction of total nitrogen entering all wastewater treatment plants in Austria has to be achieved (Council of the European Community, 1991). Even though the Austrian report of 2014 states a total nitrogen reduction of 80 % in the country and therefore the results go far beyond the objective of the European directive, a drastic increase of nitrogen emissions should still be avoided (BMFLU, 2014).

Since there are no guidelines in Austria on when or whether a permit from the relevant water authorities is necessary for installing a heat exchanger in the sewer, a project outline was submitted to the water authorities for approval of the planned heat exchanger in Amstetten. In the project documents the influences of the heat exchanger on the hydraulics of the sewer, as well as on the cleaning capacity of the wastewater treatment plant, were explained in detail. Amongst other reasons the water authorities decided that no permit is needed in this case, because the mean wastewater temperature during the biological treatment exceeds 14.8 °C, which is already significantly higher than the rated wastewater temperature of 14 °C. The maximum expected heat reduction of 0.2 °C to 0.3 °C after the heat exchanger would therefore have no significant influence on the cleaning capacity of the treatment plant. These favourable conditions exist in Amstetten due to wastewater discharge from a paper mill with temperatures of around 34 °C, however, for that reason the example from Amstetten of when or if a permit is needed cannot be taken as a guideline for other locations in Austria (Kaltenbrunner and Kretschmer, 2012).

3.2.2 Germany

In Germany a guideline for the use of thermal energy from wastewater has been developed by the German Association for Water, Wastewater and Waste (DWA). The first part of the guideline addresses the influence of the heat exchanger on the sewer pipe whereas the second part is concerned with the impact of temperature changes at the wastewater treatment plan.

Several conditions have to be satisfied so that a heat exchanger can be mounted in a sewer pipe. No considerable reduction of the hydraulic capacity of the sewer section must occur due to the heat exchanger and no areas with increased solid deposits must be created. Furthermore, the general operability of the sewer must not be affected. This includes for example routine flushing processes and cleaning procedures. Another important aspect is that the accessibility under compliance with safety regulations has to be guaranteed and maintenance and repair works in the sewer, as well as on the heat exchanger, have be possible in the whole section. If one or more of the mentioned requirements are not fulfilled, an appropriate itemization is necessary (DWA, 2009).

Regarding guidelines for changes in wastewater temperature due to thermal use of wastewater it is important to take a look at the German law concerning emissions of wastewater treatment plant effluents. Comparable to Austria the emission rates of ammoniac nitrogen and TNb are linked to certain temperature limits, however, the emission limits differ in the two countries. In Germany the maximum ammoniac nitrogen levels in the effluent are limited to 10 mg/l and TNb to 18 mg/l or 13 mg/l depending on the size of the treatment plant. These limits have to be complied with if the wastewater temperature exceeds 12 °C at the outlet of the biological treatment tank. Instead of the 12 °C limit the period between May 1st and October 31st can be defined for keeping the emission limits. Furthermore, the TNb can have higher concentrations of up to 25 mg/l if the total reduction compared to the influent is minimum 70 % (AbwV, 2004). The DWA guidelines further elaborate that during winter months or at lower wastewater temperatures at least nitrification has to be guaranteed and therefore temperature limits for ammoniac nitrogen emissions have been reduced in some federal states to 8 °C or 10 °C depending on the federal states. Independent from the previously stated regulations the guideline recommends that if temperature changes do not exceed 0.5 K and wastewater temperatures in the activated sludge tank to not decrease below the temperature used as a design criteria, heat recovery from the sewer does not influence the cleaning capacity of the wastewater treatment plant and therefore no special permit is needed. If the temperature changes, however, do exceed the maximum limit of 0.5 K a detailed case-by-case review of the influence is necessary (DWA, 2009).

3.2.3 Switzerland

In Switzerland a guideline was published by the office of Waste, Water, Energy and Air (WWEA) regarding the design principles, potentials, as well as the regulatory framework, for thermal use of wastewater. The regulatory framework is divided into thermal use upstream and downstream of the wastewater treatment plant, however, some of the requirements are applicable for both.

In both cases in general water has to be used as the heat transfer fluid between the heat exchanger and the heat pump. In individual cases other fluids may be used as well if they are approved by the WWEA. The refrigerant in the heat pump has to be chosen in accordance with the chemical risk reduction ordinance. Furthermore, while removing deposits from the heat exchanger toxic or persistent substances must not enter the wastewater stream and wastewater from cleaning processes, as well as heat transfer fluids, must be disposed of correctly (AWEL, 2010).

The thermal wastewater energy in the public sewer belongs to the owner of the sewer system. Consequently a use of the energy needs the approval of the owner and also from the wastewater treatment plant holder, as the cleaning capacity may be influenced. In the agreement for the thermal use of wastewater energy several aspects have to be considered. According to the law in Switzerland industrial wastewater discharge into the sewer must not exceed 60 °C and after mixing with the wastewater stream the temperature must be maximum 40 °C (GSchV, 1998).

However, for temperature changes not caused by discharges into the main sewer minimum or maximum values of change have not been stated. They can still be defined by the owner of the sewer or the wastewater treatment plant in case of the installation of a heat exchanger (AWEL, 2010). In addition to this the operation of the heat pump must not reduce the inlet temperature of the wastewater treatment plant below 10 °C as this is the design value for the cleaning capacity of the wastewater treatment plant and the temperature limit above which the ammoniac nitrogen emissions are limited to 2 mg/l or a 90 % reduction (GSchV, 1998). After all, water pollution control has first priority for the wastewater treatment plant operation and therefore heat pumps with a negative influence on the cleaning capacity of the wastewater treatment plant can be forced to shut down for a certain period by a cantonal directive. On the other hand if the theoretical temperature changes at the inlet of the treatment plant due to heat recovery or reheating are below 0.1 °C no permit from the canton is necessary (AWEL, 2010).

For regulations regarding the thermal use of energy from treated wastewater the main focus is put on the influence from temperature changes on the receiving waters. The temperature conditions of the receiving water have to stay close to natural conditions at the point of the inlet (GSchV, 1998). Temperature changes of the waterway must not exceed 3 °C due to heat recovery or heat input in comparison to the natural state and if the stream is a habitat for trout the changes are limited to 1.5 °C. The maximum water temperature due to heat input is limited to 25 °C. All values are valid after the treated wastewater and the receiving water are mixed well. Nevertheless, if lower water temperatures are necessary for protecting the water body, lower limits for the maximum temperature can be set, which could lead to a shutdown of the heat pump for certain time periods. Furthermore, rapid temperature changes of the outflow have to be avoided and must not exceed temperature variations of more than 1 °C in the receiving water. A survey has to confirm that the outflow of the wastewater treatment plant and the receiving water are mixing rapidly, before the thermal use of the outflow can be permitted. In addition to the criteria mentioned above a minimum dry weather discharge of 500 l/s in the receiving water is necessary in order to release water used for heating or cooling processes (AWEL, 2010).

In summary it is necessary to deliberate whether the benefits from using thermal energy from wastewater as a renewable energy source outbalance the need for water protection in the individual cases. The WWEA recommends allocating quotas for the use of thermal wastewater energy at different time steps in order to study the influence on the water bodies (AWEL, 2010).

3.3 Temperature development in sewers

3.3.1 Measured wastewater temperature in literature

This chapter focuses on wastewater temperature data found in the literature. It helps to get a basic understanding of the range of temperature wastewater has throughout the months and to be able to evaluate the wastewater temperature data measured in the study area described in the results section. However, available data is very limited, as wastewater temperature in the sewer has not been considered by many studies. Apart from the book by Bischofsberger and Seyfried (1984), most studies regarding wastewater temperature have been conducted after the year 2005.

Bischofsberger and Seyfried (1984) measured wastewater temperature in Hamburg from April 1982 until May 1983 at five different locations. Two measuring points were located in a sanitary sewer, while the other three were located in a combined sewer. At the same time groundwater temperature was measured at different distances of the measuring point. The mean wastewater temperature fluctuated between maximum 21 °C and a minimum of around 12 °C depending on the time of year. The wastewater temperature in the combined sewer was in average around 1 °C higher than in the sanitary sewer. The diurnal curve showed a minimum in the morning between 06:00 and 08:00, which was between 6 % and 9 % below the mean temperature of the day, and two maxima in the afternoon between 14:00 and 16:00 and between 22:00 and 24:00. The maxima were less pronounced than the minimum and exceeded the daily mean value only by around 3 % to 5 %. No significant wastewater temperature difference was found between workdays and the weekend. Furthermore, the measuring points in the sanitary sewer showed no significant temperature difference. The measured wastewater temperature in the combined sewer, however, increased by 1.1 °C from one measuring point to the next point in flow direction. On rainy days a decrease of wastewater temperature in the combined sewer was recorded. In general Bischofsberger and Seyfried (1984) conclude that wastewater temperature drops fast to a temperature correlating with the groundwater temperature, when entering the sewer system, and stays at this level until entering the wastewater treatment plant.

Cipolla and Maglionico (2014) analyse wastewater temperature and flow rate, which were measured at 5 different sites in a combined sewer system from October 2005 until March 2006 in Bologna in Italy. The mean wastewater temperatures of 11 °C to 16 °C were higher than mean ambient air temperature. In January the air temperature was at its minimum with values of around -2.5 °C, wastewater temperature had, however, still more than 11 °C. They observed that even though the flow rate depended on the number of inhabitants connected upstream of the measuring point, the wastewater temperature had similar values within a range of 2 °C to 3 °C at all sites unrelated to the discharge. While daily wastewater temperature patterns have minimal excursions of around 20 %, the seasonal variations are much more pronounced. Although 20.9 °C in average were measured in October, the mean temperature dropped to 13.5 °C in December. However, it was also observed that wastewater temperature changed considerably less than air temperature in the same period.

Schmid (s.a.) uses wastewater temperatures measured at the inlet of a wastewater treatment plant in Zurich as references for the potential of heat recovery in the sewer. In winter during the heating season wastewater temperature rarely reaches values under 10 °C and in summer it exceeds 20 °C. The values were taken from all year round measurements in 2005 and 2006. Daily variations of 2 °C to 3 °C were recorded with lowest temperatures during the night as less foul water is discharged. In combined sewer systems precipitation leads to further temperature variations, as wastewater temperature decreases by a few degrees during a rainfall event.

Schilperoort and Clemens (2009) measured wastewater temperature in a combined sewer for less than 10 days in December 2008 in Ede in the Netherlands with a fibre-optic cable. The cable had a length of around 1850 meters and upstream of the sewer section about 15000 residents are connected in a drainage area of around 2 km². Wastewater temperature was measured every 30 seconds with a spatial resolution of 2 meters and 0.15 °C accuracy. Only about 2/3 of the cable were located in a continuous wastewater stream and 1/3 situated in the most upstream part of the cable only measured wastewater temperatures in case of wastewater discharge as few connections are located in this section. The wastewater temperature in the downstream part ranged between 12 °C and 14 °C, whereas temperatures in the upstream part showed much higher variations. Temperatures up to 35 °C were measured in the morning and evening hours, when warm water was used in the houses connected to this section. In sections the cable was lifted just above the wastewater level due to different reasons. In those sections recorded temperatures dropped to 11 °C or 12 °C and in-sewer air temperature rather than wastewater temperature was measured. Furthermore, decreases in temperature down to 11 °C are recorded during one storm event.

Schilperoort et al. (2012) also used a fibre-optic cable for distributed temperature sensing, for this study, however, it was placed in the sanitary sewer of separated sewer systems. One part of the study was conducted in Woensdrecht in the Netherlands, where a 1500 m long fibre-optic cable was evenly divided between a foul sewer and a storm sewer and measured temperatures in the respective sewers for two weeks between the end of April and the beginning of May in 2011 with a spatial resolution of 2 m and a temporal resolution of 1 minute. The second part of the study was carried out in Wuppertal in Germany. Here 1200 m of fibre-optic cable were divided into three equal parts in three sections of a foul sewer and measured temperatures in a period of four weeks between mid-August and September in 2011 with the same spatial and temporal resolution as in Woensdrecht. In both catchments wastewater temperatures varied between 14 °C and 17 °C, although in Wuppertal temperatures of more than 20 °C have been measured as well. Only small temperature variations can be observed along the sewer section. Upstream wastewater temperatures are, however, generally slightly higher than temperatures measured in the downstream part of the cable. An interesting observation has been made concerning temperature changes due to storm water inflow. Whereas wastewater temperatures in the sewer in Woensdrecht decreased after a storm event, wastewater temperatures in Wuppertal increased. This can be explained by taken the meteorological conditions into consideration as the temperatures in Woensdrecht were recorded in April with lower ambient temperatures and in Wuppertal the data was collected in August with warmer ambient temperatures, where the temperature of the storm water runoff was raised by the warmed up asphalt road covers.

Abdel-Aal et al. (2013) measured wastewater temperatures near Antwerp in Belgium between late February and August 2012. Three different pipe sections ranging between 175 m and 464 m length were selected for the study and wastewater, as well as in-sewer air temperature, was measured at the beginning as well as at the end of the section with an accuracy of 0.2 °C. In February wastewater temperatures of around 12 °C were recorded whereas in-sewer air temperatures of around 10 °C were measured. Both temperatures increased until August reaching around 20 °C and 24 °C respectively. Annual average differences of the wastewater temperature between the upstream and downstream measuring point in the sewer varied considerably, ranging between 0.1 °C/km and 4 °C/km. An analysis of daily temperature variations was only carried out for measurements from July and showed that wastewater temperatures ranged from 19.7 °C to 21.9 °C with increasing temperatures between 7 am and midnight and decreasing temperatures after midnight. In Table 2 the data from the literature above is summarized.

Table 2 Measured wastewater temperature in literature

Location	Time	Mean temperatures
Hamburg	April 1982 – May 1983	12 - 21 °C
Bologna	October 2005 – March 2006	11 - 16 °C
Zurich	January 2005 – December 2006	10 – 20 °C
Ede	December 2008	12 – 14 °C
Woensdrecht	April – May 2011	14 – 17 °C
Wuppertal	August – September 2011	14 – 17 °C
Antwerp	February – August 2012	12 – 20 °C

In Austria few studies have been conducted regarding wastewater temperature. Recent data was collected during the project “Energy from Wastewater” carried out by Ochsner Wärmepumpen GmbH, the University of Natural Resources and Life Sciences, Vienna, EnergieSchweiz, the Austrian Energy Agency and Fernwärme Wien GmbH between 2009 and 2012. The most comprehensive survey asked all wastewater treatment plants from 20,000 PE_{60} upward in Austria to disclose the annual wastewater flow, as well as the minimum daily mean temperature, in December, January and February at the inlet of the wastewater treatment plant. Table 3 summarizes the results of this survey. Wastewater treatment plants with a design capacity of 20,000 to 150,000 were summarized into one category and wastewater treatment plants with a design capacity larger than 150,000 belong to another category. The return rate in the first class was significantly higher than in the second class with 34.3 % and 22.22 % respectively and together the design capacity of more than 5 million PE_{60} of the wastewater treatment plants returning the survey covers 23.92 % of the total design capacity in Austria. The annual wastewater flow of the returned surveys in the category from 20,000 to 150,000 PE_{60} covered 51.06 % of the annual wastewater flow in this category, while for the category above 150,000 PE_{60} only 16.68 % of the total annual wastewater flow was covered. In total 26 % of the annual wastewater flow in Austria was covered by the survey.

Table 3 Mean discharge and minimum wastewater temperatures at the inlet of wastewater treatment plants with more than 20000 PE60 from December to February 2009 - 2012

	20,000 – 150,000 PE60	>150,000 PE60	All responses
Return rate proportion [%]	34.30 %	22.22 %	33.2 %
Design capacity [PE60]	3,703,145	1,378,500	5,081,645
Proportion of total design capacity of return rate [%]	49.39 %	13.99 %	23.92 %
Sum of annual wastewater flow [m³/a]	202,970,043	75,887,847	278,857,890
Proportion of annual wastewater flow [%]	51.06 %	16.68 %	
Proportion of total annual wastewater flow [%]	19.12 %	7.15 %	26 %
Mean min. daily mean of influent Dec. - Feb. [m³/d]	7,711	36,660	44,371
Mean min. daily mean of influent Dec. - Feb. [°C]	9.2	12.7	
Mean min. daily mean of influent Dec. [°C]	11.1	14.2	
Mean min. daily mean of influent Jan. [°C]	9.8	13.1	
Mean min. daily mean of influent Feb. [°C]	9.3	12.8	

From December to February from 2009 to 2012 the mean minimum daily mean temperature of the influent in all wastewater treatment plants in the category between 20,000 and 150,000 PE_{60} is 9.2 °C and is significantly lower than for wastewater treatment plants in the category above 150,000 PE_{60} with a mean of 12.7 °C. In all months the minimum average inlet temperature of wastewater treatment plants in the category from 20,000 to 150,000 PE_{60} is at least 2.9 °C lower than in the category above 150,000 PE_{60}, with the smallest difference in December and the largest in February. Furthermore, a general influent temperature decrease can be observed from December to February independent of the design capacity. The minimum daily mean temperature ranges from 5 °C to 23.2 °C for wastewater treatment plants from 20,000 to 150,000 PE_{60} and from 10.3 °C to 18.1 °C in category above 150,000 PE_{60}. The large differences cannot simply be explained with a difference in flow rate or a difference in location and climatic conditions and therefore highlights the importance of a detailed analysis of wastewater temperatures in the sewer for thermal use of wastewater energy.

Wastewater temperature measurements carried out in a continuous sewer system will be considered in the results and discussion section, to analyse temperature development in a main sewer. A similar study has not been conducted up to this point.

3.3.2 Main influences on the wastewater temperature

Several parameters influencing the wastewater temperature in the sewer pipe can be found in the literature. However, which parameter has the main influence differs between various sources. The main parameters are the wastewater temperature at the point of discharge, the amount of discharge, as well as heat exchange processes with the environment, and hydraulic and geometric parameters of the sewer.

The DWA (2009) notes that wastewater is discharged into the sewer with an average temperature of 20 °C to 25 °C and after mixing with wastewater from upstream connections, as well as extraneous water, the wastewater temperature decreases depending on the quantity and temperature of the water upstream. However, whereas Wanner et al. (2005) states that wastewater temperature decreases steadily towards the wastewater treatment plant because of heat exchange with the environment, the DWA (2009) describes that an exchange of heat between wastewater, in-sewer air and pipe wall occurs, but does not specify a decrease of wastewater temperature. On the contrary it is mentioned that if wastewater temperature is decreased below the surrounding soil temperature after a heat exchanger, reheating of the wastewater is possible in the subsequent sewer section.

Nevertheless, as discussed in chapter 3.3.1 wastewater temperature in the sewer is definitely lower than at the house connection due to heat exchange with the environment, the literature, however, is inconclusive on whether more heat is exchanged with the surrounding material or with in-sewer air. Dürrenmatt and Wanner (2013) and de Gussem et al. (2013) argue that the surrounding soil temperature has the main impact on the wastewater temperature, whereas Abdel-Aal et al. (2013, 2014) concludes that changes in wastewater temperature are more sensitive to in-sewer air temperature. Abdel-Aal et al. (2013) found out that, even though it was expected that more heat would transfer from wastewater to soil due to the lower temperature of soil compared to in-sewer air, the heat transfer from wastewater to in-sewer air was much higher due to lower thermal resistivity between in-sewer air and wastewater. Due to the high thermal resistivity between pipe and wastewater the pipe had the effect of a thermal insulator. In the later study this finding is qualified and soil temperature becomes the second most important parameter after in-sewer air temperature regarding wastewater temperature changes (Abdel-Aal et al., 2014).

Dürrenmatt and Wanner (2013) on the other hand identify the properties of the surrounding soil such as temperature and thermal conductivity as the most important parameters. According to the study 75 % of wastewater heat is transferred through the wetted perimeter into the soil, whereas only 31 % of the heat is going into the in-sewer air, in addition to this an increase of heat in the wastewater of around 6 % was noticed due to heat released by degradation of organic matter. As a consequence of the high exchange rate between wastewater and the surrounding soil the authors assume that the thermal properties of the sewer pipe material have significant effect on the wastewater temperature. Bischofsberger and Seyfried (1984) come to a similar conclusion, although their study goes less into detail about the heat transfer of wastewater. Their analysis shows that wastewater temperature in the main sewer lines corresponds to groundwater temperature. Therefore in their opinion the temperature of the surrounding material has more influence on the wastewater temperature than the in-sewer air temperature. Furthermore, wastewater temperature drops quickly after the private connection due to heat exchange with the soil as a consequence of little discharge and thinner pipe walls with worse insulation properties than thicker walls.

Another parameter that has an impact on wastewater temperature in combined sewer systems is precipitation. Storm water entering the sewer system leads to a decrease of wastewater temperature if the ambient air temperature, as well as the temperature of the groundcover around the entering point, has low temperatures (Cipolla and Maglionico, 2014; Wanner et al., 2005; Schilperoort et al., 2012). However, as described in a previous chapter the study of Schilperoort et al. (2012) demonstrated that warm storm water discharge is possible in summer with the consequence of a wastewater temperature increase. The temperature changes according to meteorological conditions, however, are not part of this thesis and will therefore not be dealt with in more detail.

In summary it has to be said that the main influence on wastewater temperature has not been identified yet. However, the majority of the studies conclude that most of the heat from the wastewater is transferred to the surrounding soil and therefore soil temperature is the driving factor behind wastewater temperature. The findings about in-sewer air temperature by Adel-Aal et al. (2013, 2014) should, nevertheless, not be neglected as it is one of the few studies even incorporating this parameter.

3.3.3 Possibilities for measuring wastewater temperature

In general there are two ways how wastewater temperature data can be collected in a sewer. On the one hand a measurement campaign with the purpose of measuring wastewater temperature can be conducted. On the other hand wastewater temperature is sometimes automatically measured in addition to other data such as discharge by different devices. The advantage in the first case is that more attention is put on installing sensors with high accuracy and relevant other temperatures such as soil temperature, in-sewer air temperature or ambient air temperature can be measured as well. Examples from measuring campaigns found in literature reveal that accuracy for wastewater temperature measurements is ranging from 0.1 °C to 0.2 °C, sensors with a similarly high accuracy were used for other temperatures as well (Abdel-Aal et al., 2013; Dürrenmatt and Wanner, 2013; Schilperoort and Clemens, 2009). In the second case as the emphasis is not put on measuring wastewater temperature, but on measuring other data such as discharge, the accuracy is usually lower. Examples for the range of accuracy are from 0.5 °C to 1 °C, when considering for example Nivus PCM products (Carstensen, 2014). However, it has the big advantage that wastewater temperature might be available from old measuring campaigns. An example is continuous discharge measurements for analysing the amount of infiltration water in the sewer (Karpf and Krebs, s.a.). Unfortunately only few sensors are permanently installed in sewers and also discharge measurements are just done occasionally (Gujer, 2007).

3.4 Predicting wastewater temperature in sewers

In general there are two different approaches for predicting wastewater temperature changes within the sewer and for predicting effects of heat extraction. One approach is to determine temperature changes at a certain point in the sewer considering only very limited data. An example for this method is the alligation alternate. The other approach is to model temperature changes along the longitudinal profile of the sewer, incorporating heat transfer processes with the environment. Basically two models have been developed so far for predicting changes of wastewater temperature within the sewer system. The model TEMPEST created by Dürrenmatt (2006) is much more detailed than the one created by Abdel-Aal et al. (2014), which is aimed to be more simple than TEMPEST. The alligation alternate, as well as both models, will be described in the following chapters in detail in order to give an overview of the current state of methods for predicting wastewater temperature in sewer systems. In the results and discussion section advantages and disadvantages of the individual methods will be analysed and recommendations of which methods could be used for granting permits for the installation of a heat exchanger are given. The last chapter is given an overview about other areas, where temperature modelling in pipes is used, which might be used in the future.

3.4.1 Alligation alternate

The alligation alternate is a relatively simple method for calculating the wastewater temperature, in the following called T^*, after the mixing of two flows of wastewater with different temperatures and different discharge rates. The only data needed for the calculation are wastewater temperature and discharge of the two flows mixing. In the case of heat extraction the two flows are not two separated flows mixing at a certain points, but rather two points within the sewer system. One is the point of heat extraction and the other is the inlet of the wastewater treatment plant.

(1) $T^* = \frac{Q_1 * T_1 + (Q_2 - Q_1) * T_2}{Q_2}$ (AWEL, 2010)

In formula (1) Q_1 is the discharge at the extraction point, whereas Q_2 is the discharge at the inlet of the wastewater treatment plant. T_1 and T_2 are the wastewater temperatures at the respective point. T^*, however, does not represent any changes in temperature that occur due to heat exchange processes with the in-sewer air, the sewer pipe and the soil.

3.4.2 TEMPEST

TEMPEST is the first software program developed for modelling wastewater temperature in sewers. It consists of balance equations for mass, heat and momentum for sewer lines (Dürrenmatt and Wanner, 2008). Each sewer line is subdivided into conduits and nodes. Nodes are located at points in the sewer, where lateral inflows occur, or when the pipe geometry or material properties or the conditions in the surrounding soil change. Mathematically speaking the mass balance equations are symbolized by the conduits and the nodes symbolize a set of the variables going into the mass balance equations of the sequential conduit, which are constant for the individual conduits (Dürrenmatt, 2006).

The model underlying the software tool uses the set of balance equations for mass, heat and momentum as well as a number of transfer processes including heat flux between wastewater, soil and in-sewer air, heat transfer processes and heat production by biochemical reactions for modelling the wastewater temperature at the end of a conduit (Dürrenmatt and Wanner, s.a.). This results in a large amount of input data needed for the model. The necessary data is listed in detail in Table 10. When applying the software tool the amount of input data decreases drastically to 15 parameters, as some values are included as default values in the computer application or calculated through other parameters. Those parameters are discharge, wastewater temperature, ambient air temperature, ambient relative humidity, ambient air pressure, an air exchange coefficient, sewer pipe type, sewer length, nominal diameter of the pipe, wall thickness, slope of the pipe, COD degradation rate, soil type, penetration depth and soil temperature. The input mask illustrated in Figure 5 includes all the above mentioned parameters. While some fields have to be filled in with specific values others such as sewer pipe type and soil type can be chosen from predefined types, containing standard values for certain factors for example the thermal conductivity, the friction coefficient and the fouling factor (Dürrenmatt and Wanner, 2008).

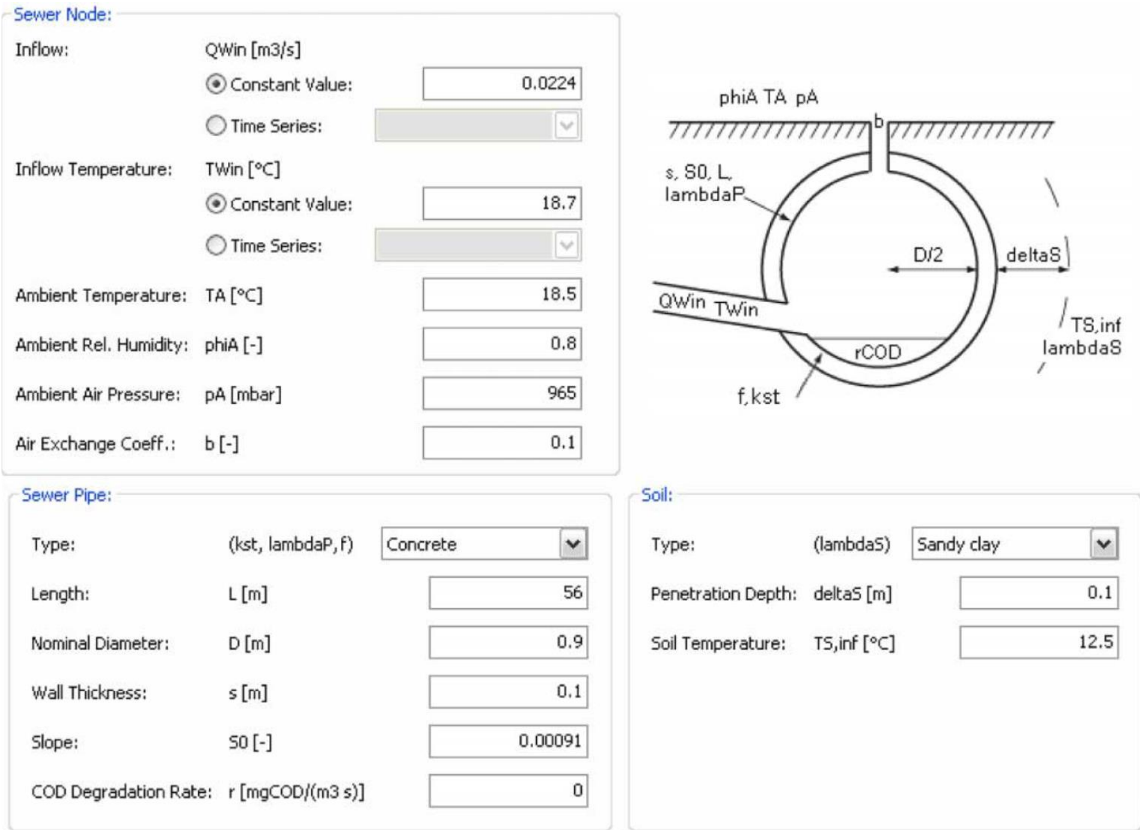


Figure 5 Input mask in TEMPEST (Dürrenmatt and Wanner, 2008)

Within the software program the hydraulics are calculated with the de St. Venant equations, whereas the airflow is modelled with a different model (Dürrenmatt and Wanner, 2008). The spatial resolution can be defined by the user, by specifying the number of grid points in the pipe (Dürrenmatt and Wanner, 2013). Dürrenmatt (2006) made 18 assumptions and simplifications in order for the model to work. A few of these will be mentioned exemplarily in the following list.

- Wastewater has the same hydraulic and thermal properties as water
- All pipes have a circular cross section
- The heat transfer processes between sewer and soil are limited to a certain layer of soil around the pipe with a specific thickness
- It is assumed that lateral inflows mix rapidly with the wastewater in the main sewer and therefore gradients over the cross section can be neglected

When looking at a model it is important to determine the effect of each parameter on the result. Dürrenmatt and Wanner (2013) and Dürrenmatt (2006) made a sensitivity analysis with the parameters wastewater temperature upstream, ambient air temperature, discharge, relative humidity, pressure, sewer length, friction coefficient, pipe diameter, slope, wall thickness, penetration depth, thermal conductivity of the soil, thermal conductivity of the pipe, soil temperature, wall thermal diffusivity, COD degradation rate and the fouling factor. The calculated downstream wastewater temperature reacted most sensitively to changes in the parameter wastewater temperature upstream, which however, changes with the length of the pipe. Other influential parameters are the soil temperature and the thermal conductivity of the soil. Changing the other parameters had little effect on the result.

The model can be used for several applications. One option is to use the model for determining the different heat fluxes in the system and therefore the main influences on wastewater temperature. The case study of Dürrenmatt and Wanner (2013) shows that heat flux between the wastewater and the surrounding soil can be accounted for 75 % of the total heat loss, whereas only 20 % are lost to evaporation and even less can be attributed to the convective heat flux (11 %). Furthermore, heat production by biochemical reactions represents an insignificant contribution of around 6 %. Due to the constant heat transfer between wastewater and the surrounding soil, it becomes obvious that the material properties of the sewer pipe, as well as the soil properties, have an important effect on wastewater temperature. Another application of the model is using it to determine the influence of thermal use of wastewater in the sewer on the wastewater temperature at a downstream part of the sewer. As temperature reduction at the extraction site can be calculated, the influence of the reduction further downstream before the installation of a heat pump, however, can only be modelled. Another useful application for the model is for evaluating different extraction sites. If the wastewater treatment plant operator defines a minimum inflow temperature at the wastewater treatment plant, the software tool can be used to determine how much heat can be extracted at various sites without the inlet temperature at the wastewater treatment plant dropping below the specific value.

3.4.3 Model by Abdel-Aal et al.

Abdel-Aal et al. (2013, 2014) realized that there is a lack of available models for wastewater temperature prediction in sewer and therefore aimed to develop a relatively simple model themselves. Abdel-Aal et al. (2014) developed a model, which needs less input data than TEMPEST and is therefore more practical and easier to handle in their opinion. However, information about the model is much less detailed than for TEMPEST and therefore not all aspects can be described here. The model consists of energy balance equations between in-sewer air and wastewater, as well as wastewater and the surrounding soil. After the establishment of the energy balances, thermal resistivity is calculated by using the heat transfer coefficients between water and air and water and soil (Abdel-Aal et al., 2013). Inserting the values of thermal resistivity between water and air R_{wa} and water and soil R_{ws} into equation (2) together with wastewater temperature T_j, soil temperature T_s, in-sewer air temperature T_{air}, mass flow M and specific heat capacity of water c_p, the downstream wastewater temperature T_{j+1} of each sewer increment can be calculated.

(2) $$T_{j+1} = T_j - \left(\frac{\frac{1}{R_{wa}} * (T_j - T_{air}) + \frac{1}{R_{ws}} * (T_j - T_s)}{M * c_p}\right)$$ (Abdel-Aal et al., 2014)

The model was applied in a case study in Antwerp, where also the modelled values were compared with measured wastewater temperature. Overall an average modelling error of 0.45 °C was found with a minimum of 0.001 °C and a maximum of 1.6 °C (Abdel-Aal et al., 2013). A sensitivity analysis of the model showed that the modelled wastewater temperature downstream is most sensitive to changes in the wastewater temperature upstream. The second most sensitive parameter is in-sewer air temperature followed by soil temperature (Abdel-Aal et al., 2014).

Besides the option of calculating downstream wastewater temperature, the model developed by Abdel-Aal et al. (2013) can be also used to estimate the required length for heat recovery to reach a certain capacity of thermal energy. However, further adjustments of the model are considered, to make it even simpler and therefore more user-friendly.

3.4.4 Temperature models in other areas

Literature about temperature modelling in pipes is very scarce also in areas outside of heat recovery from sewers. The only field, where models can be found, is heat loss from district heating systems. Although there are other areas, which could probably use temperature modelling in pipes such as gas or oil pipelines, no literature was found on that matter.

On the subject of district heating system models the main focus is also not put on temperature modelling in the pipes, but more on the overall optimization of the system. However, some of the models include specific methods for modelling heat loss from pipes in the distribution system, which could be used for modelling heat exchange between wastewater pipes and their environment. As some of the literature referred to in other papers is difficult to obtain, this section focuses on available models. The most important problem for a future adaption of district heating models for wastewater temperature modelling, apart from the fact that for district heating pressurized pipe systems are used and for sewer pipes usually not, is as the example from Larsen et al. (2002) shows that heat loss from district heating models is mainly calculated by taking into account the temperature of the supply pipe as well as the return pipe. As there is no return pipe in a sewer system the model cannot immediately be used for calculating heat loss from wastewater pipes. Furthermore, in district heating the whole pipe system is a loop, where no additional temperature increase occurs within the system. In the sewer system on the other hand temperature changes can occur with every house connection. However, some findings can be transferred to temperature predicting in sewer pipes as well. Benonysson et al. (1995) for example stress that heat loss from a pipe is related to the temperature difference between the water in the pipe and the surrounding soil. Therefore heat loss increases when the water temperature in the pipe increases or when soil temperature decreases.

Analysing possibilities for adapting models from district heating for sewer pipes, however, exceed the scope of this thesis.

4. Material and methods

In the following chapter the material and methods used for this thesis are going to be explained.

In order to gain a basic understanding of wastewater temperatures in the sewer, as well as of thermal use of wastewater, and its influences on the wastewater temperature and especially on the inlet temperature of a wastewater treatment plant an online literature research was undertaken. The research started with a top-down design to get a general overview at the beginning and to go into further details according to the general findings afterwards.

The literature found regarding wastewater temperature in sewers was scarce and little information on temperature changes over the longitudinal profile in a sewer system could be found. Two methods regarding the modelling of wastewater temperature in the sewer emerged from the literature research as the most promising for determining effects of thermal use of wastewater on the inlet temperature of a wastewater treatment plant. In order to gain a further understanding of the parameters needed for the two methods a bottom-up research has been conducted find solutions on how to obtain those parameters inside and outside of the field of sanitation.

The first part of the study focuses on the analysis of temperature data from a specific case study, whereas the second part deals with the evaluation of different methods for predicting wastewater temperature changes in sewers.

The data used for the evaluation is taken from a measuring campaign conducted in 2005, in which sewer infiltration water was analysed in a combined sewer. Therefore the flow rate was measured every three minutes at 18 different sites inside of the sewer system of a specific drainage area over five months with a Nivus PCM3 ultrasonic sensor. At the same time wastewater temperature data was recorded in the same time steps with an accuracy of +/- 1 K. The temperature data, however, has not been analysed until now. The sensors were placed at the inlet and outlet of seven combined sewer overflow structures as well as in two manholes.

In addition to this five rain gauges were installed in the area in order to obtain detailed precipitation data. For the further assessment of the data only days with dry weather flow were used. This excludes all data from days were any precipitation was recorded in the rain gauges, as well as days where the flow rate was exceptional high due to preceded rain fall (Kraus, 2006). In order to find those days, the mean hourly value of each measuring point on days without precipitation in each month was graphically compared. Days with elevated discharge were therefore clearly visible in the figures. The calculation of the average value is described in the following paragraph.

In order to get a basic understanding of the data mean hourly flow rate and temperature were calculated for every day and every measuring point. These were further combined into a mean hourly value for every month and every measuring point as well as a mean overall value for every month. Furthermore, the mean daily value of all the dry weather days was calculated for every measuring point. The diurnal pattern was derived from the hourly means of each measuring point in each month, which gives a basic understanding of the relation of wastewater temperature to discharge and for validating the data, but it was not used for the actual analysis of temperature development. The hourly means of each month were further brought together in one figure in order to see changes in temperature or flow rate between the months at one measuring point.

In a next step the temperatures and discharges measured at the seven combined sewer overflow structures were combined into one value per combined sewer overflow structure by calculating the mean of the measured values at the inlet and the outlet. In this step measuring points with anomalies were excluded from further analysis. The values were used for an analysis of the longitudinal section in order to see if reheating or cooling takes place in the sewer system. Also the discharge was analysed in the longitudinal profile to have comparison to the temperature profile.

Following the longitudinal evaluation changes in wastewater temperature and discharge over time were examined in order to see the influence of seasonal changes on both. For this the monthly mean values of each measuring point were analysed, by comparing them on a month to month basis. This was done by comparing the absolute values of each month as well as comparing relative changes between the individual months. For explaining some changes in the pattern also changes on a day to day basis were used in the analysis.

In order to find correlations between the wastewater temperature and the surrounding temperature the monthly wastewater temperature of each measuring point was graphically compared with ambient air temperatures, groundwater temperatures, river water temperatures of a nearby river as well as soil temperatures. The ambient air temperature was taken from the Central Institute for Meteorology and Geodynamics (Zentralanstalt für Meteorologie und Geodynamik - ZAMG) from a measuring point approximately 5 to 10 km from the drainage area. Daily mean values, as well as monthly mean air temperature values, were available. A private measuring system is located in the area as well, however, there is no data available from the year, when the study was conducted in the sewer system. The groundwater temperature, as well as the river water temperature, was taken from eHYD a digital map combining the hydrological data of Austria, both measuring points lay within a kilometre from the sewer system in the second half of the system and only monthly mean values were available. Soil temperatures were modelled by the Institute of Meteorology at the University of Natural Resources and Life Sciences, Vienna using the SoilTempSimV3B model, which calculates soil temperature at different depths with daily time steps. It is a one-dimensional simulation model, which includes the effect of freezing and thawing of soil water. The necessary input data include daily mean, maximum and minimum air temperatures, global radiation, ground coverage, snow, actual daily evaporation and daily values of the pore volume of the soil and volumetric soil water content, as well as details of the soil composition, annual mean air temperature and other empirical parameters (Grabenweger et al., 2013). Soil temperature was modelled for different soil depths ranging from 1 m to 3.5 m below ground level. The output was daily mean, maximum and minimum soil temperatures with an accuracy of +/- 1 °C. For comparison the daily soil temperature were summarized into monthly mean values. The mean monthly temperatures of groundwater temperature, river water, soil and air were compared with wastewater temperatures in one step, to find simple correlations. To determine the influence of the surrounding material in more detail the daily mean values of wastewater was compared with the daily mean soil and air temperature. As the soil temperature was available at different depths the depth correlating best with the depth of the combined sewer overflow structure was used for analysis.

For the second part the advantages and disadvantage of the methods for wastewater temperature modelling described in the theoretical part of the thesis will be evaluated based on their accuracy, the needed data input summarized in Table 10 as well as the output. The methods include allegation alternate, the model by Abdel-Aal et al. and TEMPEST as well as the addition of using ambient air temperature and soil temperature for an evaluation of possible wastewater temperature.

5. Results and discussion

5.1 General data analysis and data validation

5.1.1 Study area

The data used for the evaluation is taken from a measuring campaign conducted in 2005, in which flow rate and wastewater temperatures were measured every three minutes at 10 different sites inside of the main sewer system of a specific drainage area over five months. The specific location of the study area has to be anonymised by the order of the operator of the system. At 7 out of the 10 sites measures were taken at the inlet as well as at the outlet of combined sewer overflow structures in the sewer. Measures were taken in one more combined sewer overflow structure at M09, however, only the temperatures and discharge at the inlet were recorded as the second sensor was placed outside of the wastewater stream in the storm water outlet of the combined sewer overflow structure. The sensors at measuring points M07 and M08 were placed in manholes and as only one sensor was placed no second value for comparison was available. Measuring points with the same combined sewer overflow structure number are placed in the same structure. Figure 6 illustrates a combined sewer overflow structure as well as the approximate position of the sensors in the inlet and the outlet. In Table 4 the individual measuring points and their position are summarized.

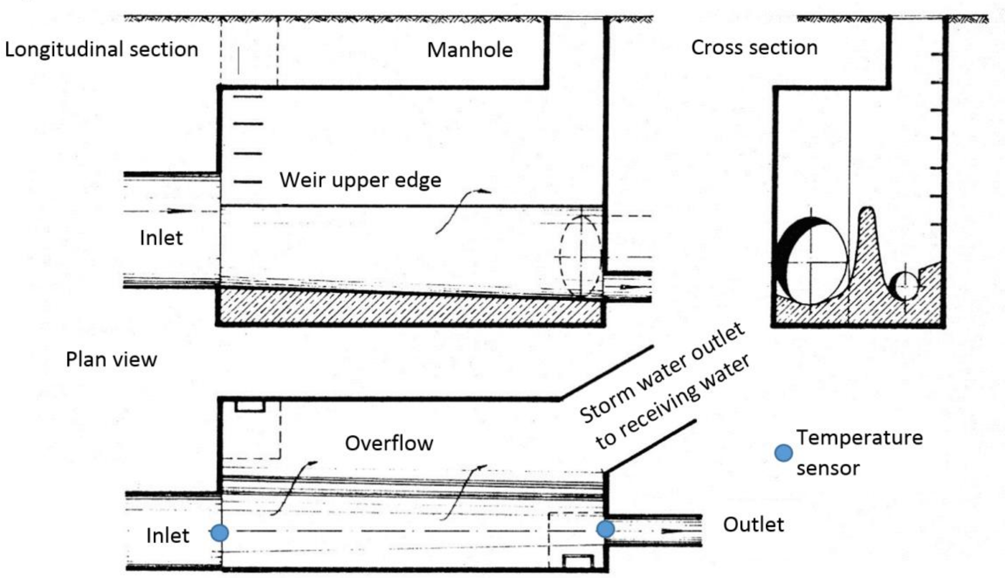


Figure 6 Schematic drawing of a combined sewer overflow structure (ÖWAV, 1987 quoted by Ertl 2010)

Table 4 Location of temperature sensors

Measuring point	Location	Measuring point	Location
M01	Inlet of combined sewer overflow structure 1	M02	Outlet of combined sewer overflow structure 1
M03	Inlet of combined sewer overflow structure 2	M04	Outlet of combined sewer overflow structure 2
M05	Inlet of combined sewer overflow structure 3	M06	Outlet of combined sewer overflow structure 3
M07	Manhole	M08	Manhole
M09	Inlet of combined sewer overflow structure 4	M10	Storm water outlet of combined sewer overflow structure 4
M11	Inlet of combined sewer overflow structure 5	M12	Outlet of combined sewer overflow structure 5
M13	Inlet of combined sewer overflow structure 6	M14	Outlet of combined sewer overflow structure 6
M15	Inlet of combined sewer overflow structure 7	M16	Outlet of combined sewer overflow structure 7
M17	Inlet of combined sewer overflow structure 8	M18	Outlet of combined sewer overflow structure 8

The positions of the measuring points within the sewer system, as well as major inflows into the main sewer, are illustrated in Figure 7. The size of the arrow illustrating an inflow into the main sewer corresponds to the length of sewer line connected to the main sewer as individual discharge values were not available. The sewer length between the first and the last measuring point is approximately 17 km and an additional six kilometres of sewer are located upstream of the first measuring point M01/02. The main sewer is a combined sewer such as the majority of the drainage area. However, a few separated sewer systems are located in the drainage area as well. The main sewer pipe is located at a depth of 1.5 m to 3.5 m. On the map in Figure 7 the measuring points of river water temperature, ground water temperature and ambient air temperature are illustrated as well. Furthermore, the position of the river in comparison to the main sewer is illustrated. The exact location of the sewer system is withheld on purpose.

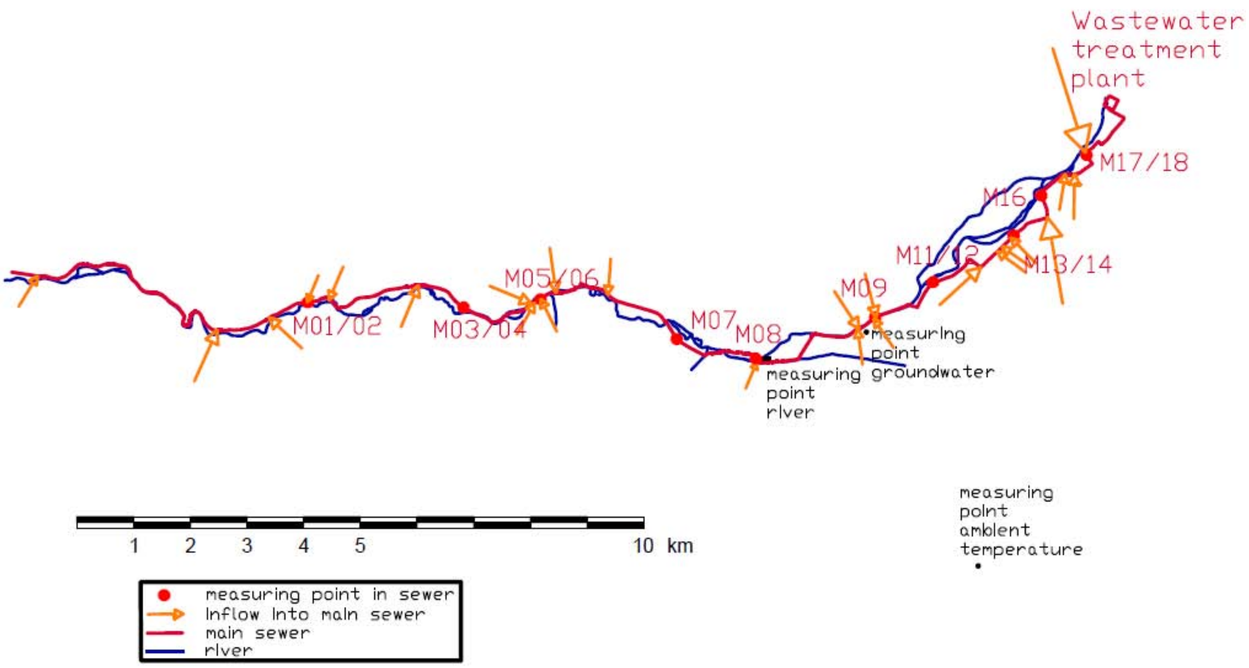


Figure 7 Schematic layout of the study area

5.1.2 Analysis of dry weather flow

The data of the five rain gauges installed in the area were analysed, to obtain an overview of the days with precipitation. As the sewer in the study area is a combined sewer, in the case of precipitation, rainwater and wastewater runoff in the same pipe. In order to eliminate the influence of rainwater temperature on wastewater temperature only days with dry weather flow were used for further analysis, days were precipitation was recorded were excluded from the study. A total of 51 days without precipitation was found between March and July 2005. Furthermore, days on which the flow rate was exceptionally high due to preceded precipitation were excluded as well. For this the mean hourly discharge value of the individual days calculated at each measuring point was used. Figure 8 represents the mean hourly discharge of all days without precipitation in March and shows a case where no precipitation was recorded on the 20th and 21st of March, however, the elevated discharge on those days suggests an influence from preceded precipitation and therefore they were excluded from the analysis. In total four days were influenced by preceded precipitation including also the 23rd of June as shown in Figure 9 and the 15th of July as illustrated in Figure 10. On the 22nd of June precipitation was recorded shortly before midnight. Therefore rainwater coming into the sewer through infiltration influenced the discharge values between 1 am and 3 am on the 23rd of June. On the 15th of July the discharge is elevated throughout the morning hours until 12 am. It exceeds the average discharge of the other days by around 20 l/s. The higher discharge can be explained by ongoing precipitation on the preceded days. This left 47 days for the analysis. However, some more days had to be taken out of the study at different measuring points due to measuring errors. The specific cases will be explained in the next chapter.

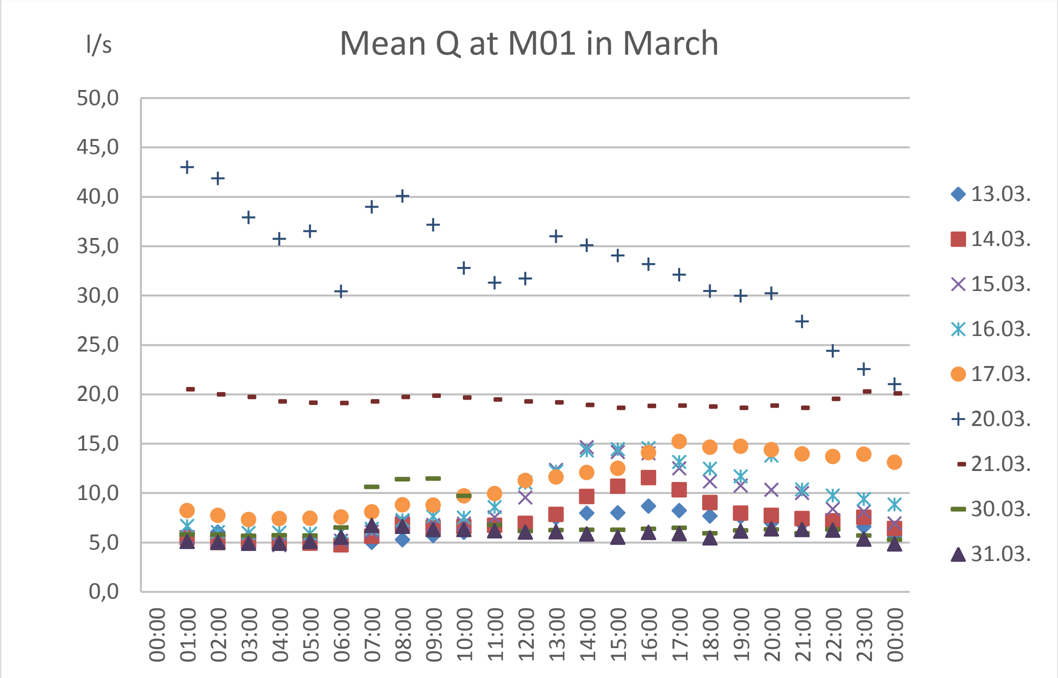


Figure 8 Mean discharge at M01 in March

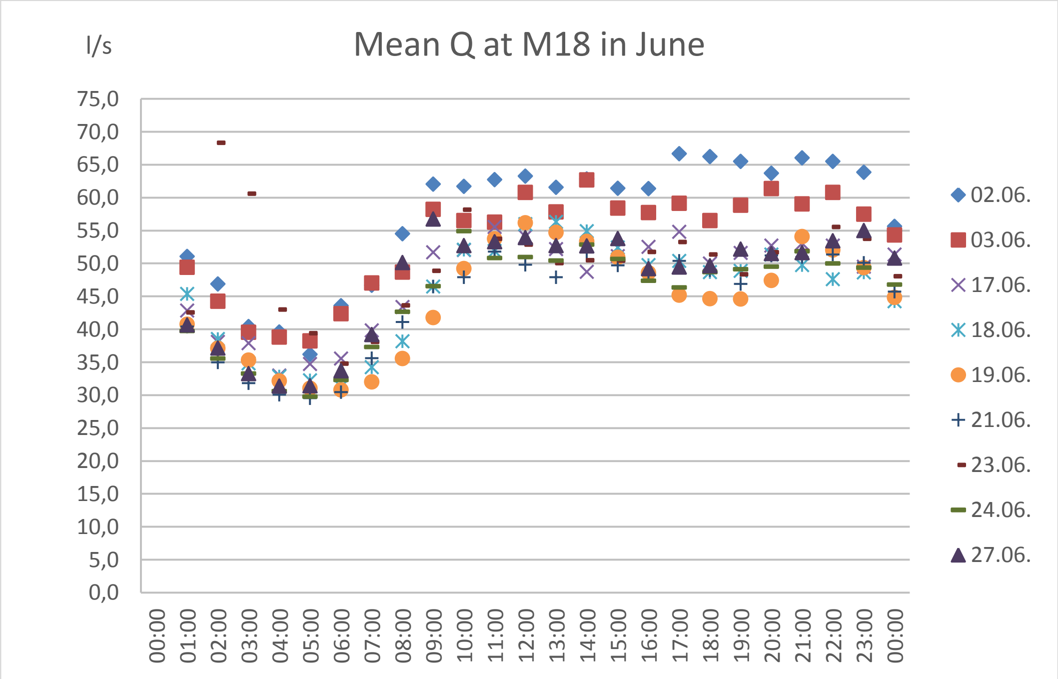


Figure 9 Mean discharge at M18 in June

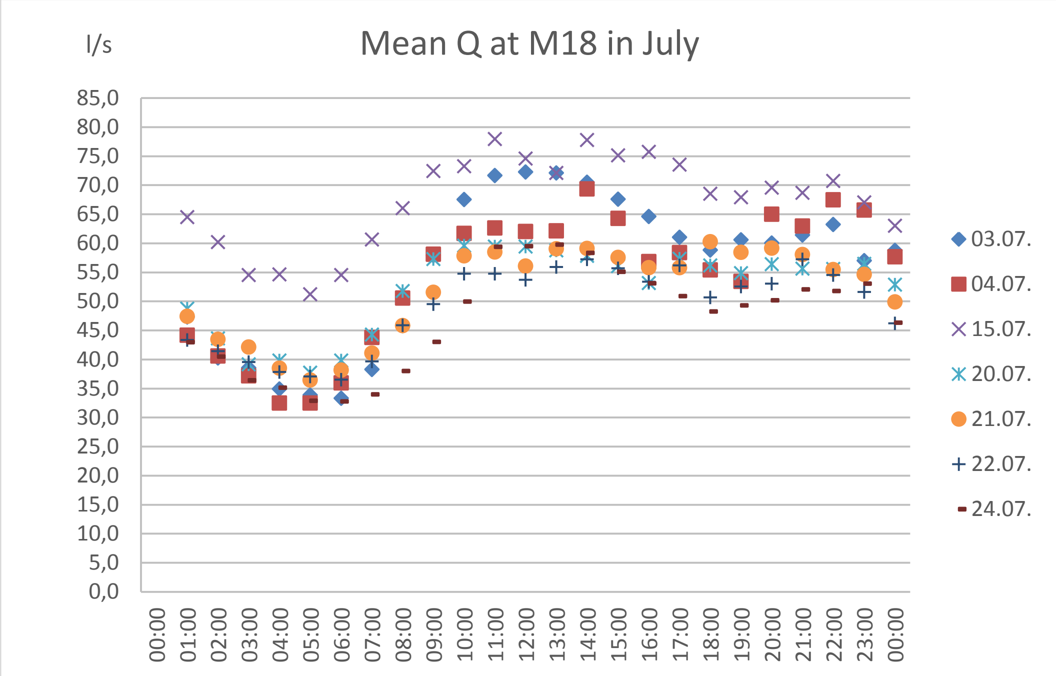


Figure 10 Mean discharge at M18 in July

5.1.3 Analysis of the diurnal cycle at measuring points

In this chapter changes of mean monthly wastewater temperature and discharges throughout the day at several measuring points will be described. The diurnal curve shows a similar pattern for both discharge and temperature at most of the measuring points in the majority of the months. Therefore the prevailing pattern will be described in the following chapter as well as several exceptions. Furthermore, days with measuring errors will be highlighted and influences of these measuring errors will be discussed.

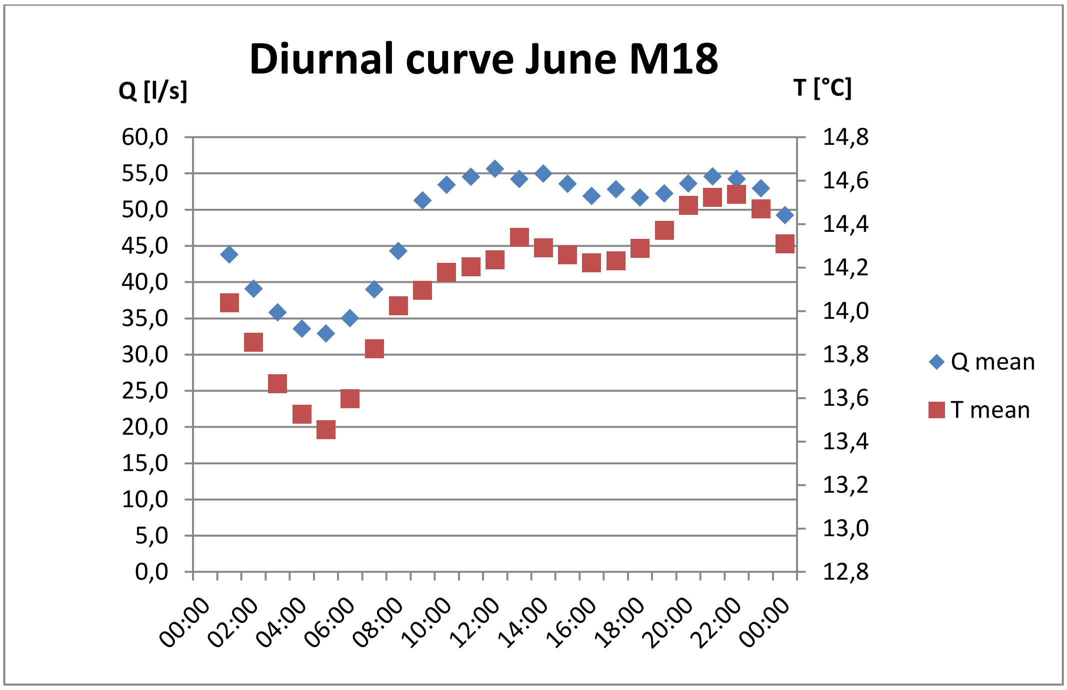


Figure 11 Diurnal curve from June at M18

Figure 11 illustrates the predominant discharge and temperature pattern during one day. Both start with a decline from midnight to around 5 am. At this time the lowest point in the curve is reached. The low of the discharge curve is in general more evident than the low of the temperature curve. Deviation from the mean monthly discharge vary between -38.3 % below the average in June at M16 and only -9.3 % from the average in May at M02. Variations in the low point of the temperature curve are less distinct, ranching from a -8.8 % deviation in March at M06 to -1.4 % deviation in July at M03. From around 5 am to approximately 10 am a relatively steep increase occurs, which is followed by the first peak of the day at 1 pm. Overall this first peak occurs between 11 am and 3 pm depending on the measuring point. Here again the peak of the discharge curve is in generally higher than the peak of the temperature curve. In March the discharge of the first peak exceeds the average discharge by 35.1 % at M01 and also the least pronounced first peak can be found at M01. It was recorded in April and differed from the average by only 8.5 %. The highest first peak in the temperature curve can be found in March at M06 with a deviation of 11.7 % from the mean temperature. The smallest temperature peak can be found at M03 in July. As the temperature variations in this month are relatively small at this measuring point the peak is only 0.4 % above the monthly average. After a slight decline, temperature and discharge start rising again around 6 pm, reaching a second peak at 10 pm at M18 illustrated in Figure 11. In general the second peak can be found between 8 pm and 10 pm. Both the highest and the lowest second discharge peak were recorded in March. The highest exceeded the mean value by 28.9 % at M01, whereas the lowest was measured at M06 with a deviation of 1.9 %. The highest deviation for the second peak from the average wastewater temperature can be found at M02 in March with 7.7 %. The second peak in wastewater temperature is lowest at M02 in July, where it exceeds the average temperature by only 1.2 %. Until midnight temperature and discharge are decreasing again. Bischofsberger and Seyfried (1984) and Abdel-Aal et al. (2014) describe a similar pattern measured in their case studies. However, only one peak was found by Abdel-Aal et al. (2014).

This pattern reoccurs at most of the other measuring points as well as in other months. Even though the exact times of the maximum and minimum values are a little bit shifted compared to Figure 11, the main pattern with a low in the morning, followed by a steep increase and two peaks during the day stays the same. The pattern can be explained by higher water consumption at the times of peaks in the morning and in the evening and in connection with this also the use of warmer water, like for example using showers, dishwashers or washing machines. However, a few exceptions to this pattern must be noted as well. One irregularity can be found in March, where the discharge curve shows only one peak, which occurs in the afternoon around 4 pm. The temperature curve on the other hand still has two peaks and is at a low at the same time as the discharge curve peaks, as illustrated in Figure 12. The peak in discharge can be explained by melting water infiltrating into the sewer system in March during the afternoon. This leads to an increase of discharge. At the same time the wastewater temperature decreases, which could be an indication that the temperature difference between melting water and wastewater causes a decrease in wastewater temperature. However, the decrease is below 0.5 °C and it does not decrease below the lowest temperature of the day. Therefore the temperature of the infiltrating melting water may have some influence on the wastewater temperature, but it may not be the main influence.

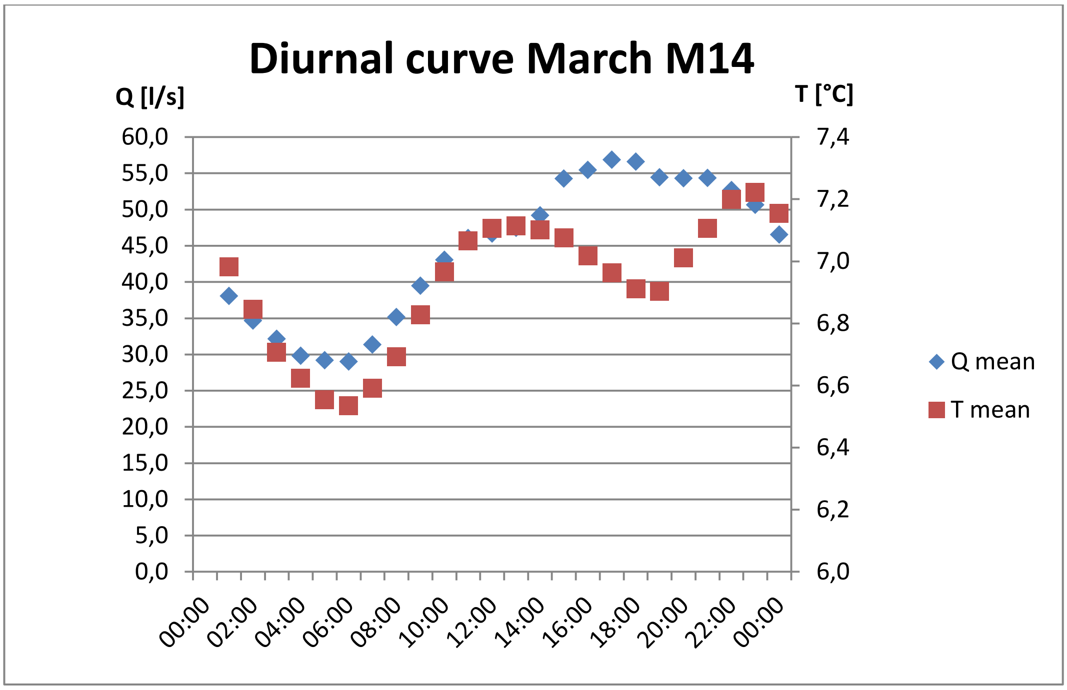


Figure 12 Diurnal curve in March at M14

This pattern can be found at every measuring point along the main sewer line in March, with an exception being measuring point M06 as visible in Figure 13. Here also only one major discharge peak was recorded. However, it occurs in the morning at around 9 am. This deviation from the prevailing discharge pattern can be explained by the fact that in March data was recorded at only two days and one of them showed a slight change in the pattern. As no data was recorded on the other days, they have been excluded from the analysis of data from measuring point M06. Furthermore, a considerable higher fluctuation of wastewater temperature is recognizable due to the missing data. At M07 and M09 the sensor also recorded no data at one day in March, which was excluded from the respective mean values as well.

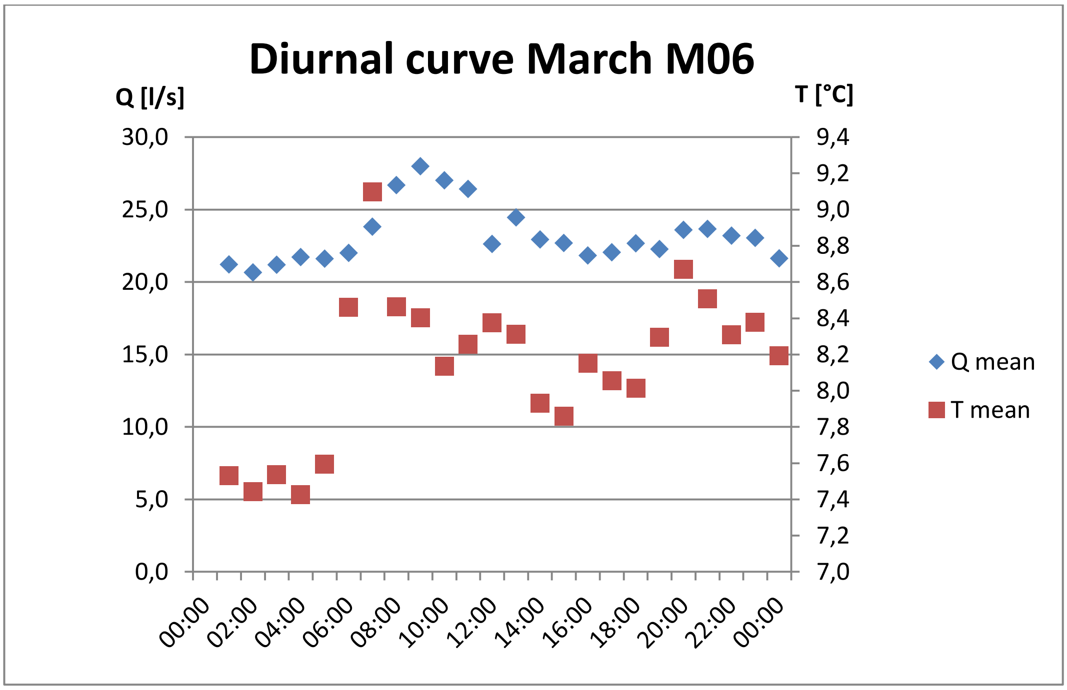


Figure 13 Diurnal curve in March at M06

Apart from March, measuring errors were also found in July at three measuring points. At M01 no data was recorded for five out of six dry weather days, at M03 the sensor worked at two out of six days and at M05 there was an error on two days. The lack of data due to measuring errors mainly leads to a distortion of the daily discharge and temperature pattern. However, the monthly mean value is not significantly influenced by this, when comparing the mean values of measuring points with fewer days of error or without error with other measuring points. Therefore, the mean monthly values for the following analysis are calculated only from days without measuring errors, even though this leads to a difference in days used for calculating the mean temperature at a few measuring points in March and July.

Another exception occurs in July at M05 as shown in Figure 14. The mean hourly temperature at 3 pm is significantly higher than in the hour before and afterwards. It exceeds the preceding and the following values by more than 1 °C. This can be explained by an exceptionally high mean temperature value on the 20th of July at 3 pm of around 20.3 °C. The highest temperature measured at this day is 26.5 °C. At the same time a slight increase in discharge was recorded, however, it was not significant enough to influence the average value the same way the increase in temperature did. Unfortunately the reason for the high wastewater temperature at this time and day cannot be determined further. The same peak can obviously also be found at M06 as it is the measuring point at the outlet of the same combined sewer overflow structure. This indicates that the high temperatures did not occur due to a measuring error, as they were recorded at both sensors, therefore the data was included into the analysis. However, no significant influence on the measured wastewater temperature at the sensor M07 downstream of M05/06 or on the monthly mean value was found. Therefore the data was included into the study.

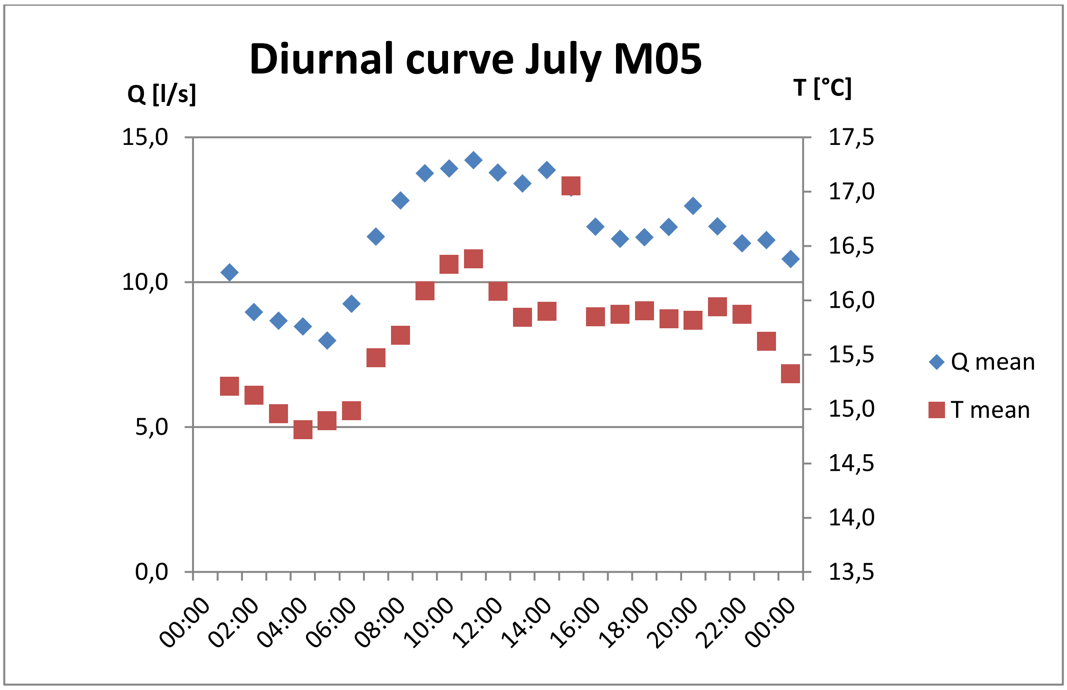


Figure 14 Diurnal curve in July at M05

5.1.4 Analysis of wastewater temperature at combined sewer overflow structures

The discharge data was validated in the previous study. However, as the temperature data was not used for the former study there was no validation performed for the temperature data. As temperature and discharge were measured at the inlet of the combined sewer overflow structure and at the outlet of the same structure at most measuring points, a comparison of the two values is a good indication of whether the sensors worked correctly or not, as the distance between both is rather short and the conditions, as well as the discharge, do not change. This helped identifying measuring errors that were not recognized before.

When comparing the discharge at M13 and M14 for example, where the first one is the inlet of a combined sewer overflow structure and the second one is the outflow of the same structure, it becomes evident that they correlate well as no inflow or outflow occurs between the two measuring points. In Figure 15 the mean monthly discharge of M13 and M14 is displayed. The values of both are nearly the same and therefore overlap almost perfectly. The small distortion, however, lies within the range of measuring errors. In a next step the wastewater temperature is compared at the same measuring points in Figure 16 including not only the monthly mean wastewater temperature at the respective points, but also a range for the measuring error of +/1 °C. Even though the recorded temperature values do not overlap as perfectly as the discharge values do, no significant difference was found and a measuring error at one of the sensors can be ruled out.

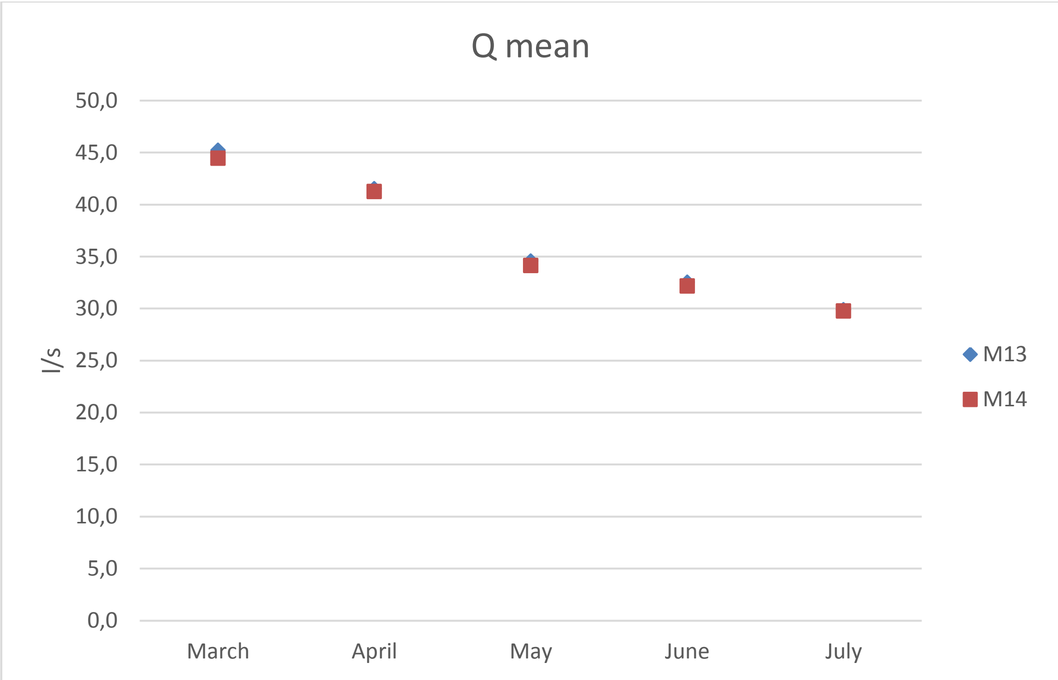


Figure 15 Comparison of discharge at M13 and M14

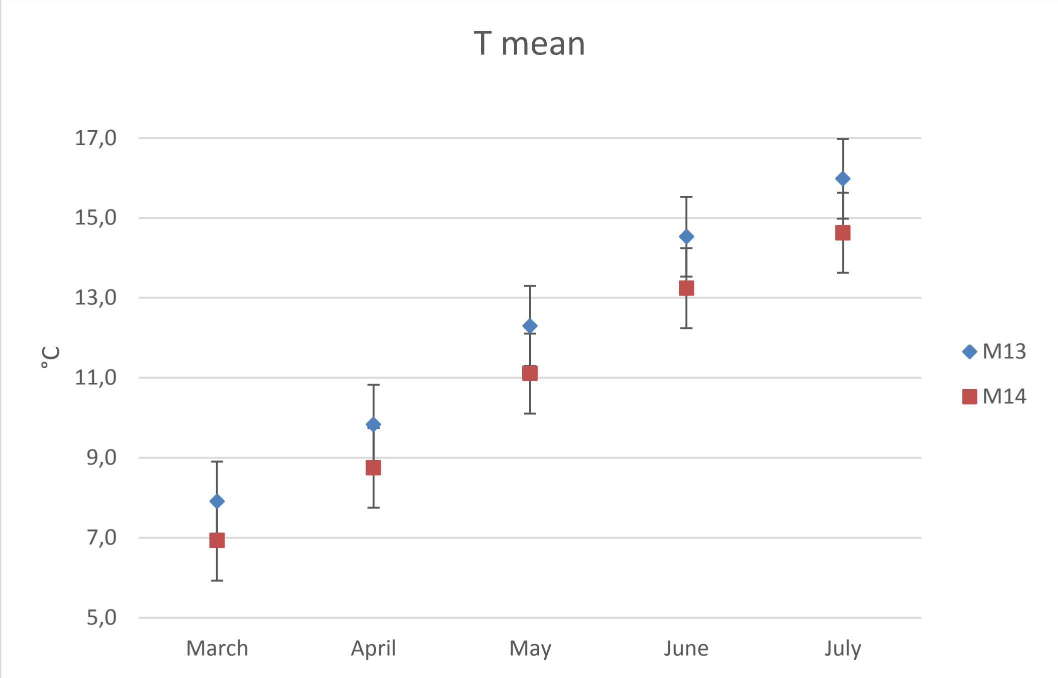


Figure 16 Comparison of wastewater temperature at M13 and M14

Most of the inlet and outlet measuring points fitted together like M13 and M14. However, three exceptions must be noted, which lead to the exclusion of two measuring points. Regarding the measuring points M03 and M04 a deviation in the temperature data was found. At the measuring points M03 and M04 the temperature difference was higher than 2 °C in March as shown in Table 5 and therefore exceeds the measuring error of +/- 1 °C. However, as the maximum possible difference is only exceeded in March and both values fit into the overall temperature distribution, meaning that neither has significantly higher or lower wastewater temperature than the measuring points upstream and downstream, it was decided to calculate the mean value of M03 and M04 and use it the spatial and temporal analysis. Nevertheless, results including M03/04 have to be evaluated with great caution.

Table 5 Difference in temperature between M03 and M04

Month	Temperature Difference [°C]
March	2.1
April	1.9
May	1.8
June	1.7
July	1.7

One of the cases where a measuring point had to be excluded due to irregularities is the measuring point M15 located at the inlet of a combined sewer overflow structure. In May much lower temperatures were recorded at M15 than at M16 the outlet measuring point as shown in Figure 17. When looking at the discharge, shown in Figure 18, on the other hand the discharge measurements in May display no differences. Even though the temperature difference between M15 and M16 in May is only 1.8 °C and therefore within the measuring error, it was decided that M15 will be excluded from the analysis, because the relatively low mean value does not correlate with the temperatures measured at the other sites and the reason for the low temperature cannot be found. Therefore only measurements taken at M16 were used for the further study.

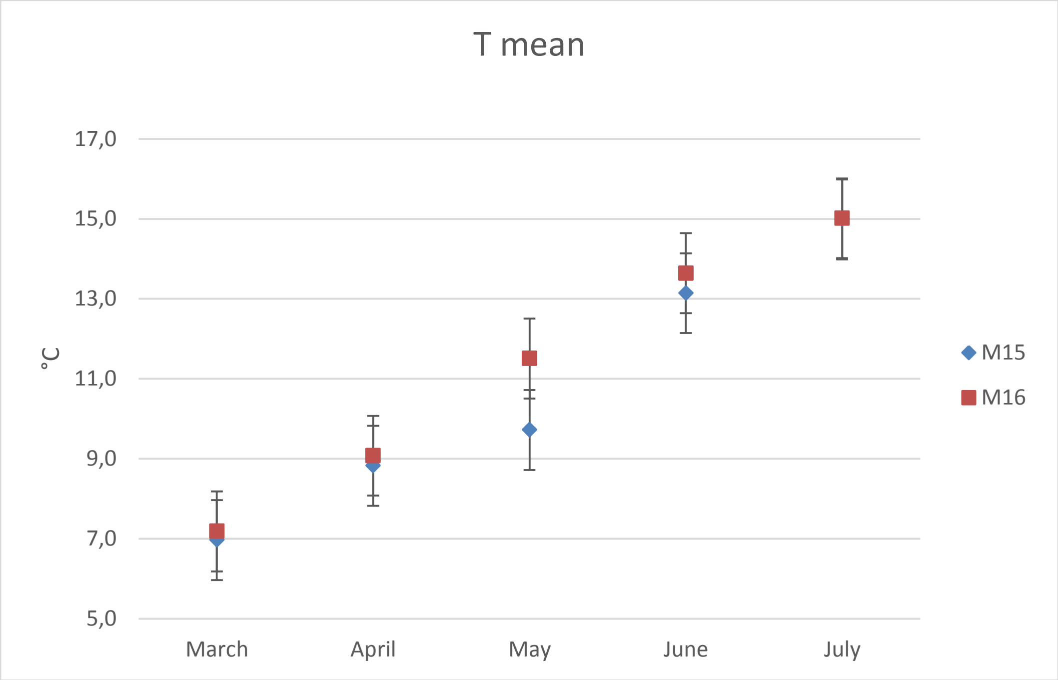


Figure 17 Measuring error at M15 in May

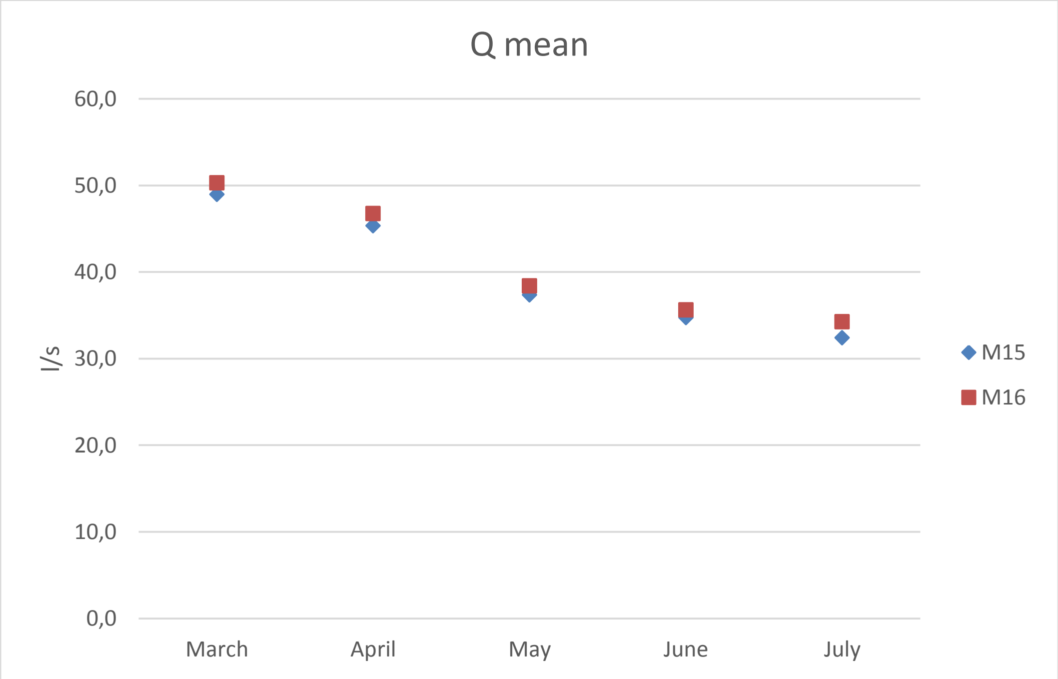


Figure 18 Comparison of discharge at M15 and M16

Furthermore, the measuring point M10 was excluded from the evaluation. At M10 there is clearly no connection to the wastewater stream in the sewer. This is suggested by the fact that no discharge was measured throughout the months, as well as the relatively low temperatures measured at M10 compared to M09 as shown in Figure 19. It is not obvious what kind of medium was surrounding the sensor at M10, as the values were analysed for correlations with air temperature, soil temperature and river water temperature and no significant connection was found. Therefore the temperatures measured cannot be considered for any further analysis.

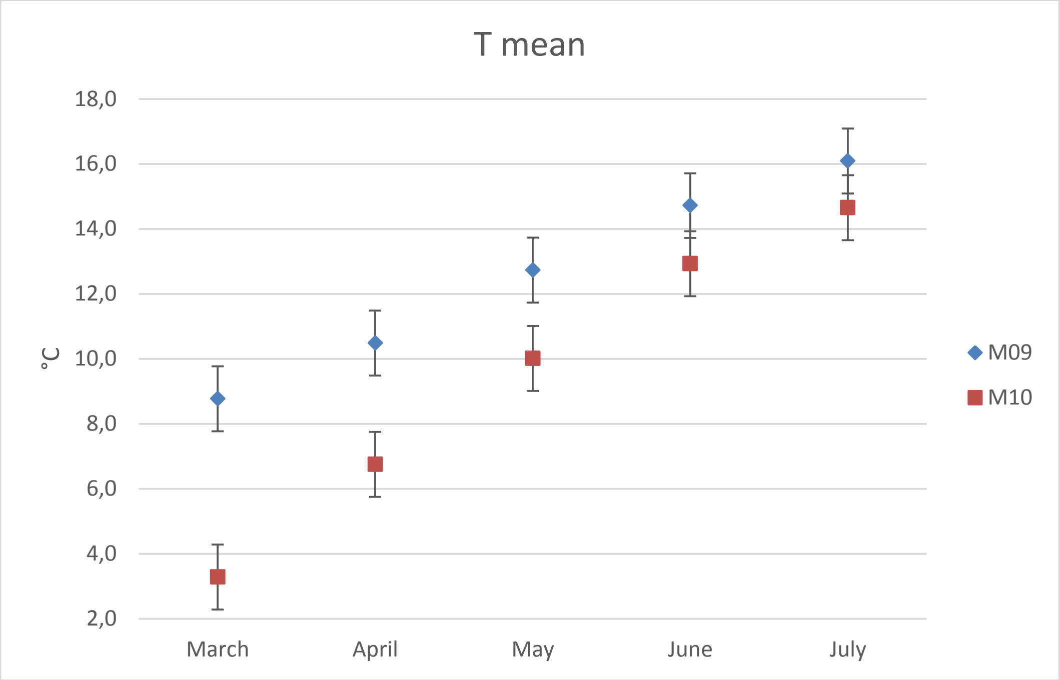


Figure 19 Comparison of wastewater temperature at M09 and M10

The figures illustrating wastewater temperature and discharge of the other measuring points including M01, M02, M03, M04, M05, M06, M11, M12, M17 and M18 can be found in the appendix as Attachment 1 to Attachment 10.

5.2 Temperature development in the sewer system

This chapter focuses on the wastewater temperature development in the sewer system taking into account the development over the longitudinal section, the development over time as well as major influences on the respective wastewater temperature. The discussion and interpretation of the results from the temperature development is placed at the end of this chapter, as this section is more or less independent from the second objective.

5.2.1 Changes of discharge and wastewater temperature over the longitudinal section

This part of the thesis discusses the changes of discharge and wastewater temperature along the longitudinal profile over the months as one aim of this study is to determine wastewater temperature development in the main sewer

Figure 20 shows the changes in discharge between the measuring points from March to July. The variation between the months will be discussed in the following chapter as this section focuses on the changes in the longitudinal section.

Figure 20 Longitudinal profile of the discharge

As visible in Figure 20 discharge increases from measuring point to measuring point as the inflow into the main sewer system is increasing the total discharge in each section. However, the amount of change between the individual measuring points differs depending on the number of house connections draining into the sewer between the measuring points. The smallest increase can be found between M08 and M09 in April with 1.3 l/s difference, whereas the largest increase was recorded between M16 and M17/18 in July with 17.3 l/s difference. The increase in discharge between measuring point M16 and M17/18 exceeds the increase between any other measuring points throughout the months. This can be explained by the large catchment area connected to the main sewer between those points as illustrated in Figure 7.

In order to make the increase between the individual points comparable, it is necessary to convert the absolute changes to changes in discharge per kilometre. For example, the absolute increase of discharge between M05/06 and M07 is one of the largest between two measuring points ranging from 5.8 to 10.3 l/s, however, when looking at the changes of discharge per kilometre, it becomes obvious that the increase per kilometre is not exceptionally high. When looking at Figure 21, it becomes obvious that the change is even smaller than variation between other measuring points with only 3.5 to 2.0 l/s/km. The increase between M16 and M17/18 on the other hand is still significantly higher than the others, as discharge increases rapidly on a short distance due to lateral inflow from a large catchment.

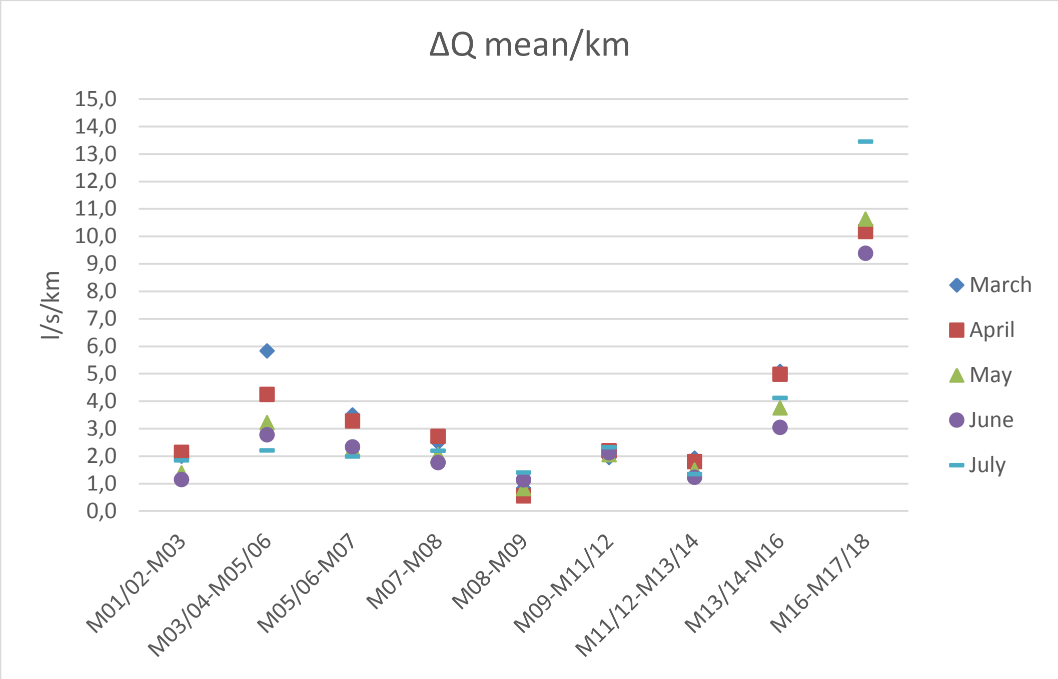


Figure 21 Change in mean discharge per kilometre between the measuring points

When looking at the temperature changes between the measuring points along the longitudinal profile, it looks very different compared to the discharge profile. In Figure 22 the wastewater temperature of each measuring point between March and July is displayed, including the measuring error range of +/- 1.4 °C or +/- 1 °C depending on whether it is a mean value of two measuring points or a single value. For the combined mean value the uncertainty was calculated as 1.4 °C due to the propagation of error. An enlarged version of the same figure can be found in the appendix as Attachment 11.

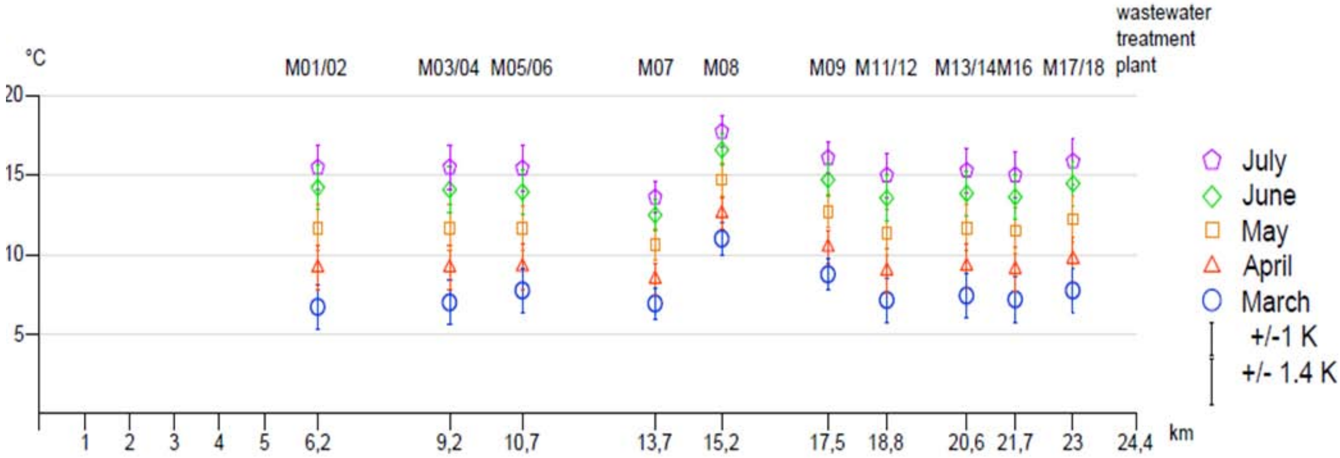


Figure 22 Changes in temperature between measuring points

Figure 22 illustrates that wastewater temperature is not changing significantly between the first measuring point M01/02 and the last measuring point M17/18. When just looking at Figure 22, there seems to be an evident fluctuation in temperature. For example the measured wastewater temperature at M07 is constantly lower than the wastewater temperature at M05/06. However, when considering the measuring error of 1 °C, the changes are not significant, as they are ranging between -0.8 °C and -1.8 °C. The only exception is the measuring point M08, where wastewater temperature exceeds all other measuring points throughout the months. The fact that the wastewater temperature is considerably higher at M08 than at the other measuring points can be explained by its location. It is located relatively close to a few lateral inflows coming from a separate sewer system, which has the effect that the wastewater temperature has not yet decreased to the steady point it reaches at all the other measuring points. This explanation is further supported by the fact that wastewater temperature has decreased again at the downstream measuring point. In other case studies an increase in temperature might also be caused by indirect discharges of industrial water into the sewer system, which can have higher temperatures than municipal wastewater. This is not the case for this study as there is no knowledge of indirect discharges being located in the area. In general, however, there is no significant change of wastewater temperature in the main sewer between the measuring points.

In order to compare the temperature changes between the different measuring points, the temperature change per kilometre was calculated. The results are illustrated in Figure 23. Most values stay within a range of less than +/- 1 °C/km between two measuring points. The only exception is again the temperature change between M07 and M08, where temperature increases at a rate of 2.8 °C/km. The explanation is the same as before, being the proximity to a separated sewer inlet.

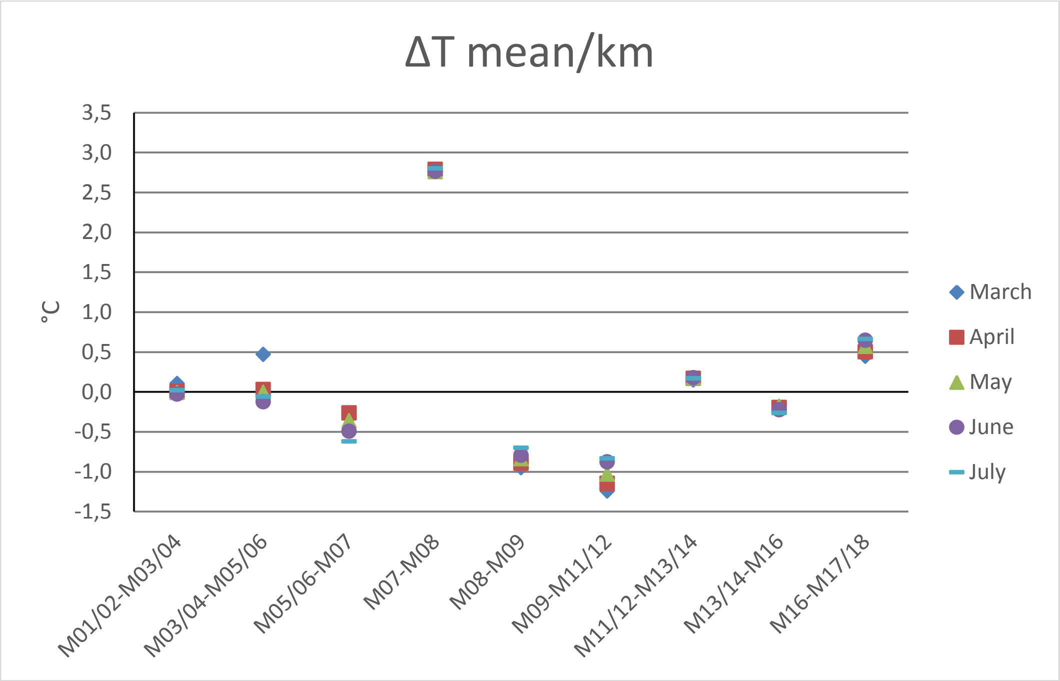


Figure 23 Temperature change per kilometre between the measuring points

In Table 6 the mean water use per capita, as well as the respective temperatures of the purpose for the water use, is listed. The data for the mean water use was taken from Neunteufel et al. (2012), whereas the temperature data are estimates based on standard settings of household appliances as well as on drinking water temperature. The temperature of drinking water in the area is assumed to be 12 °C as the groundwater temperature ranges around this value. For the washing machine two different settings were analysed. One time a washing program with 30 °C was used for the calculation and the other time a washing program with 60 °C. Both times it was assumed that one third of the total water used by the machine is warm water and the other two thirds are cold water. In total an average wastewater temperature of 18.9 to 20.1 °C was calculated. For the further analysis the mean value of 19.5 °C will be used as a reference level, which is in close proximity to the wastewater temperature levels mentioned by DWA (2009) and AWEL (2010).

Table 6 Mean water use per capita and resulting wastewater temperatures

household appliances	mean water use per capita [l/pd]	mean temperature [°C]
Dishwasher	3	30
Washing machine	14	18 - 28
Bathtub	4	35
Shower	25	35
Toilet	34	12
Water tap	36	12
Mean wastewater temperature		18.9 – 20.1

Even though wastewater enters the sewer system with a mean temperature of approximately 19.5 °C, it drops rapidly within the sewer system. Once wastewater temperature has reached a certain level it neither increases nor decreases along the longitudinal profile of the sewer system. This interpretation contrasts with that of Abdel-Aal et al. (2013) and Dürrenmatt and Wanner (2008), who both found out that wastewater temperature decreases in the flow direction. However, their findings are based on measurements taken in a sewer section without lateral inflow and over a comparatively short length, therefore their conclusion deviate from the findings of this study.

No significant connection can be found between changes in discharge and changes in temperature in the longitudinal profile. While discharge is increasing between the measuring points, wastewater temperature stays at a relatively stable level. Nevertheless, the wastewater temperature level and the discharge vary over time. The development of both will be described in the following chapter.

5.2.2 Changes over time in discharge and temperature

In this chapter changes of discharge and wastewater temperature e over time will be examined. This includes changes in the longitudinal section, variations at the individual measuring points and deviations of the diurnal curve.

In Figure 20 and Figure 22 in the previous section it is illustrated that discharge as well as wastewater temperature change over time. At each measuring point the mean value from March to July is displayed. A certain trend is visible in both figures. However, while in Figure 20 March has in general the highest discharge and July the lowest, the pattern is reversed in Figure 22, where wastewater temperatures are lowest in March and highest in July. This leads to the assumption that while mean wastewater temperature increases from March to July, discharge is decreasing over the same time period. To elaborate further on this thesis Figure 24 and Figure 25 are introduced, which show the same data set as Figure 20 and Figure 22, with the difference of having the months displayed on the x-axis and therefore giving a better overview of the development of both discharge and wastewater temperature over the months.

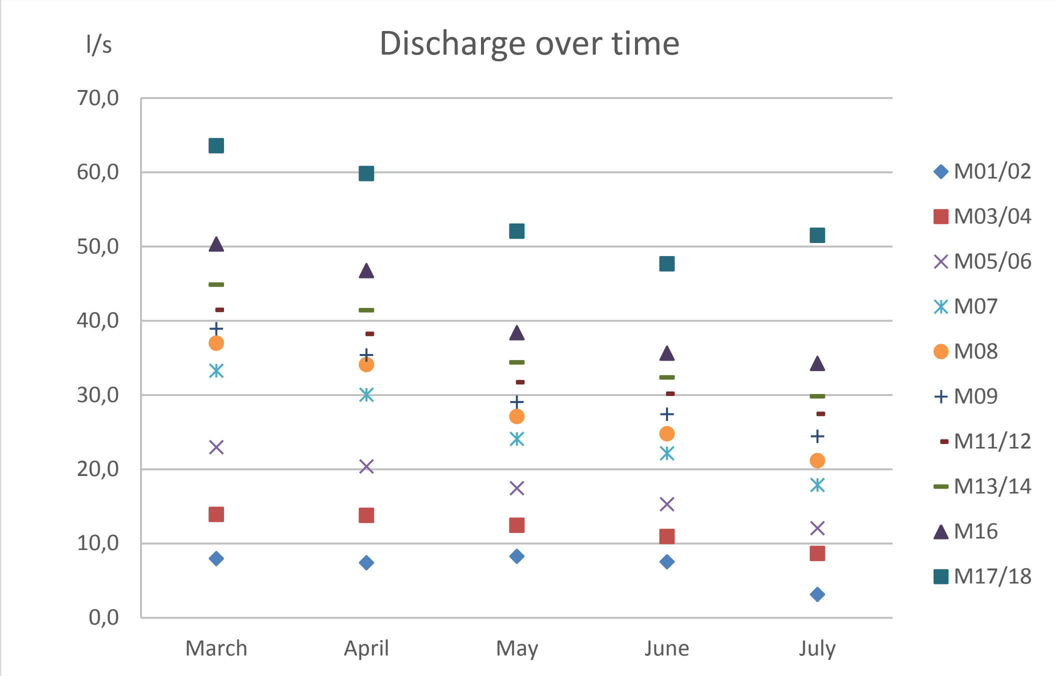


Figure 24 Discharge changes over time

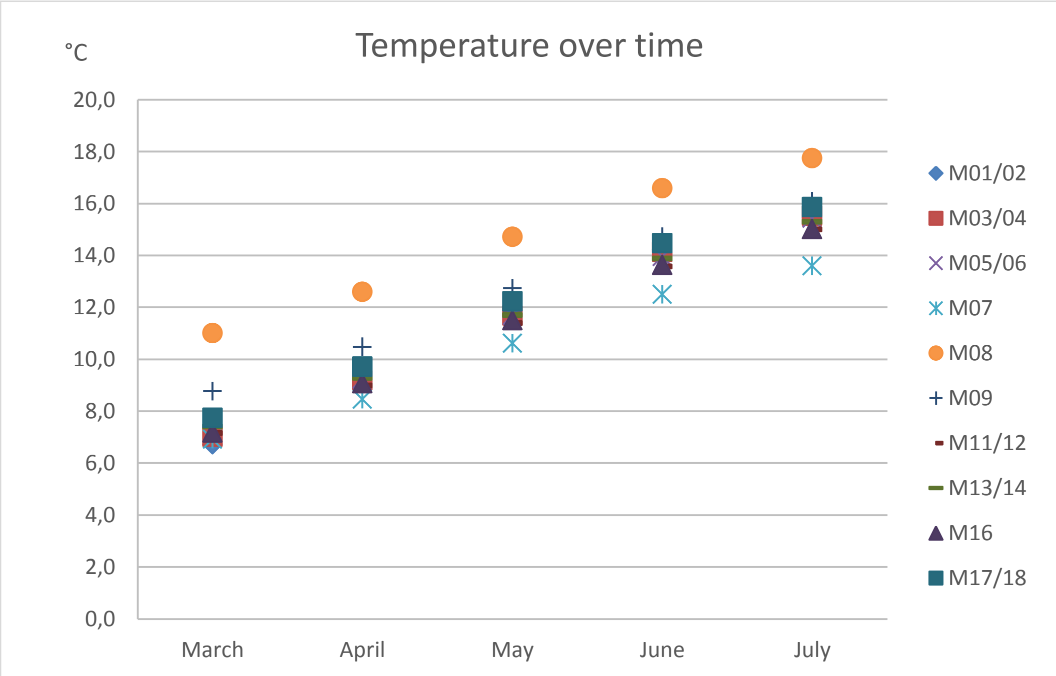


Figure 25 Wastewater temperature changes over time

Figure 24 shows a constant decrease of discharge from March to July for most of the measuring points. For the measuring points containing two numbers such as M01/02 the mean value of the inlet value and the outlet value of the specific combined sewer overflow structure was used. There is a trend visible that from March to June the decrease of discharge is steeper at measuring points further downstream, then again from July to June this trend changes and measuring points further upstream have a steeper decline in most of the cases. The mean decrease of discharge between March and April is 2.7 l/s ranging between reductions of 3.8 l/s at M17/18 and only 0.1 l/s at M03/04. Between April and May discharge is in average decreasing the most between all months. A mean decrease of 5.2 l/s was recorded, having its maximum at M16 with 8.3 l/s and the smallest reduction at M03/04 with 1.3 l/s. One exception must be noted, however, as discharge at M01/02 is increasing by 0.9 l/s between April and May. This can be explained by an illicit connection of a well to the sewer system on the 11th of April, which can be seen in Figure 26. The illicit connection existed until the middle of July. When looking at the wastewater temperature at the measuring point M01, it is evident that the influence of the well water in the sewer is not significant. The change in flow rate between May and June is decreasing at an average of 2.1 l/s, ranging from a maximum of 4.4 l/s at M17/18 to a minimum of 0.7 l/s at M01/02. Between June and July the average decrease in discharge is 2.3 l/s. Therefore it is similar to the preceding month, however this time the maximum decrease was found at M01/02 with 4.4 l/s and the minimum was recorded at M16 with 1.4 l/s. An exception to the overall pattern is the measuring point M17/18, where an increase of discharge by 3.9 l/s was found between June and July. One explanation for this change is an increase of water usage in July due to high air temperature. As a large drainage area is connected to the main sewer between measuring point M16 and M17/18 and an increase in water consumption would have an influence on discharge in this area. However, no validation for this was undertaken and other explanations could be possible as well.

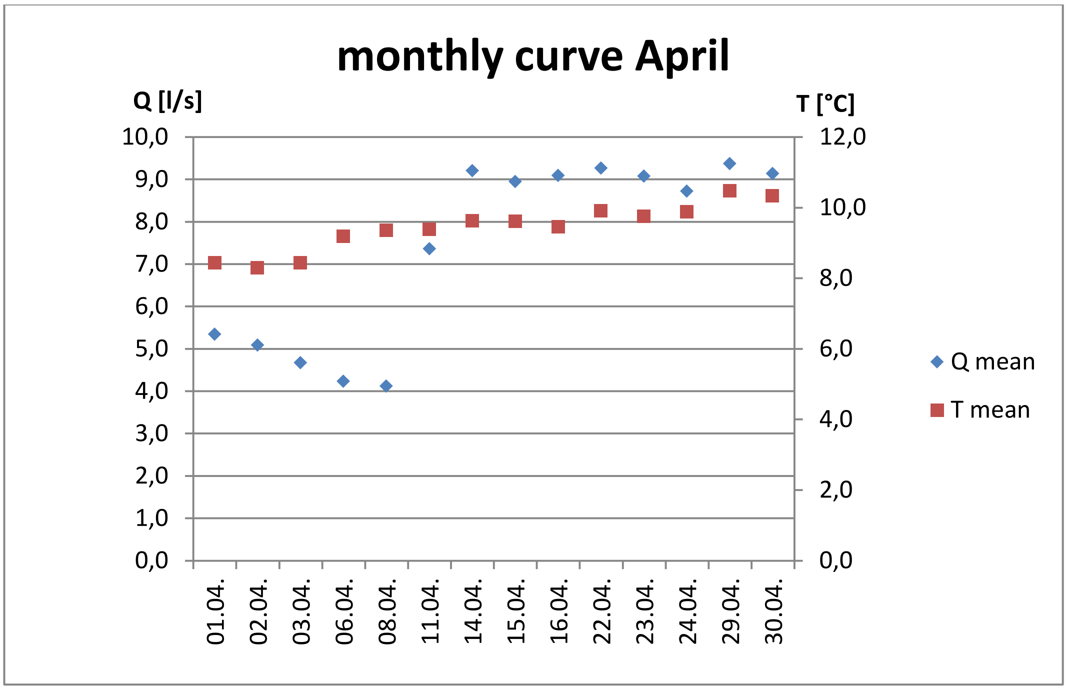


Figure 26 Change of discharge due to illicit connection of a well

Figure 25 on the other hand shows a constant increase of wastewater temperature at every measuring point, which is the reversed trend compared to Figure 24. Furthermore, the significantly higher temperature at M08 throughout the months is clearly visible and M07 can be identified as having one of the lowest wastewater temperatures of all measuring points. In March the average wastewater temperature was 7.8 °C with the lowest temperature of 6.7 °C at M01/02 and the highest temperature of 11 °C at M08. Between March and April the average wastewater temperature increase was 1.9 °C, with the largest difference being 2.5 °C at M01/02 and the smallest being 1.5 °C at M05/06. In April mean wastewater temperature varies between 8.5 °C at M07 and 12.6 °C at M08. Wastewater temperature increases most between April and May with an average of 2.4 °C at all measuring points except for M01/02. The highest increase can be found at M03/04 with wastewater temperatures rising by 2.5 °C between April and May. The lowest increase between April and May was recorded at M08 with a 2.1 °C increase. In May wastewater temperature ranges between 10.6 °C at M07 and 14.7 °C at M08. The temperature difference between May and June was in average 2.2 °C with a maximum at M01/02 with 2.5 °C and a minimum at M07 with 1.9 °C. Mean wastewater temperature in June was found to have a minimum of 12.5 °C at M07 and a maximum temperature of 16.6 °C at M08. The wastewater temperature increase between June and July was the smallest of all months at all measuring points. An average increase of only 1.3 °C was recorded with a maximum of 1.5 °C at M05/06 and the lowest increase at M07 with only 1.1 °C. In general wastewater temperature in July ranged from 13.6 °C at M07 to 17.8 °C at M08. The mean, minimum and maximum temperature of each month is further summarized in Table 7.

Table 7 Mean, maximum and minimum wastewater temperature of each month

	Mean temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]
March	7.8	11.0	6.7
April	9.6	12.6	8.5
May	12.0	14.6	10.6
June	14.2	16.6	12.5
July	15.5	17.8	13.6

When comparing the wastewater temperature measured in this study with wastewater temperature found in literature from Table 2 it is noticeable that wastewater temperature measured in other studies is generally higher than in this study. Wastewater temperature found in literature never decreases below 10 °C even in winter, whereas the lowest mean wastewater temperature recorded in this study was 6.7 °C. Furthermore, the highest temperatures found in literature from March to July are also never reached by this study. The lower temperatures measured in this study area is definitely a disadvantage for using the thermal energy of wastewater for heating buildings as the possible heat extraction is considerably lower than in the other studies.

The changes in discharge and temperature over time can also be seen, when comparing the diurnal curve of the different measuring points at each month. Figure 27 and Figure 28 represent characteristic distributions of wastewater temperature and discharge from March to July in the study area. The increase of wastewater temperature by 1 °C to 2 °C throughout the months, as well as the decrease in discharge at the same time, is clearly visible. Furthermore, the changes in the daily discharge pattern in March, as discribed in chapter 5.1.3, are illustrated well in Figure 28. As discussed before the infiltration of melting water into the sewer system lead to the deviation of the general diurnal discharge curve in March. The infiltration water, furthermore, causes the higher discharge in the earlier months of the year, as the influence of infiltrating melting water is decreasing, the discharge is decreasing as well. The higher discharge, however, has no significant inlfuence on the wastewater temperature, as no change in the temperature pattern is seen in March in the figures below.

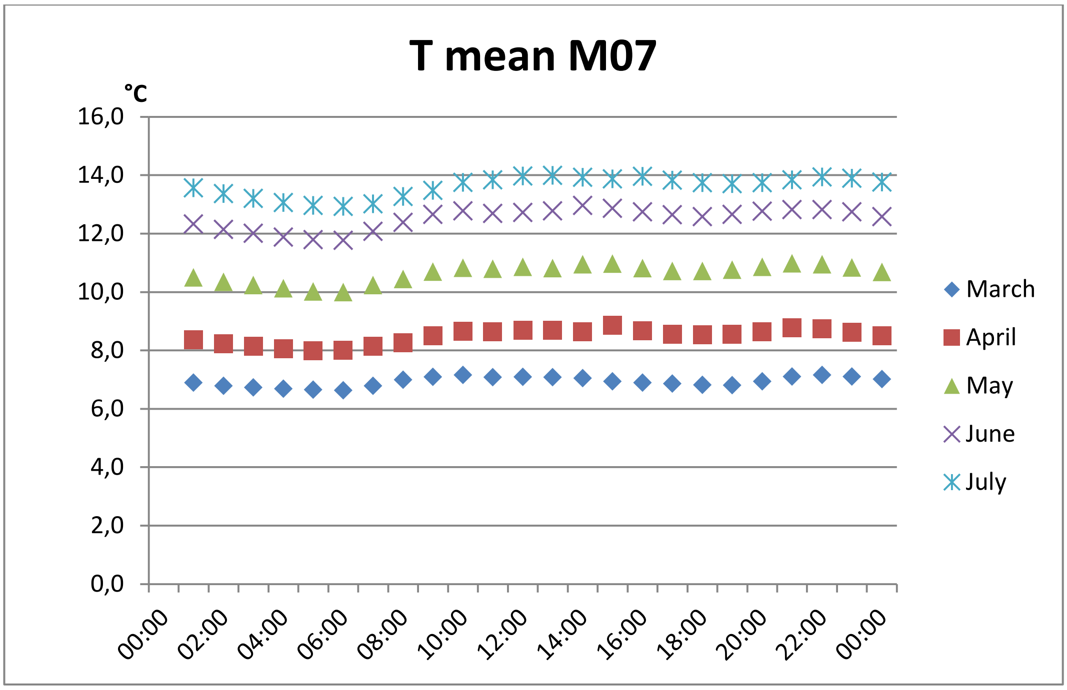


Figure 27 Diurnal temperature curve at M07

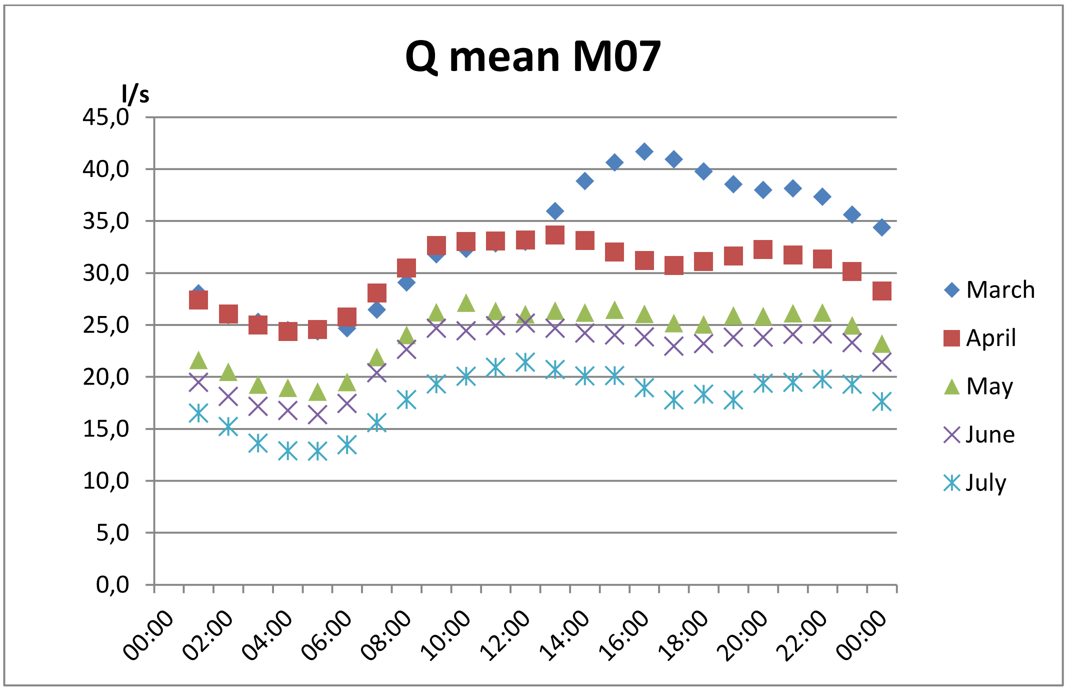


Figure 28 Diurnal discharge curve at M07

One significant change was recorded at M01 and M02, where the discharge between June and July dropped by more than half from 7.5 l/s to 3.1 l/s. The extent of change is illustrated in Figure 29, even though the figure is only showing average hourly discharge of M01, the pattern for M02 and the combined values are very similar. One reason for the low discharge in July is that the sensor was not recording any data for most of the month and only discharge data of one dry weather day was recorded. Furthermore, a significant decrease of discharge was recorded between the 4th and the 20th of July as shown in Figure 30. This is the result of the well mentioned before being disconnected from the sewer system again. At the same time wastewater temperature seems to be decreasing slightly as discharge in July is decreasing, however, the change is less than 0.5 °C within the month.

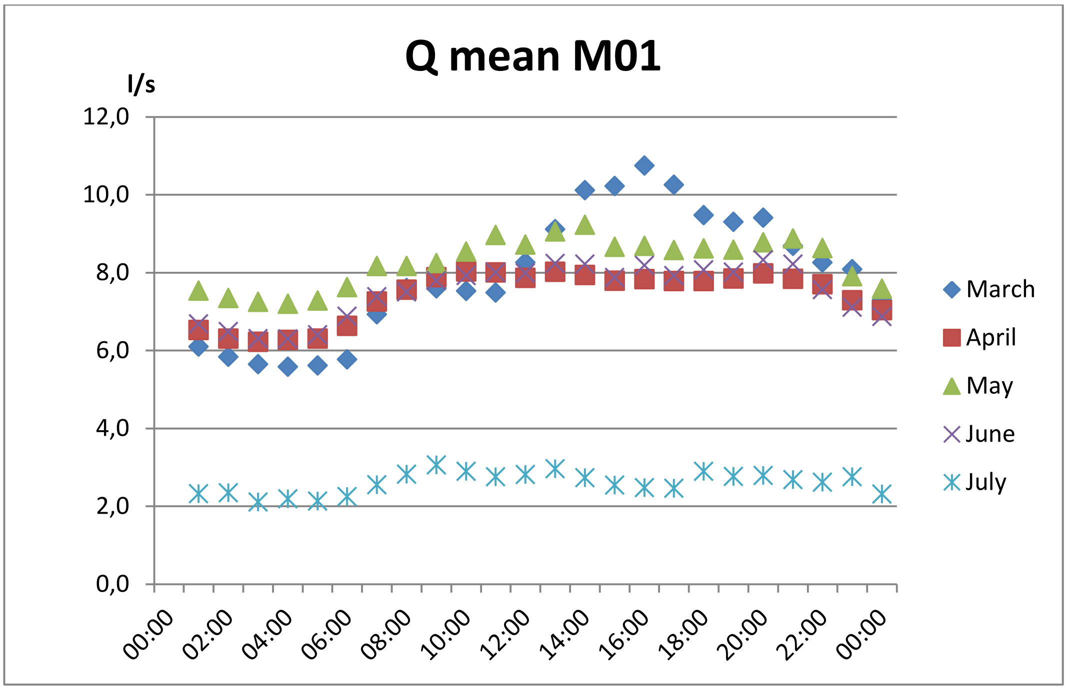


Figure 29 Diurnal discharge curve at M01

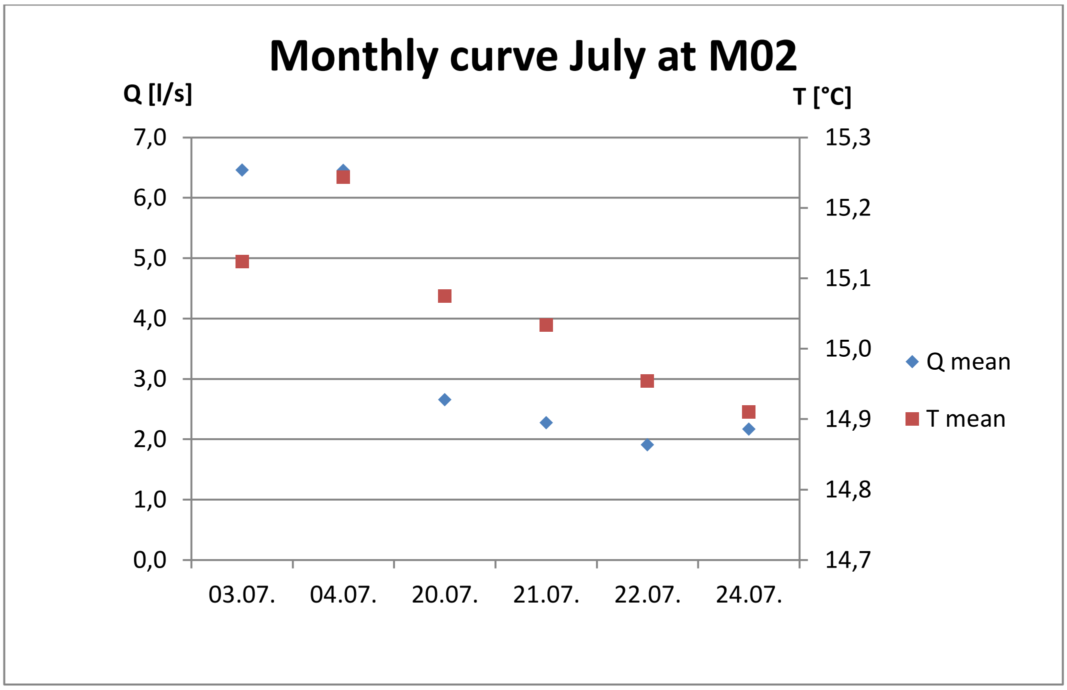


Figure 30 monthly discharge and temperature curve in July at M02

In conclusion wastewater temperature is increasing from March to July while discharge is decreasing at the same time. For the thermal use of wastewater looking at data from the heating period would be especially interesting, as it cannot be simply assumed that the trend continuing throughout the year as wastewater temperature is largely influenced by the temperature of the surrounding media. Therefore temperatures of the pipe environment are analysed in the following chapter.

5.2.3 Main influences on wastewater temperature in the sewer

This subchapter deals with fulfilling the second aim of the study, which is determining what has the biggest influence on wastewater temperature. Wastewater temperature is entering the sewer system with an average of 19.5 °C, however, as described earlier wastewater temperature in the main sewer levels off to an average temperature, which depends on the month. As a first step ambient temperatures that might have an influence on wastewater temperature in the sewer such as soil temperature, ambient air temperature, groundwater temperature as well as river water temperature were collected. River water temperature was included into the study due to the fact that the main sewer is located in close proximity to a river as illustrated in Figure 7. Groundwater data was excluded from the study early on as the groundwater level at the measuring point is located at a depth of 8 – 10 m and therefore influences on the sewer can be neglected. Furthermore, there seems to be no interaction between groundwater and river in this area, eventhough the groundwater measuring spot is relatively close to the river.

In Figure 31 the mean monthly temperature of air, groundwater, river water and soil at different depths is illustrated, as well as the range of wastewater temperature reaching from the lowest monthly mean value of the month to the highest monthly mean value, is within at those months. Groundwater temperature is still present in this figure to show that there is no significant movement and therefore an influence on the wastewater temperature can be rueled out. The other tempertures describe a similar trend as the wastewater temperature and are increasing throughout the months, with an exception of soil temperture at 3.5 m depth, wich is in average higher in March than in April. Regarding the range of wastewater temperature displayed, this covers the maximum and minimum mean wastewater temperature measured from March to July, possible measuring errors, however, are not included, which would increase the range by +/- 1 °C.

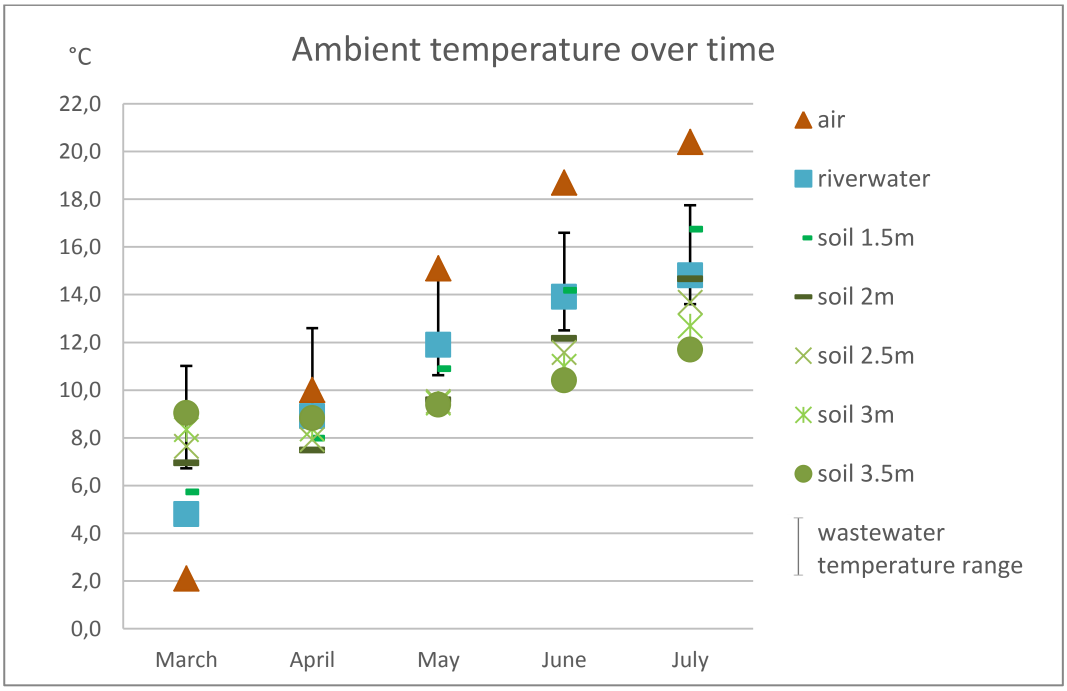


Figure 31 Ambient temperature in relation to wastewater temperature over time

Figure 31 illustrates that in March soil temperature between a depth of 2 m and 3.5 m overlaps with the wastewater temperature, whereas soil temperature at 1.5m depth as well as river water temperature and air temperature are in average lower. This distribution changes in April, when soil temperature is in general lower than wastewater temperature except at a depth of 3.5m. Air temperature and river water temperature on the other hand lie within the range of wastewater temperature. In May the only temperatures correlating with wastewater temperature are river water temperature and soil temperature at 1.5 m depth. At this time mean monthly air temperature is already exceeding mean wastewater temperature. In June the same distribution can be found, with air temperature being significantly higher than wastewater temperature. In July on the other hand wastewater temperature overlaps again with river water temperature as well as soil temperature at 1.5 m, 2 m and 2.5 m depth. This, however, does not give an answer on the question, which medium influences the wastewater temperature most. It shows, however, that the soil, river water and air temperature are increasing at a different rate than wastewater temperature.

For a more detailed analysis mean wastewater temperature, soil temperature and air temperature were evaluated on a daily basis. River water temperature was unfortunately not available on at this temporal resolution, but as wastewater temperature is not directly connected to river water anyways, soil temperature should be accurate enough for the analysis of the pipe environment. As the soil temperature was not measured but modelled, the influence of the sewer is not accounted for in the results and the modelled values might not represent soil temperature in the whole drainage system if soil types vary along the main sewer as a standard values was used for the whole area. Furthermore, the accuracy of the modelled soil temperature is +/- 1 °C. Since the main sewer and therefore the measuring points are located at different depths below the ground surface, it is necessary to look at soil temperature profiles in different depths as well. Figure 33, Figure 34 and Figure 35 show daily mean air temperature, as well as daily mean soil temperature at different soil depths and daily mean wastewater temperature at measuring points, which are located at the respective soil depths. However, as only dry weather days were used for the evaluation of wastewater temperature, there are time gaps in the figures below, which are not illustrated. In order to give a better understanding of how soil temperature and air temperature change throughout the month Figure 32 illustrates wastewater, soil and air temperature including days with rainfall for air and soil temperature. The other months are illustrated in the appendix as Attachment 12, Attachment 13, Attachment 14 and Attachment 15.

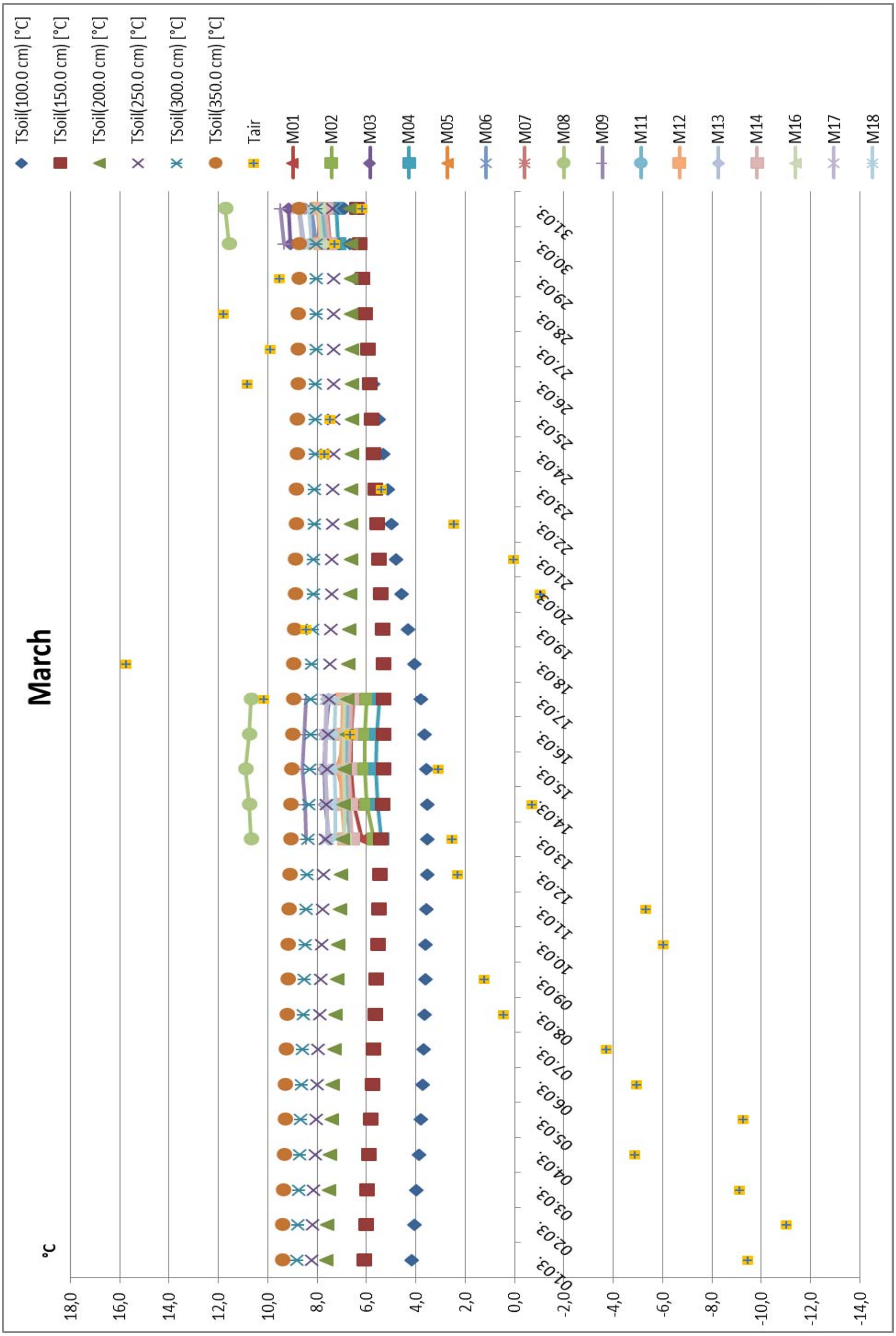


Figure 32 Wastewater, soil and air temperature in March

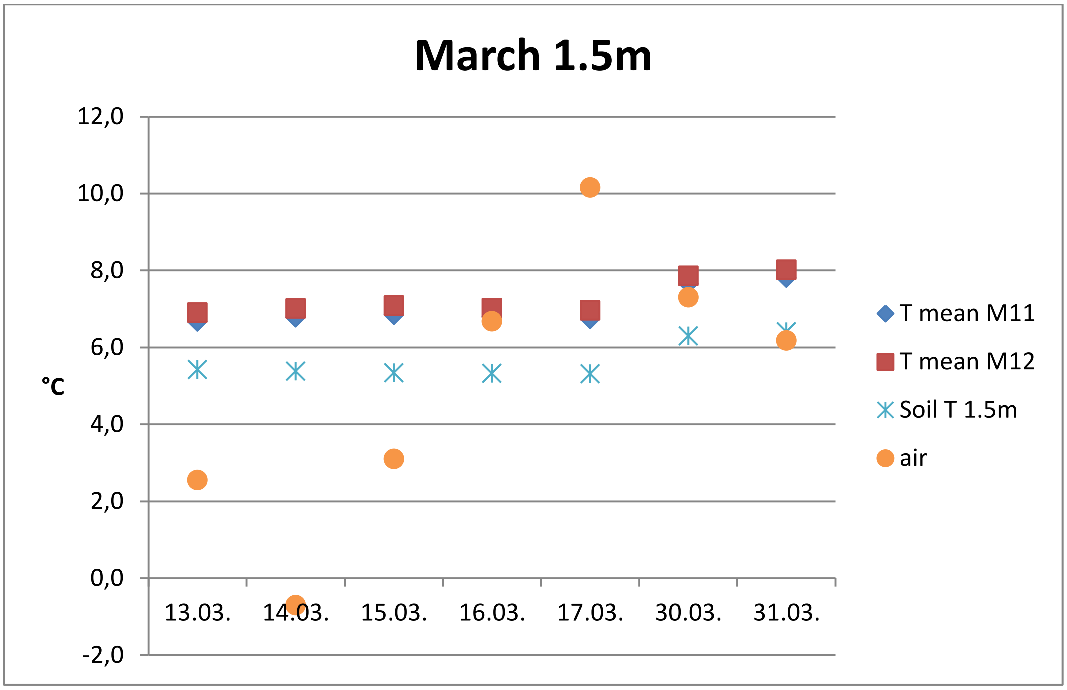


Figure 33 Daily mean wastewater temperature, soil temperature at 1.5 m depth and air temperature in March

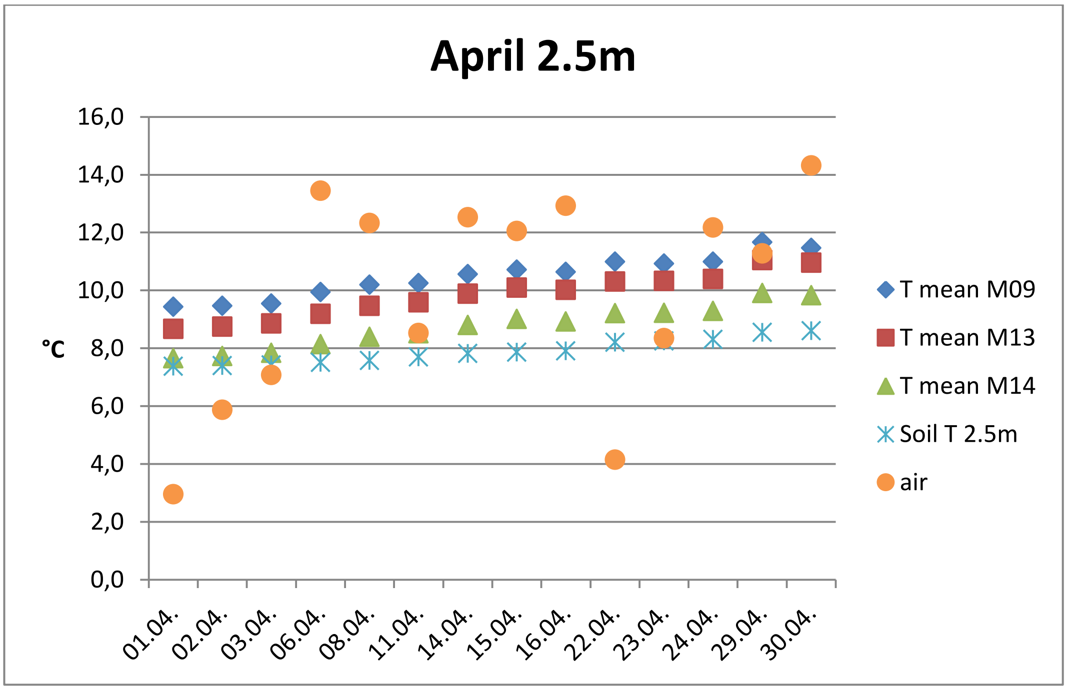


Figure 34 Daily mean wastewater temperature, soil temperature at 2.5 m depth and air temperature in April

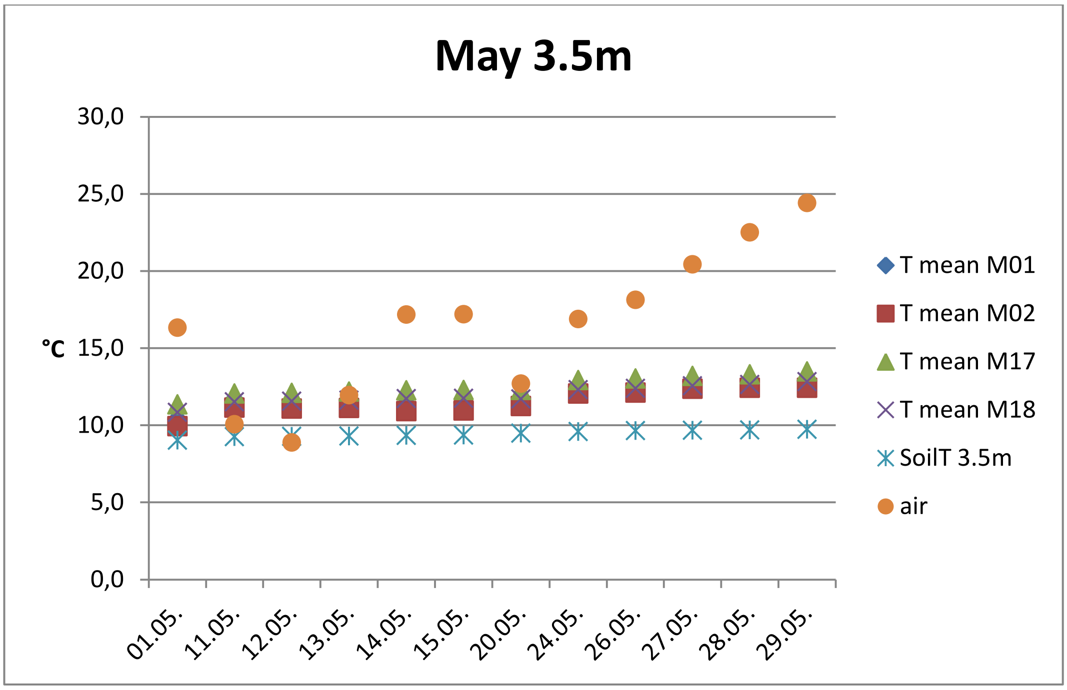


Figure 35 Daily mean wastewater temperature, soil temperature at 3.5 m depth and air temperature in May

In the figures above it is clearly visible that soil temperature and wastewater temperature describe a similar trend throughout the month, whereas air temperature is fluctuating considerably. Cipolla and Maglionico (2014) also came to the conclusion that wastewater temperature is more stable over time than ambient air temperature. Nevertheless also, the differences between soil temperature and wastewater temperature exceed the measuring and modelling error in several months as summarized in Table 8. In general wastewater temperatures fit best to soil temperature at a depth of 1.5 m to 2 m throughout the months as deviation is the smallest. However, heat exchange between sewer pipe and soil was not taken into account in the soil temperature model, it has to be assumed that real soil temperatures around the sewers differ from the modelled values. The fact that soil temperature is in average lower than wastewater temperature, with the exception in July at 1.5 m depth and in March at 3.5 m depth, confirms the assumption that wastewater temperature is quickly adapting to the lower soil temperatures. The effect of higher soil temperatures compared to wastewater temperature can unfortunately not be determined with the available data, as the sewer is located at different depths and therefore the sections where soil temperature exceeds wastewater temperature in March and July are rather short. Furthermore, the depth of the sewer may vary between the individual measuring points as well.

Table 8 Mean deviation of wastewater temperature from soil temperature at different soil depths from March to July

	mean deviation at 1.5m depth	mean deviation at 2m depth	mean deviation at 2.5m depth	mean deviation at 3m depth	mean deviation at 3.5m depth
March	-1,5	-0,2	-0,3	0,8	1,7
April	-1,1	-1,8	-1,8	-0,8	-0,6
May	-0,3	-1,9	-2,4	-2,1	-2,5
June	0,6	-1,9	-2,5	-2,8	-3,9
July	1,7	-0,9	-1,9	-2,5	-3,9

The correlation of wastewater temperature and soil temperature can be further explained by the high thermal conductivity of wastewater, which is assumed to be similar to the thermal conductivity of water. The thermal conductivity of water is comparable to the conductivity of soil, whereas the thermal conductivity of air is much lower. Standard values are summarized in Table 9. It has to be considered that heat transfer through convection or radiation are important factors as well in the heat exchange processes in the sewer. In the table values of thermal diffusivity, which is describing the pace at which heat is moving through the material, are provided as well. Thermal diffusivity of air exceeds the values of water and soil by far, therefore heat transferred from the outside air moves fast to the in-sewer air when air is exchanged, the temperature differences, however, are not transferred at the same pace to wastewater or the surrounding soil.

Table 9 Thermal conductivity and diffusivity of different materials (Baehr and Stephan, 2008)

	Thermal conductivity (W/Km)	Thermal diffusivity ($10^{-6}m^2/s$)
Air at 0 °C	0,02418	18,83
Air at 20 °C	0,02569	21,47
Water at 5 °C	0,5705	0,1358
Water at 10 °C	0,58	0,1384
Water at 15 °C	0,5893	0,1409
Water at 20 °C	0,5984	0,1434
Concrete at 20 °C	1,0	0,54
Soil, coarse gravel at 20 °C	0,52	0,14
Soil, sand dry at 20 °C	0,27	0,2
Soil, sand wet at 20 °C	0,58	0,33
Soil, clay at 20 °C	1,28	1,0
Brick at 20 °C	0,38…0,52	0,28…0,34

While the result of Dürrenmatt and Wanner (2013), that more heat is transferred from wastewater through the wetted perimeter than through convection or evaporation, supports the findings of this study, Abdel-Aal et al. (2013) on the other hand concluded that more heat was transferred to in-sewer air than to the soil, because of the lower thermal resistivity between air and wastewater. This, however, does not necessarily indicate that ambient air temperature has more influence on wastewater temperature. As Wanner et al. (2004) describe the influence of ambient air temperature on wastewater temperature decreases with the retention time of in-sewer air and the sewer length. Both Wanner et al. (2004) and Dürrenmatt and Wanner (2013) even concluded that reheating after heat extraction in the sewer is possible if the wastewater is below soil temperature or smaller than 8 °C. Therefore the soil temperature has a significant influence on the wastewater temperature.

5.2.4 Discussion of the results from the temperature development analysis

In this thesis it was calculated that wastewater enters the sewer system with a mean temperature of around 19.5 °C. This lies in close range to wastewater temperatures mentioned by DWA (2009) and AWEL (2010). However, a more detailed analysis of the wastewater temperature at the house connection could also bring some further insights and should be considered for a further study. Once wastewater has entered the sewer its temperature decreases rapidly and reaches a certain level, which is depending on the month. This level was found out to neither increase nor decrease along the longitudinal profile of the studied sewer system. This finding correlates with the observations from Bischofsberger and Seyfried (1984), who also found no significant change in wastewater temperature within the main sewer to the wastewater treatment plant. Also Schilperoort et al. (2012) found out that in a separated sewer wastewater temperature in the analysed sewer section only varies very little. Even though this interpretation contrasts with that of Abdel-Aal et al. (2013) and Dürrenmatt and Wanner (2008), who both found out that wastewater temperature decreases in the flow direction, it is not necessarily a contradiction as their findings are based on measurements taken in a sewer section without lateral inflow and over a comparatively short length. Therefore, their conclusion deviates from the findings of this study and from the results of Bischofsberger and Seyfried (2013). However, the influence of lateral inflow on to the temperature development in the longitudinal section should not be underestimated. If no lateral inflow occurs over a significant flow length, it most probably has an effect on wastewater temperature. It would be interesting to analyse temperatures of a wastewater system, where there is no lateral inflow for a longer pipe section and evaluate the temperature development in this section and after this section, to see if wastewater temperature changes afterwards. This would be especially interesting in connection with using the thermal energy contained in wastewater, as more inside is needed on how wastewater temperature develops after heat extraction. At the moment it is not clear on whether a new constant temperature level is established after wastewater temperature is reduced or if wastewater temperature increases again to the original temperature level due to lateral inflows.

No significant connection was found between changes in discharge and changes in temperature in the longitudinal profile. While discharge is increasing between the measuring points, wastewater temperature stays at relatively stable level. Nevertheless, the wastewater temperature level and the discharge vary over time. As mentioned before lateral inflow has to have some influence on the overall wastewater temperature. However, the amount of discharge necessary to keep the wastewater temperature at a certain level cannot be identified with this data. Another study with regards to this topic could be interesting.

In order to fulfil the second task mentioned in the objects changes in wastewater temperature from March to April were analysed. It was concluded that wastewater temperature is increasing from March to July. Discharge on the other hand is generally decreasing over the same time. This again emphasis the findings from before that discharge has no significant influence on wastewater temperature. However, in literature also the contrary can be found. Cipolla and Maglionico (2014) argue that wastewater temperature is more influenced by changes in flow rate than changes in air temperature. This might be true when considering a short time period, as air temperature is fluctuating considerably more than wastewater temperature, however, over a longer time period this result is not supported by the findings of this thesis.

Unfortunately the time period analysed in this study does not include the common heating period. Therefore an analysis of this period is necessary for analysing the potential of thermal use of wastewater as the trend cannot be simply projected onto the preceding and following months. A better understanding of wastewater temperatures in the heating period would also be interesting as wastewater temperature in the study area deviates significantly from wastewater temperature described in literature. If the contrast is already so high in March, the question would be, how low wastewater temperature decreases in the other months, especially as no other study measured temperatures below and average of 10 °C even in winter. For elaborating further on this problem it was necessary to look at the main influences on wastewater temperature.

The result of this study regarding the main influences on wastewater temperature is that soil temperature has a higher influence on wastewater temperature than ambient air temperature. This finding is also supported by the study of Dürrenmatt and Wanner (2013). Also Abdel-Aal et al. (2014) identified soil temperature as one of the main influences on wastewater temperature, however, according to their results in-sewer air temperature is even more important. It was not possible to verify their findings with the available data. Therefore for future studies measuring in-sewer air temperature in addition to wastewater temperature would be beneficial in order to get a better understanding of the importance of heat transfer process from wastewater to in-sewer air. Furthermore, using measured soil temperature instead of modelled soil temperature could also lead to a more accurate representation of the actual conditions in the area. This is definitely a disadvantage of this study. Overall the influence of ambient air temperature should not be neglected completely as it highly depends on the retention time of in-sewer air temperature and it further has an influence on soil temperature over longer time periods (Wanner et al., 2004). Also the probability of reheating after heat extraction due to higher soil temperatures should be analysed in future studies as it might change the viability of a heat recovery system.

5.3 Predicting wastewater temperature in sewers

For predicting wastewater temperature development in sewers four different methods are discussed in the following chapter. On the one hand there are relatively simple methods for example an alligation alternate or taking measurements. On the other hand, wastewater temperature can also be predicted with more complicated models such as the model described by Abdel-Aal et al. (2013, 2014) or the model behind the TEMPEST software tool. In Table 10 the necessary input data for the different methods is summarized as well as possible sources for the various parameters. The sources for the parameters include taking measurements in and around the sewer, extracting the information from the implementation plan, where information about underground pipes and cables is available in Austria, using predefined values from literature, calculating different parameters, using data from meteorological services as well as obtaining data from models and estimations. While the more simple methods need much less data, the more complicated ones promise a more accurate result. All of the methods have some advantages and disadvantages, which will be discussed further, and therefore an evaluation of which one fits best must be carried out from case to case. A comparison and interpretation of the results is placed at the end of the chapter.

Table 10 Input data for different methods

	Alligation alternate	Measure-ments	Abdel-Aal et al. (2013, 2014)	TEMPEST	Model behind TEMPEST	Data sources
Discharge (Q)	x	x	x	x	x	M/ME
Ww temperature	x	x	x	x	x	M
Ambient air temperature		x		x		MS
Undisturbed soil temperature		x	x	x	x	M/L/ME
Average in sewer air temperature			x		x	M
Ww flow velocity			x		x	M
Fouling factor			x		x	L
Ww specific heat capacity			x		x	L

	Alligation alternate	Measure-ments	Abdel-Aal et al. (2013, 2014)	TEMPEST	Model behind TEMPEST	Data sources
Ww depth			x		x	M/C
Width of ww level			x		x	C
Ww wetted perimeter			x		x	C
Reynolds number			x		x	C
Nusselt number			x		x	C
Prandtl number			x		x	C
Air specific heat capacity			x		x	L
Air flow			x		x	M
Pipe length			x		x	IP
Pipe diameter			x		x	IP
Wall thickness			x		x	IP/L
Wall thermal conductivity			x		x	L
Penetration depth			x		x	L
Soil thermal conductivity			x		x	L
Thermal resistivity between water and in-sewer air			x			C
Thermal resistivity between water and soil			x			C
Dynamic viscosity			x			L
Heat transfer coefficient between water and in-sewer air			x			C
Heat transfer coefficient between water and pipe			x			C
Mesh size			x			ME

	Alligation alternate	Measure-ments	Abdel-Aal et al. (2013, 2014)	TEMPEST	Model behind TEMPEST	Data sources
COD degradation				x	x	L
Pipe bottom slope				x	x	IP
Ambient air pressure				x		MS
Ambient relative humidity				x		MS
Air Exchange coefficient				x		L
Pipe Material				x		IP
Soil Type				x		M/IP
Ww thermal conductivity					x	L
Cross sectional area of ww in sewer					x	C
Ww density					x	L
Friction slope					x	L
Temperature in condensation layer					x	M/L
Evaporation enthalpy					x	L
Reaction enthalpy					x	L
Ww Hydraulic radius					x	C
Karman constant					x	L
Air thermal conductivity					x	L
Air flow velocity					x	M
Water vapour in the air [kgvapour/kgair]					x	M/L
Cross sectional area of air in sewer					x	C
Perimeter of air in sewer					x	C

	Alligation alternate	Measure-ments	Abdel-Aal et al. (2013, 2014)	TEMPEST	Model behind TEMPEST	Data sources
Air density					x	L
Water vapour partial pressure in the headspace					x	L
Saturation partial pressure at the water surface					x	L
Relative humidity of in-sewer air					x	M/L
Air Hydraulic radius					x	C
Friction coefficient of the pipe					x	IP
Wall thermal diffusivity					x	L
Pipe wall temperature					x	M
Soil specific heat capacity					x	L
Soil density					x	M
Soil thermal diffusivity					x	L

Measure (M)
Implementation plan (IP)
Literature (L)
Calculate (C)
Meteorological service (MS)
Model estimation (ME)

5.3.1 Evaluation of alligation alternate

As visible in Table 10 for an alligation alternate only the wastewater discharge and the wastewater temperature are needed. This is a clear advantage of the method. As a result wastewater temperatures after thermal use of wastewater can be generated by measuring temperature and discharge at only two different locations, one being the point considered for heat extraction the other one being the inlet of the wastewater treatment plant. The expenditure of time, as well as monetary expenses, is kept to a minimum. On the other hand the accuracy of this method is relatively low and care must be taken when selecting the extraction site. In order to illustrate how accurate the method is, the available data was used to perform an alligation alternate with measures from different points in the sewer and in different months. Furthermore, it was evaluated how the results of the alligation alternate change if the upstream temperature is reduced by 0.1 °C or 0.5 °C in order to simulate the effects of heat extraction. As wastewater temperatures at the inlet of the wastewater treatment plant are not available in this case, the temperature at M17/18 was used to represent the inlet of the wastewater treatment plant. Table 11, Table 12, Table 13 and Table 14 present different scenarios of how the application of an alligation alternate influences the predicted wastewater temperature at M17/18 if the wastewater at the upstream point stays the same or is cooled down by a certain value. In the second column the measured temperatures at the various points can be found in order to have a comparison for the results. The third column the temperature at M17/18 was calculated using the alligation alternate and the measured temperature at the respective upstream measuring point. In the last two columns the upstream temperature was reduced by 0.1 °C and by 0.5 °C and the temperature at M17/18 was again calculated with the alligation alternate.

Table 11 Temperature prediction at M17/18 in March with the alligation alternate using M01/02 as the starting point in °C

Measuring point	Measured temperature	Temperature calculated with alligation alternate	Reduction of upstream temperature by 0.1 °C	Reduction of upstream temperature by 0.5 °C
M01/02	6.7	6.7	6.6	6.2
M17/18	7.8	7.6	7.6	7.6

Table 12 Temperature prediction at M17/18 in March with the alligation alternate using M07 as the starting point in °C

Measuring point	Measured temperature	Temperature calculated with alligation alternate	Reduction of upstream temperature by 0.1 °C	Reduction of upstream temperature by 0.5 °C
M07	6.9	6.9	6.8	6.4
M17/18	7.8	7.3	7.3	7.1

Table 13 Temperature prediction at M17/18 in March with the alligation alternate using M08 as the starting point in °C

Measuring point	Measured temperature	Temperature calculated with alligation alternate	Reduction of upstream temperature by 0.1 °C	Reduction of upstream temperature by 0.5 °C
M08	11.0	11.0	10.9	10.5
M17/18	7.8	9.7	9.6	9.4

Table 14 Temperature prediction at M17/18 in March with the alligation alternate using M16 as the starting point in °C

Measuring point	Measured temperature	Temperature calculated with alligation alternate	Reduction of upstream temperature by 0.1 °C	Reduction of upstream temperature by 0.5 °C
M16	7.2	7.2	7.1	6.7
M17/18	7.8	7.3	7.2	6.9

Attachment 16 in the Appendix shows the results from every measuring point in every month. In general the predicted wastewater temperature calculated with the alligation alternate was smaller than the measured temperature even if no temperature reduction at the upstream measuring point was assumed. This would be an advantage of the method if it is considered to use an alligation alternate for predicting wastewater temperatures, as the real temperature is underestimated and therefore the temperatures at the wastewater treatment plant and consequently the cleaning capacity are better than expected. When looking at the influence of temperature reduction on the result it shows that the further away the upstream measuring point is from M17/18 the smaller is the impact of a wastewater reduction. This can be explained by the fact that the bigger the proportion of discharge is at the measuring point compared to the inlet of the wastewater treatment plant, the higher is the influence of the measured wastewater temperature at this point. A temperature reduction of 0.5 °C at M01/02 for example has no influence on the temperature at M17/18, when comparing it to the result of the alligation alternate with no changes in wastewater temperature. Reducing the wastewater temperature by 0.5 °C at M16 on the other hand, leads to a decrease of 0.4 °C at M17/18. This is also an important aspect for the selection of a site for thermal use of wastewater, because even though a higher discharge provides higher potential it also decreases the possibility for reheating if it is located close to the wastewater treatment plant.

Another important issue is the selection of the upstream measuring point. When comparing the results of M07 and M08 in Table 12 and in Table 13 it becomes obvious that even though the measuring points are only 1.5 kilometre away from each other and the discharge only increased by around 3 l/s the high temperature difference measured at the respective points has a significant effect on the predicted wastewater temperature at M17/18. While calculations done with the temperature at M07 underestimate the temperature at M17/18, using temperatures from M08 lead to an overestimation of temperature at M17/18, which could have negative impacts on the viability of heat recovery system as it is assumed that more energy is available than there is in reality. However, an overestimation of wastewater temperature at M17/18 was only noticed if the wastewater at the upstream measuring point is higher than the measured wastewater temperature at M17/18 by a certain value. The specific value again depends on the proportion of the discharge at the measuring point compared to M17/18.

Another implication of the findings above is that measuring errors have a higher influence on the results the closer they occur to the wastewater treatment plant. In addition to the influence of discharge proportion and temperature another disadvantage of the alligation alternate is that influences of soil and air temperature on the wastewater temperature are not considered as well as changes along the longitudinal profile as only point measures are considered. Therefor heat exchange processes between the site of heat extraction and the wastewater treatment plant, which may lead to a reheating of the wastewater as described by Wanner et al. (2004) and Dürrenmatt and Wanner (2013) are not taken into account.

5.3.2 Evaluation of wastewater, air and soil temperature measurements

The second method listed in the table is not a method for predicting wastewater temperature per se. However, measuring the four parameters listed in Table 10 over several months as well as at different locations and analysing their correlations can give a more detailed understanding of influences on wastewater temperature and its development over the year. This can be especially helpful, when evaluating results from an alligation alternate. Nevertheless, there is no specific tool available at the moment on how the information can used to increase the accuracy of the alligation alternate.

Ambient air temperature is measured with high accuracy throughout Austria and therefore this information is readily available. Even though air temperature does not correlate with wastewater temperature according to the findings of this study and is therefore not so valuable for an analysis, it is necessary modelling soil temperature with the presented model. The modelled soil temperature can be used for a first evaluation, as it is a simpler and less expansive method than measuring soil temperature at various locations and depths in the study area. However, if a more detailed evaluation is desired, measuring soil temperature at the study site will lead to a higher accuracy of the analysis. As seen in section 5.2.3 wastewater temperature correlate with soil temperature. This information can be used to gain a basic understanding of what will be the minimum possible wastewater temperature in the sewer, as wastewater temperature will not drop below the lowest soil temperature without human interaction such as heat extraction. It can, however, also exceed soil temperature, especially if warm industrial wastewater is discharged into the main sewer. Even if wastewater temperature is reduced below soil temperature due to heat extraction, wastewater temperature will afterwards approach mean soil temperature again (Wanner et al., 2004; Dürrenmatt and Wanner, 2013). As described earlier it is assumed that heat stored in the soil and the pipe can lead to a reheating of the wastewater after heat extraction, if the wastewater temperature is reduced below a certain degree. Wanner et al. (2004) draw the line at 8 °C. If wastewater is decreased below 8 °C after the heat extraction, reheating takes place in flow direction. Dürrenmatt and Wanner (2013) on the other hand do not state a specific value. In their opinion wastewater temperature can increase again after heat extraction if soil temperature exceeds wastewater temperature. This corresponds to the statement above. However, the influence of heat extraction on the wastewater temperature cannot be analysed in more detail with this method. On the other hand if a more detailed analysis than an alligation alternate is desired ambient air temperature and soil temperature are also required for the two available models and acquiring this information is not a disadvantage.

5.3.3 Evaluation of the model by Abdel-Aal et al.

Even though the method used by Abdel-Aal et al. exceeds the number of parameters used in the previously discussed methods by far, with 27 parameters it still not the method needing the most input data. As illustrated in Table 10 most of the data can be found in literature, however, some parameters need to be measured, which corresponds to higher financial expenses, but also higher accuracy. As Abdel-Aal et al. (2014) identified soil temperature and in-sewer air temperature to be the most sensitive parameters for variations in wastewater temperature, a high data accuracy of those parameters is essential. Obtaining in-sewer air temperature involves a higher effort than obtaining for example ambient air temperature. The additional expenses, however, are relatively low if wastewater temperature data is not available and has to be measured anyways. Unfortunately even though the in-sewer air temperature is actually measured by many devices for calibration, the measured data is not stored. Measuring soil temperature on the other hand is more expensive as various sites at different depths need to be evaluated. An alternative for this is using modelled soil temperature as it was used for this study. This method is comparably cheap and simple, the accuracy on the other hand is much lower and will therefore reduce the accuracy of the overall result. Abdel-Aal et al. (2014) used measured data with an accuracy of 0.2 °C. The modelling error, however, still ranged between -1 °C in February and 0.76 °C in April. Furthermore, considering the sensitivity analysis performed in the study a high accuracy is most important regarding the upstream wastewater temperature as increasing it by 400 % led to an increase of 260 % in wastewater temperature downstream, while increasing soil temperature and in-sewer air temperature by the same rate only led to an increase of wastewater temperature downstream between approximately 18 % and 25 %. This raises the question to what extend data with high accuracy is necessary for all parameters or if focusing on measuring the most important parameter with high accuracy is enough depending on the overall achievable accuracy.

Apart from the difficulties with finding the right data accuracy for the model, there is another disadvantage which needs to be eliminated before the model can be applied in a larger sewer system. Until now effects of lateral flow have not been incorporated and as a result the model can only be used for a pipe section without lateral inflow and not for modelling the wastewater temperature in a whole system. Furthermore, a higher sensitivity to some parameters for example soil thermal conductivity will be necessary in the future (Abdel-Aal et al., 2013).

Unfortunately only two papers have been published so far and not a lot of information on the details of the model is available as it is still under development. Consequently a detailed evaluation is difficult and general application is not possible at the moment. However, it is intended as a user-friendly model. Therefore if a software program or a more detailed model is ever published, it will offer a good alternative to TEMPEST for occasions, where a detailed analysis of wastewater temperature development is necessary.

5.3.4 Evaluation of TEMPEST

The model behind TEMPEST is by far the method needing the most input data. 48 different parameters are needed to model wastewater temperature in one conduit. This number is drastically reduced when looking at the input data for the simulation program TEMPEST, which only needs 11 parameters and some of the values are available in an integrated library. In this library default values for soil types and pipe materials are available. TEMPEST has the advantage of having a simple user interface and that it is not necessary to install a software program as the program is available as a single file and already available (Dürrenmatt, 2015). The model can be used for estimating changes in a single sewer line as well as for simulating a larger system as lateral inflows can be taken into account (Dürrenmatt and Wanner, 2008). However, as acquiring data from every conduit connected to the main sewer is economically not feasible as well as the computational load for calculating the individual sewer sections, the practical applicability is reduced, when trying to model wastewater temperature for an extensive sewer system (Dürrenmatt and Wanner, 2013; Dürrenmatt, 2015).

The accuracy of the model was found to be sufficient. Nevertheless, it highly depends on the accuracy of the input data. As some of the input data is not easily available one of the aims when developing TEMPEST was that for some of the input data only estimates can be used. This, however, leads to a decrease of accuracy in the input data and as a result to a decrease in accuracy of the modelled wastewater temperature, while the workload stays on a relatively high level. In addition due to the varying quality of input data a sensitivity analysis for each case is necessary. The sensitivity analysis performed by Dürrenmatt (2006) revealed that also for this model the wastewater temperature upstream is by far the most sensitive parameter. When changing the wastewater temperature upstream by 1 % the modelled wastewater downstream increases by 0.98 % after 500 m. The most sensitive parameters following upstream wastewater temperature are the undisturbed soil temperature, the soil thermal conductivity as well as the soil penetration depth. A change in those parameters by 10 % results in a change of modelled wastewater temperature by 0.5 – 1 % and the influence is therefore much smaller than from wastewater temperature changes upstream. Other parameters such as degradation rate and fouling factor do not have a significant effect on the modelled wastewater temperature, which leads to questioning the necessity of including those parameters at all (Dürrenmatt and Wanner, 2013). A sensitivity analysis of the results can further help to determine, which parameters should be obtained with a higher accuracy, if input data with a lower accuracy was used at the beginning. This could save some money, if the result is that for some of the parameters the low accuracy is enough as they do not have a significant influence on the result (Dürrenmatt, 2015). However, considering the presented results above it is very unlikely that inaccurate wastewater temperature or soil temperature lead to highly accurate results. Furthermore, the question remains if the default values for soil type and material type can represent the actual conditions in the study area and give satisfying results.

Even though the model was developed several years ago, only a few applications exist and it was used only once outside of Switzerland, where it was developed (Dürrenmatt, 2015). This indicates that the practicability of the model is relatively low. Furthermore, at the moment it is not indented for being used as a tool for predicting influences of thermal use of wastewater on the inlet temperature of a wastewater treatment plant. Therefore even though TEMPEST is the only accessible model for wastewater temperature modelling, an application has to be taken under careful consideration as the work load may not justify the results, especially if the input data is not available with high accuracy. Consequently applying TEMPEST should only be considered if a slight change of temperature at the inlet of the wastewater treatment plant can have negative effects on the cleaning capacity and thermal use of wastewater is still desired and if the input data is available with a high accuracy.

5.3.5 Discussion of the methods for predicting wastewater temperature in sewers

The methods presented in this thesis can be summarized into simple methods and complex methods. Both methods can be important for an evaluation of a viability study for thermal use of wastewater as the necessary accuracy and data availability might differ from case to case.

When comparing the alligation alternate to using different measurement for predicting wastewater temperature, it must be noted that both methods have their advantages and disadvantages. Using an alligation alternate is by far the simplest method, as only two parameters have to be considered and as the most of the examples in the previous chapter showed, the majority of the results is underestimating the real temperature and would therefore offer a cautious method for estimating changes in wastewater temperature at the inlet of a wastewater treatment plant due to thermal use of wastewater. However, this study also shows that including more measurements or modelled data such as air temperature and soil temperature does not involve significantly more effort, but presents a possibility to get a better understanding of the temperature conditions in the catchment including absolute minimum temperature. It is also important to take wastewater temperature measurements at several sites within the sewer system to make what the average wastewater temperature in the sewer is. Using only different measurements on the other hand only sets the boundaries for wastewater temperature, but offers no information about the impact of thermal use of wastewater on the inlet temperature of a wastewater treatment plant. Therefore further research on how soil and air temperature information can be used for predicting wastewater temperature development is necessary. Also using an alligation alternate for a first estimation should not be discarded immediately, it should only be used with caution and results should be evaluated with other temperature measurements to evaluate the plausibility.

On the other hand two more complex models were described in the thesis including TEMPEST and the model described by Abdel-Aal et al (2013, 2104). At the beginning of the thesis applying those models was planned, however, as the model described by Abdel-Aal et al (2013, 2104) is still under development and the fact that some of the data for TEMPEST, it was decided that only a literature research will be conducted for the evaluation of the models. This is clearly a disadvantage, when looking at the recommendations given for the application of the models. Therefore it would be recommended that both models are applied in a further study in order to be able to compare the results of both with the same data set. However, judging from the literature available, a few conclusions can be made. Both models have the disadvantage that a high amount of input data is needed compared to the simple methods. Nevertheless, this offers the advantage that more accurate results can be obtained with them. Unfortunately at the moment none of the models is actually used to estimate the impact of thermal use of wastewater on the inlet temperature of a wastewater temperature, even though they are the only models available. On the one hand there is a problem with the high computational load of TEMPEST, which makes the application in a larger sewer system very complicated (Dürrenmatt, 2015) and on the other hand the model described by Abdel-Aal et al. (2013, 2014) is still in a developing stage and does not include lateral inflows into the sewer at the moment. Unfortunately TEMPEST is at the moment not developed further to make it more user friendly, even though it would have the advantage of being a published program already (Dürrenmatt, 2015). Therefore developments of the model described by Abdel-Aal et al (2013, 2014) will be important in the future as having a user friendly model for calculating the impact of thermal use of wastewater in the sewer on the inlet temperature of a wastewater treatment plant could have a positive effect on the propagation of the use of this energy source. Applying TEMPEST, however, could be considered if all the necessary input data is easily available. The computational load is not decreased, but the accuracy of the result could be worth the effort in some cases.

Overall it has to be said that neither one method nor the other is the optimal way of predicting changes in wastewater temperature. The selection of the appropriate approach has to be done on a case to case basis depending mainly on the prevailing wastewater temperature as well as on the available data. The decision on whether thermal use of wastewater is applied in a sewer or not should not only depend on the results of a model estimation, but also on the conditions at the wastewater treatment plant.

6. Conclusion and outlook

In conclusion it was found out in this thesis that even though wastewater is entering the sewer at the house connections with an estimated average temperature of 19.5 °C, wastewater temperature decreases rapidly to a certain level in the main sewer. When analysing the available data it is noticed that as the temperature measures have an accuracy of +/-1 °C the temperature changes in the longitudinal section are insignificant except for a temperature increase at M08. However, this temperature increase has no evident influence on further temperature development in the system as wastewater temperature decreases to the mean value at the next measure point. Therefore it is plausible that the higher temperatures are a result of the measure point being in close proximity to the inlets of the village and a few connections of sanitary sewers leading into the main sewer system at this point. Consequently wastewater temperature is constant through the longitudinal profile of the sewer. This is an interesting finding, when considering the thermal use of wastewater as many other studies suggested that wastewater temperature is decreasing within the sewer system. However, it needs to be analysed whether a temperature reduction at a certain point will lead to a new temperature level with lower temperature or if wastewater temperature will come back to the original level after a certain flowing distance. In order to validate the results of this study it would be interesting to evaluate wastewater temperature data from other areas in order to see if the same pattern prevails. It is very likely that more temperature data is available from other discharge measuring campaigns throughout Austria and just has not been analysed yet.

The study further verified that wastewater temperature is constantly increasing between March and July, whereas discharge in the sewer is decreasing. This development indicates that wastewater temperature is not mainly influenced by the amount of discharge present in the sewer. However, seasonal changes of the ambient conditions are a possible explanation. Wastewater temperature changes at about 2 °C from month to month at every measuring point with the smallest change between June and July, where it only increase with about 1.5 °C and the biggest change between April and May. For determining what leads to this specific increase an evaluation of potential external impacts was undertaken. Unfortunately temperature data from the heating period was not available, where the temperature development would be most interesting in regards to heat extraction. In further studies analysing the temperature changes in the winter months as well will be necessary.

Several possible influences on wastewater temperature including soil temperature, air temperature, river water temperature and ground water temperature were analysed and it was concluded that the biggest influence on wastewater temperature comes from the soil temperature surrounding the pipe. It was found out that daily mean wastewater temperature and soil temperature are correlating throughout the months, whereas ambient air temperature for example is fluctuating considerably more. Furthermore, wastewater temperature never falls below soil temperature in the respective time period, this leads to the assumption that wastewater temperature is reduced by heat transfer to the soil, however, as soil temperature is increasing in this process, wastewater temperature never reaches undisturbed soil temperature. Analysing measured soil temperature and in-sewer air temperature for an evaluation in addition to the other parameters, could give further insight into heat exchange processes and into wastewater temperature development. Therefore it would be helpful if measuring devices using in-sewer air temperature for calibration would also record the data for further usage.

For predicting wastewater temperature four different methods were selected and discussed in this thesis. On the one hand there are relatively simple methods for example an alligation alternate or taking different measurements. On the other hand wastewater temperature can also be predicted with more complicated models such as the model described by Abdel-Aal et al. or the TEMPEST model. The necessary input data for the different methods varies considerably as does the accuracy of the results. While the more simple methods need much less data, the more complicated ones promise a more accurate result. For all of the methods some advantages and disadvantages were found. Therefore an evaluation of which one fits best must be carried from case to case.

The alligation alternate has the clear advantage of only needing two input parameters, as a result can be generated by measuring temperature and discharge at only two different locations, one being the point considered for heat extraction the other one being the inlet of the wastewater treatment plant. The expenditure of time, as well as monetary expenses, is therefore kept to a minimum. On the other hand the accuracy of this method is relatively low. The bigger the proportion of discharge is at the measuring point compared to the inlet of the wastewater treatment plant, the higher is the influence of the measured wastewater temperature at this point. Therefore also measuring errors have a higher influence on the results the closer they are to the wastewater treatment plant. In addition the selected point for temperature measurements has an influence on the results as wastewater temperature may differ from the mean temperature in sewer, as it was shown in this study, which could lead to a deviation of the result. Furthermore, influences of soil and air temperature on the wastewater temperature are not considered as well as changes along the longitudinal profile. Therefore only applying an alligation alternate for predicting the influence of thermal use of wastewater on the inlet temperature of a wastewater treatment plant can lead to imprecise results.

The second method for predicting wastewater temperature discussed in this thesis is measuring wastewater temperature, discharge and ambient air temperature and using them for a first estimation of how wastewater temperature might develop over time and where the limits are. The ambient air temperature can be further used for modelling soil temperature at various depths in order to decrease monetary expanses. Measuring these four parameters over several months as well as at different locations and analysing their correlations can give a more detailed understanding of influences on wastewater temperature and its development over the year. Nevertheless, there is no specific tool available on how the information can be used for predicting the influence of thermal use of wastewater on the inlet temperature of a wastewater treatment plant. One possibility is to use this method in combination with an alligation alternate. For example results from the alligation alternate can be compared to average soil temperature to get an understanding of whether there could be reheating of wastewater after heat extraction or not. This method is recommended for getting a first understanding of the condition in the sewer. It can be further used for a first estimate for the potential of thermal use of wastewater. Further studies should be undertaken to get a better understanding of how the method can be applied in practice. If a more detailed analysis is necessary one of the two models could be an option.

Even though the method used by Abdel-Aal et al. (2013, 2014) exceeds the number of parameters used in the previously discussed methods by far, with 27 parameters it still needs less input data than the model from TEMPEST, which is an advantage of the method. Unfortunately only two papers have been published so far and not a lot of information on the details of the model is available as it is still under development. Although the effort for obtaining some of the input data such as average in-sewer air temperature is higher compared to the TEMPEST model, it is aimed to be a more user-friendly model with high result accuracy. However, at the moment it cannot be used for modelling larger systems as lateral inflows are not incorporated in the model at the moment, which is a major disadvantage for practical use. Nevertheless, if a software tool or a more detailed model is ever published and if the model is extended in order to include lateral inflows, it will offer a good alternative to TEMPEST for occasions, where a detailed analysis of wastewater temperature development in the sewer is necessary. Applying the model with the available data from Austria in further studies would be interesting.

TEMPEST on the other hand has the advantage of having a high accuracy and of already being available as a computer application online. The actual accuracy of the result, nevertheless, still depends on the accuracy of the input data. Furthermore, the high amount of input data, as well as the computational load, are considerable disadvantages of the software tool. In addition to this some of the input data for the software tool is not easily available. Therefore even though TEMPEST is the only accessible model for wastewater temperature modelling, an application has to be taken under careful consideration as the work load may not justify the results, especially if the input data is not available with high accuracy. Consequently applying TEMPEST is only recommended if the data is available. However, without adaptations to the model of Abdel-Aal et al. (2013, 2014) it presents the only option for modelling wastewater temperature in the sewer.

Nevertheless, even though it was observed that wastewater temperature levels off to a certain temperature within the sewer, which is mainly influenced by soil temperature and increases from March to July, it cannot be resolved if the level is restored after wastewater is changed due to thermal use or if a new level is established. From the four different methods for predicting wastewater temperature in the sewer presented in this thesis the most promising is using different measurements in order to get a basic understanding of possible limits for wastewater temperature. Even though the model described by Abdel-Aal et al. (2013, 2014) seems like a promising method for a more detailed analysis, it is at the moment still in the stage of development. Due to the fact that ambient conditions are fully neglected when using only an alligation alternate, this method alone does not give a precise evaluation of impacts of thermal use of wastewater and should only be used in connection with different measurements if a more detailed analysis is desired. The fourth method is TEMPEST, which is by far the most complex method, because of the high amount of input data needed and the computational load and the applicability is therefore limited. Overall if thermal use of wastewater in the sewer is desired in a certain area, it will be necessary to look also at the wastewater treatment plant and evaluate if the cleaning capacity there is enough even if the wastewater temperature is changed a little bit.

In order to get a better understanding of wastewater temperature more studies should be conducted regarding wastewater temperature development along the longitudinal section of a sewer as well as regarding the influences on wastewater temperature. If more temperature data from other discharge measuring campaigns is available, it should be evaluated as well. Furthermore, the possibility of recording in-sewer air temperature with standard measuring devices would not only help the understanding of the temperature conditions in the sewer, but would also increase the applicability of the model described by Abdel-Aal et al. (2013, 2014). Having more data available as well as more user-friendly tools could improve the process for permit granting for the thermal use of wastewater in Austria in the future.

7. Summary

According to the IPCC (2007) continuing with the current rate of greenhouse gas emissions will very likely result in an increase in global warming as well as other changes in the climate. Alongside many sectors that need to be addressed, a promising solution to prevent further increase of greenhouse gas emissions and to keep future negative impacts on a minimum level is changing the energy supply to renewable resources. The necessity for this is also expressed by the European Union's target for increasing the share of renewable energies to 20 % of the energy supply by 2020 (EC, 2014).

One technology that is being discussed in connection with this is using the thermal energy contained in wastewater as an alternative energy source for heating or cooling of buildings. This technique is already applied in Germany, Scandinavia and Switzerland and some facilities have been in use for more than 30 years. In Austria the technology is applied at only a few locations, one of them being Amstetten in Lower Austria. The thermal energy of wastewater is recovered with a heat pump and a heat exchanger installed in the sewer or in the outlet of the wastewater treatment plant (Projektteam „Energie aus Abwasser", 2012). If the heat recovery takes place in the sewer, the subsequent cooling of the wastewater can lead to decreased nitrification and nitrogen removal in the wastewater treatment plant as these processes are temperature-sensitive (AWEL, 2010). In order to prevent negative impacts from heat recovery in the sewer on the performance of the wastewater treatment plant a permit of the responsible water authority is necessary for the installation of a heat exchanger in the sewer to facilitate prove that thermal use of wastewater will have no significant influence on the performance of the wastewater treatment plant. However, only a few studies have been conducted about wastewater temperature development in sewers and even less have focused on predicting changes of the wastewater temperature in the sewer system and on impacts of heat recovery. Due to the little information available and as the technology is not commonly applied in Austria at the moment no guidelines have been developed yet for Austria on how to deal with this problem. As a result of the lack of data this thesis analyses temperature development in the sewer as well as main influences on wastewater temperature. Furthermore, different methods for predicting wastewater temperature changes in sewers are evaluated, which could be used by the water authorities for granting permits for thermal use of wastewater in the sewer.

The data used for the first part of the thesis is taken from an older measuring campaign, in which flow rate and wastewater temperature were measured every three minutes at 18 different sites inside of the sewer system of a specific drainage area over five months with a Nivus PCM3 ultrasonic sensor. Wastewater temperature data was recorded with an accuracy of +/- 1 °C. The sensors were placed at the inlet and outlet of seven combined sewer overflow structures as well as in two manholes. For the assessment of the data only days with dry weather flow were used, in order to eliminate the influence of rain water on the wastewater temperature in the combined sewer.

Mean hourly flow rate and temperature were calculated for every day and every measuring point. These were further combined into mean value for every day as well as for every month at every measuring point. In a next step the mean monthly temperatures and discharges measured at seven combined sewer overflow structures were combined into one value by calculating the mean of the measured values at the inlet and the outlet. In this step, measuring points with anomalies were excluded from further analysis. For the mean value the uncertainty was calculated as 1.4 °C due to the propagation of error. The values were used for an analysis of the longitudinal section in order to see how wastewater temperature changes in flow direction in the sewer system. Also the discharge was analysed in the longitudinal profile to have comparison to the temperature profile.

The analysis of the temperature data revealed that even though wastewater is entering the sewer at the house connecting with an estimated average temperature of 19.5 °C, which was calculated using standard values from literature, temperature levels off rapidly to a certain value. When considering the accuracy of +/-1 °C the wastewater temperature changes in the longitudinal section of the analysed sewer are insignificant except for a temperature increase at M08. However, this temperature increase has no influence on further temperature developments in the system as temperatures are back to the mean value at the next measure point. Therefore it is plausible that the higher temperatures at this measuring point are a result of the measure point being in close proximity to the inlets of the village and some sanitary sewers leading into the main sewer system at this point. Consequently wastewater temperature is relatively constant through the longitudinal profile of the sewer. Discharge measured in the sewer on the other hand showed an expected significant increase between the measuring points due to the lateral inflows into the main sewer.

Following the longitudinal evaluation, changes in wastewater temperature and discharge over time were examined in order to see the influence of seasonal changes on both. It was found out that wastewater temperature is constantly increasing by about 2 °C between March and July, whereas discharge in the sewer is decreasing over the same time period. This development indicates that wastewater temperature is not considerably influenced by the amount of discharge present in the sewer. However, seasonal changes in the ambient conditions are a possible explanation.

Possible influences on wastewater temperature were found to be ambient air temperature, soil temperature from 1.5 m depth to 3.5 m depth, as the sewer pipe is located at those depths, ground water temperature and river water temperature, if a river is present and close to the sewer in the relevant study area. The ambient air temperature was taken from the Central Institute for Meteorology and Geodynamics (Zentralanstalt für Meteorologie und Geodynamik - ZAMG) from a measuring point approximately 5 to 10 km from the drainage area. Daily mean values as well as monthly mean air temperature values were available. The groundwater temperature and the river water temperature was taken from eHYD, both measuring points lay within a kilometre from the sewer system in the second half of the system and only monthly mean values were available. Soil temperatures were modelled by the Institute of Meteorology at the University of Natural Resources and Life Sciences, Vienna using the SoilTempSimV3B model, which calculates soil temperature at different depths with daily time steps and an accuracy of +/- 1 °C. Wastewater temperature was found to be in the middle of ambient air temperature as well as soil temperature and river water temperature, when considering only monthly mean values. In the study area groundwater can be found at a depth of about 10 m, which indicates that the influence on wastewater temperature can be neglected. When looking at the changes over time it becomes obvious that temperature changes for ambient air temperature, soil temperature as well as river water temperature occur differently from month to month than for wastewater.

In order to get a better understanding of which influence is most important regarding the wastewater temperature, daily mean wastewater temperature, daily mean soil temperature at different depths and daily mean ambient air temperature were compared. It was found out that daily mean wastewater temperature and soil temperature are correlating throughout the months, whereas ambient air temperature is fluctuating considerably more. Furthermore, wastewater temperature never falls below soil temperature in the respective time period. This leads to the assumption that wastewater temperature is reduced by heat transfer to the soil, however, as soil temperature is increasing in this process wastewater temperature never reaches undisturbed soil temperature.

The second part of the study focused on possibilities for predicting wastewater temperature in the sewer. Four different methods were described and their advantages and disadvantages are discussed in this thesis. On the one hand there are relatively simple methods for example an alligation alternate or using different measurements for an evaluation. On the other hand wastewater temperature can also be predicted with more complicated models such as the model developed by Abdel-Aal et al. or the TEMPEST model. The necessary input data, the accuracy as well as the practical applicability for the different methods varies considerably. Therefore an evaluation of which one fits best must be carried from case to case.

For an alligation alternate only the wastewater discharge as well as the wastewater temperature are needed as input parameters. This is a clear advantage of the method. The expenditure of time as well as monetary expenses are kept to a minimum. On the other hand the accuracy of this method is relatively low. The bigger the proportion of discharge is at the measuring point compared to the inlet of the wastewater treatment plant, the higher is the influence of the measured wastewater temperature at this point. Furthermore, influences of soil and air temperature on the wastewater temperature are not considered as well as changes along the longitudinal profile.

The second method for predicting wastewater temperature discussed in this thesis is using measured wastewater temperature, wastewater discharge, ambient air temperature and modelled soil temperature for a first estimation of how temperature might develop over time and were the wastewater temperature limits are. Nevertheless, there is no specific tool available on how the information can used for predicting the influence of thermal use of wastewater on the inlet temperature of a wastewater treatment plant. If a more detailed analysis is necessary one of the two models could be an option.

Even though the method used by Abdel-Aal et al. (2013, 2014) exceeds the number of parameters used in the previously discussed methods by far, it still needs less input data than TEMPEST. Although the effort for obtaining some of the input data such as average in-sewer air temperature is higher compared to the TEMPEST model, it seems like a more user-friendly model. However, at the moment it cannot be used for modelling larger systems as lateral inflows are not incorporated in the model at the moment. Therefore if a software program is ever published and if the model is extended in order to include lateral inflows, it will offer an additional tool, where a detailed analyses of wastewater temperature development is necessary.

Tempest has the advantage of having a high accuracy and of already being available as a software tool online. The actual accuracy of the result, however, still depends on the accuracy of the input data. Furthermore, the high amount of input data as well as the computational load are considerable disadvantages of the software tool. In addition to this some of the input data is not easily available. Therefore even though Tempest is the only accessible model for wastewater temperature modelling, an application has to be taken under careful consideration as the work load may not justify the results. Consequently applying TEMPEST is only feasibly under specific circumstances and should only be considered if the model by Abdel-Aal et al. is not available and a detailed analysis is desired despite the disadvantages of TEMPEST.

In conclusion even though it was observed that wastewater temperature levels off to a certain temperature within the sewer, which is mainly influenced by soil temperature and increases from March to July, it cannot be resolved if the level is restored after wastewater is changed due to a thermal usage or if a new level is established. From the four different methods discussed in this thesis, the most promising is using measurements in order to get a basic understanding of possible limits for wastewater temperature and in the future after necessary adaptations using the model by Abdel-Aal et al. for a more detailed analysis. Due to the fact that ambient conditions are fully neglected when using only an alligation alternate, this method alone cannot be recommended for evaluating impacts of thermal use of wastewater. Using the fourth method TEMPEST should be taken under careful consideration, because of the high amount of input data needed and the computational load. Overall if thermal use of wastewater in the sewer is desired in a certain area, it will be necessary to look at the wastewater treatment plant as well and evaluate if the cleaning capacity there is enough even if the wastewater temperature is changed a little bit. This can help reducing the needed accuracy for predicting changes in wastewater temperature at the inlet of a wastewater treatment plant due to thermal use of wastewater in the sewer.

8. References

1. AEVkA (2000): Verordnung des Bundesministers für Land- und Forstwirtschaft über die Begrenzung von Abwasseremissionen aus Abwasserreinigungsanlagen für Siedlungsgebiete *(Order of the Federal Minister of Agriculture, Forestry, Environment and Water Management concerning Limitations of Wastewater Emissions from Wastewater Treatment Plants for Settlement Areas)* BGBl. Nr. 210/1996 idF. BGBl. II Nr. 392/2000

91/217/EEC: Council of the European Community (ed.): Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271 (date of visit 01.09.2014).

AAEV (1996): Verordnung des Bundesministers für Land- und Forstwirtschaft über die allgemeine Begrenzung von Abwasseremissionen in Fließgewässer und öffentliche Kanalisation *(Order of the Federal Minister of Agriculture, Forestry, Environment and Water Management concerning general Limitations of Wastewater Emissions into Waterways and Public Sewers)* BGBl. Nr. 186/1996

Abdel-Aal, M., Smits, R., Mohamed, M., De Gussem, K., Schellart, A. and Tait, S. (2013): Viability of Heat Recovery from Combined Sewers. 7th International Conference on Sewer Processes and Networks, 2013, Sheffield, England.

Abdel-Aal, M., Smits, R., Mohamed, M., De Gussem, K., Schellart, A. and Tait, S. (2014): Modelling the viability of heat recovery from combined sewers. Water Science & Technology 70.2, 297 - 306.

AbwV (2004): Verordnung über Anforderungen an das Einleiten von Abwasser in Gewässer *(Order concerning Requirements for the Discharge of Wastewater into Waterways)* 2004. BGBl. I 2004, 1118 – 1119 http://www.gesetze-im-internet.de/abwv/ (date of visit 01.09.2014).

AWEL, (2010): Heizen und Kühlen mit Abwasser. Leitfaden für die Planung, Bewilligung und Realisierung von Anlagen zur Abwasserenergienutzung *(Heating and Cooling with Wastewater. Guideline for Planning, Permission and Implementation of a Facility for Using the thermal Energy of Wastewater)* http://www.awel.zh.ch/internet/baudirektion/awel/de/energie_radioaktive_abfaelle/waermenutzung_ausuntergrundwasser/abwasser.html (date of visit 03.04.2014).

Baehr, H.D. and Stephan, K. (2008): Wärme- und Stoffübertragung *(Heat and Mass Transfer).* 6th edition, Springer-Verlag, Berlin Heidelberg, Germany.

Benonysson, A., Bøhm, B. and Ravn, H.F. (1995): Operational Optimization in a District Heating System. Energy Conservation and Management 36 (5), 297 – 314.

Bischofsberger, W. and Seyfried, C.F. (1984): Wärmeentnahme aus Abwasser *(Heat Extraction from Wastewater).* Lehrstuhl und Prüfamt für Wassergütewirtschaft und Gesundheitsingenieurwesen der Technischen Universität München, Garching, Germany.

BMFLUW (2014): EU Richtlinie 91/271/EWG über die Behandlung von kommunalem Abwasser - Österreichischer Bericht 2014 *(EU Directive 91/271/EWG concerning the* *treatment of municipal Wastewater - Austrian Report).* Vienna, Austria http://www.bmlfuw.gv.at/publikationen/wasser/abwasser/EU-Richtlinie-91-271-EWG--ueber-die-Behandlung-von-kommunalem-Abwasser-Oesterr---Bericht-2014.html (date of visit 01.09.2014).

BMWFJ and BMFLUW (2010): Energie Strategie Österreich. Maßnahmenvorschläge *(Austrian Energy Strategy. Measure Recommendations).* http://www.energiestrategie.at/images/stories/pdf/longversion/energiestrategie_oesterreich.pdf (date of visit 03.04.2014).

Carstensen, R.U. (2014): Personal communication.

Cipolla, S.S. and Maglionico, M. (2014): Heat recovery from urban wastewater: Analysis of the variability of flow rate and temperature. Energy and Buildings 69, 122 – 130.

De Gussem, K.R.L., Smits, R., Donckels, B.M.R. and Weemaes, M. (2013): Impact of sewage heat extraction on waste water treatment plant performance and greenhouse gas emission. 7th International Conference on Sewer Processes and Networks, 2013, Sheffield, England.

Dürrenmatt, D.J. (2006): Berechnung des Verlaufs der Abwassertemperatur im Kanalisationsrohr *(Calculating Wastewater Temperature Development in a Sewer Pipe). Diplomarbeit,* Institut für Umweltingenieurwissenschaften, Eidgenössische Technische Hochschule Zürich.

Dürrenmatt, D.J. (2015): Personal communication.

Dürrenmatt, D.J. and Wanner, O. (2008): Simulation of the wastewater temperature in sewers with TEMPEST. Water Science & Technology 57.11. IWA Publishing 2008, 1809 – 1815.

Dürrenmatt, D.J. and Wanner, O. (2013): A mathematical model to predict the effect of heat recovery on the wastewater temperature in sewers. Water Research 48(2014), 548-558.

Dürrenmatt, D.J. and Wanner, O. (s.a.): User Manual. Tempest. Computer Program for the Simulation of the Wastewater Temperature in Sewers. Version 1.02. Eawag http://www.eawag.ch/forschung/eng/schwerpunkte/software/tempest/index_EN (date of visit 13.03.2015).

DWA (2009): Merkbaltt DWA-M114. Energie aus Abwasser – Wärme- und Lageenergie *(Energy from Wastewater – Thermal and Potential Energy)*. Hennef, Germany.

EC (2014): Facts and Figures about Urban Waste Water Treatment http://ec.europa.eu/environment/water/water-urbanwaste/implementation/factsfigures_en.htm (date of visit 01.09.2014). European Commission.

European commission (EC) (2014): What is the EU doing about climate change? http://ec.europa.eu/clima/policies/brief/eu/index_en.htm (date of visit 03.04.2014)

Grabenweger, P., Eitzinger, J. and Lalic, B. (2013): SoilTempSimV3B. A Model to Calculate Soil Temperatures Accounting for Frozen Soil Conditions. Theory Description and Technical Documentation. University of Natural Resources and Life Sciences, Vienna, Austria.

GSchV (1998): 814.201 Gewässerschutzverordnung vom 28. Oktober 1998 *(Regulation on Water Protection from the 28th of October 1998)* http://www.admin.ch/opc/de/classified-compilation/19983281/index.html (date of visit 01.09.2014).

Gujer, W. (2007): Siedlungswasserwirtschaft *(Sanitary Engineering)*. 3rd edited edition. Springer-Verlag, Berlin Heidelberg, Germany.

Intergovernmental Panel on Climate Change (IPCC) (2007): Climate Change 2007: Synthesis Report: An Assessment of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html (date of visit 03.04.2014)

Kaltenbrunner, M. and Kretschmer F. (2012): Thermische Nutzung des Abwassers – Erfahrungen beim GAV Amstetten *(Thermal Use of Wastewater – Experiences at the GAV Amstetten)*.

Karpf, C. and Krebs P. (s.a.): Bilanzierung von Fremdwasser *(Balancing of Infiltration Water)*. http://apuss.insa-lyon.fr/nrl_025_bilanzierung_von_fremdwasser.pdf (date of visit 14.04.2015)

Kind, E. and Levy, G.A. (2012): Energieeffizienz und Energieproduktion auf ARA *(Energy Efficiency and Energy Production of a Wastewater Treatment Plant)*. Im Auftrag des Bundesamtes für Umwelt (BAFU). Rev. 3. Baden, Switzerland.

Kraus, T. (2006): Praktische Abwicklung einer Messkampagne. Niederschlag-Abflussmessungen. Grundlage der Generalentwässerungsplanung *(Implementation of a Measuring Campaign in Practice. Precipitation and Discharge Measurments. Basic Principles of Sewer System Master Planning)*.

Kretschmer, F. and Ertl, T. (2010): Thermische Abwassernutzung aus siedlungswasserwirtschaftlicher Sicht *(Thermal Use of Wastewater from a Sanitary Engineering Point of View)*. Österreichischer Wasser- und Abwasserverband, Energiemanagement in der Abwasserwirtschaft - Kanal und Kläranalage.

Larsen, H.V., Pálsson, H., Bøhm, B. and Ravn, H.F. (2002): Aggregated dynamic simulation model of district heating networks. Energy Conservation and Management 43, 995 – 1019.

Neunteufel, R., Richard, L., Perfler, R., Tuschel, S., Böhm, K. and Haas, E. (2012): Wasserverbrauch und Wasserbedarf. Auswertung empirischer Daten zum Wasserverbrauch *(Water Consumption and Demand. Analysis of Empirical Water Consumption Data)*. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Vienna, Austria.

ÖWAV (1987): Regelblatt 19. Quoted by Ertl, T. (2010): VU Siedlungswasserbau und Gewässerschutz. Kanalisation und Mischwasserentlastungen *(VU Sanitary Engineering and Water Protection. Sewer system and combined sewer overflows)*. Lecture notes, Institute of Sanitary Engineering and Water Pollution Control, University of Natural Recourses and Life Sciences, Vienna, Austria.

Projektteam „Energie aus Abwasser“ (2012): Energie aus Abwasser. Abwasserwärme- und –kältenutzung mittels hocheffizienter Großwärmepumpen *(Energy from Wastewater. Using the heating and cooling potential of wastewater with highly efficient large heat pumps)*. http://www.abwasserenergie.at/fileadmin/energie_aus_abwasser/downloads/Broschuere-Energie-aus-Abwasser.pdf (date of visit 14.05.2015)

Schilperoort, R., Hoppe, H., de Haan, C. and Langeveld, J. (2012): Searching for storm water inflows in foul sewers using fibre-optic distributed temperature sensing. 9th International Conference on Urban Drainage Modelling, 2012, Belgrade, Serbia.

Schilperoort, R.P.S and Clemens, F.H.L.R. (2009): Fibre-optic distributed temperature sensing in combined sewer systems. Water Science & Technology 60(5), 1127-1134.

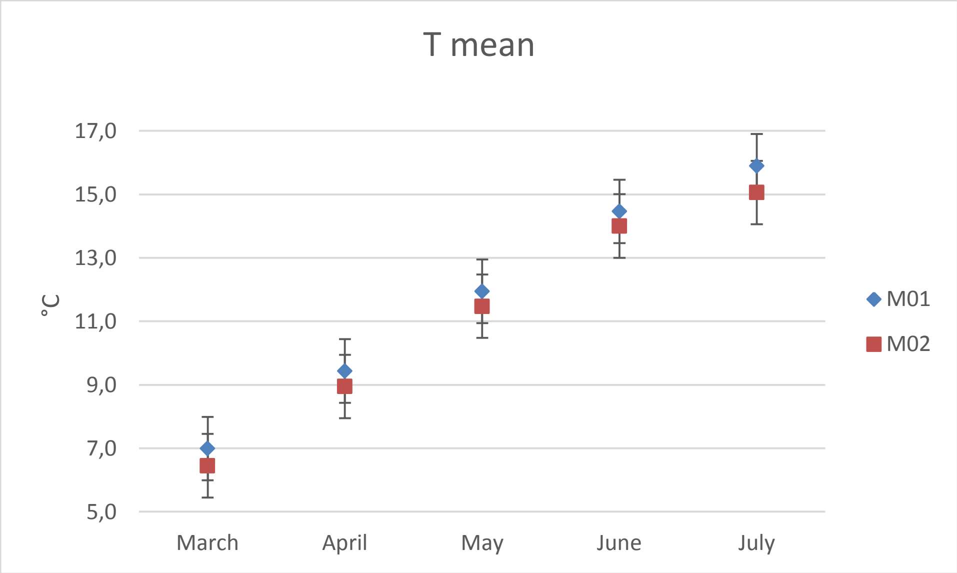
Schmid, F. (s.a.): Sewage Water: Interesting Heat Source for Heat Pumps and Chillers. Zürich, Switzerland, http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=en&name=en_508290240.pdf (date of visit 04.09.2014).

Veolia (s.a.): Invest in heat pumps. http://www.veoliawater2energy.com/en/references/heat-pumps/ (date of visit 08.05.2015)

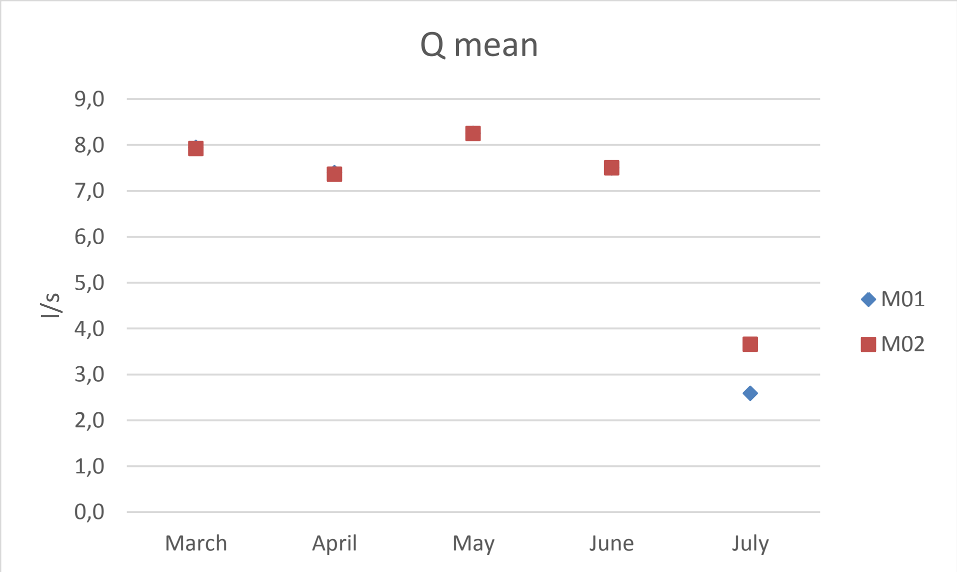
Wanner, O., Delavy, P., Eugster, J., Panagiotidis, V. and Siegrist H. (2004): Wärmerückgewinnung aus Abwassersystemen. Schlussbericht *(Heat Recovery from Wastewater Systems. Final Report)*. By order of Bundesamt für Energie, Dübendorf, Switzerland.

Wanner, O., Panagiotidis, V., Clavadetscher, P. and Siegrist, H. (2005): Effect of heat recovery from raw wastewater on nitrification and nitrogen removal in activated sludge plants. Water Research 39 (2005), 4725-4734.

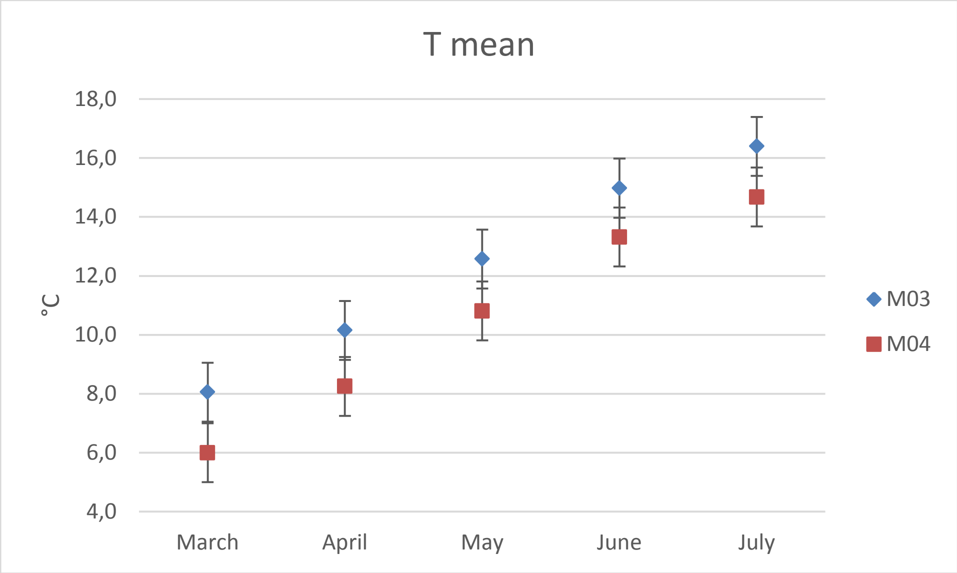
9. Appendix



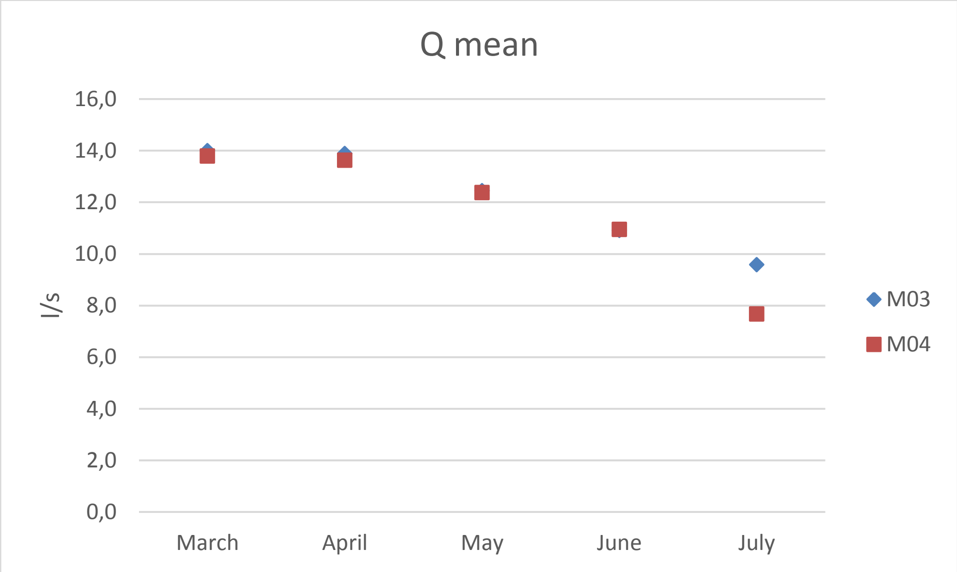
Attachment 1 Comparison of wastewater temperature between M01 and M02



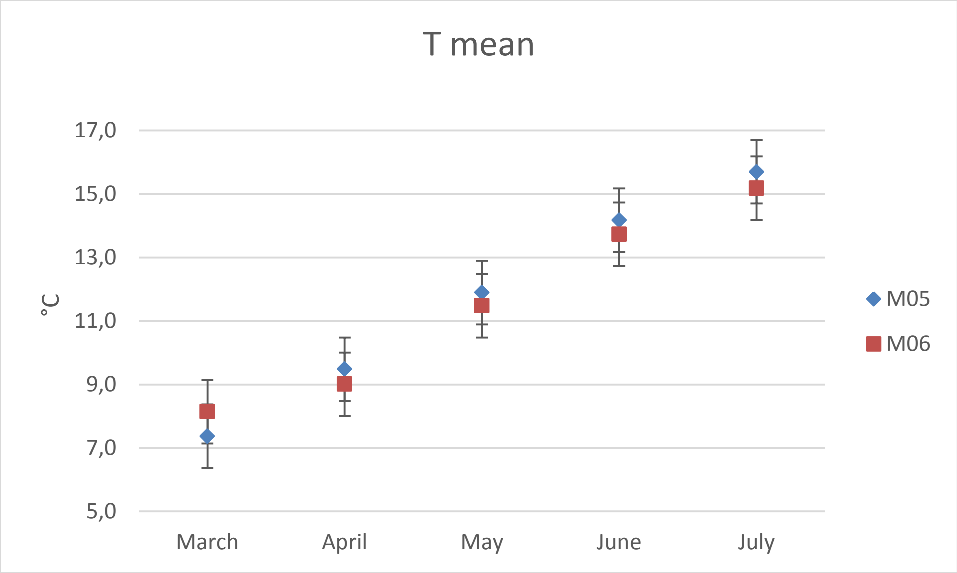
Attachment 2 Comparison of discharge between M01 and M02



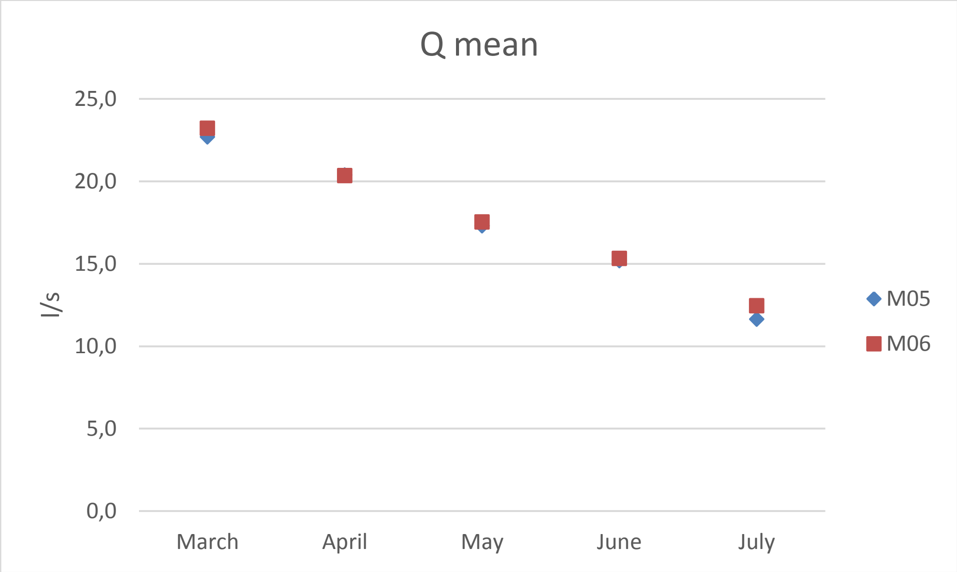
Attachment 3 Comparison of wastewater temperature between M03 and M04



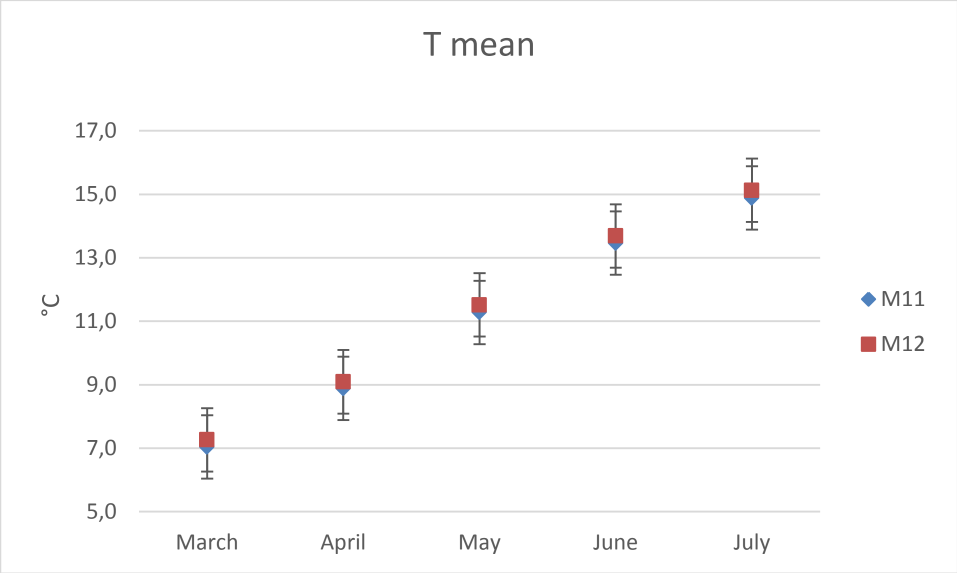
Attachment 4 Comparison of discharge between M03 and M04



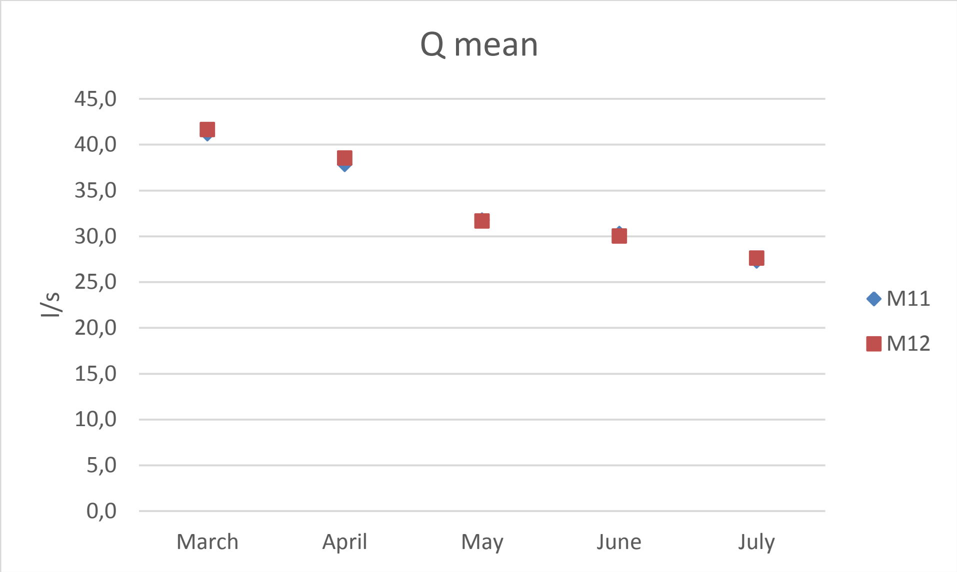
Attachment 5 Comparison of wastewater temperature between M05 and M06



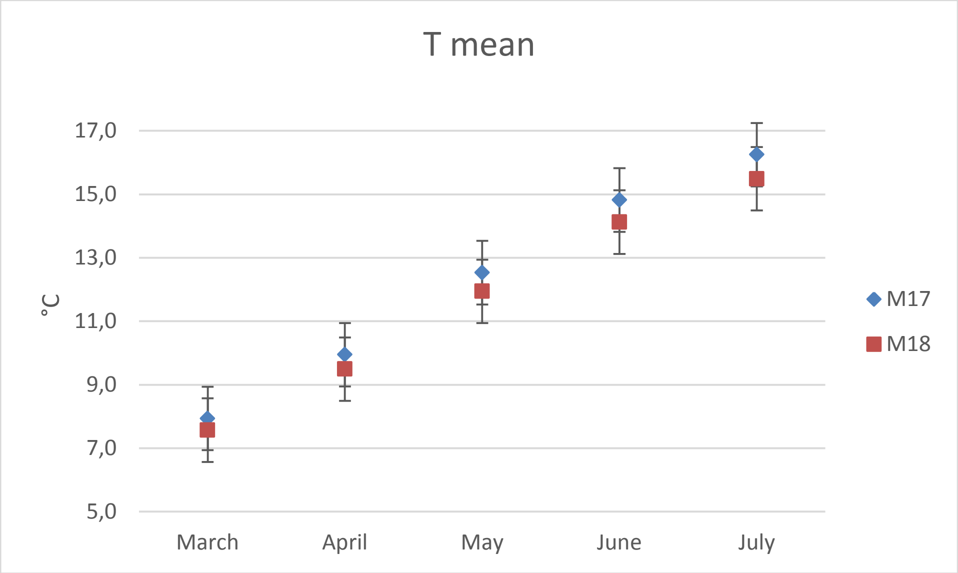
Attachment 6 Comparison of discharge between M05 and M06



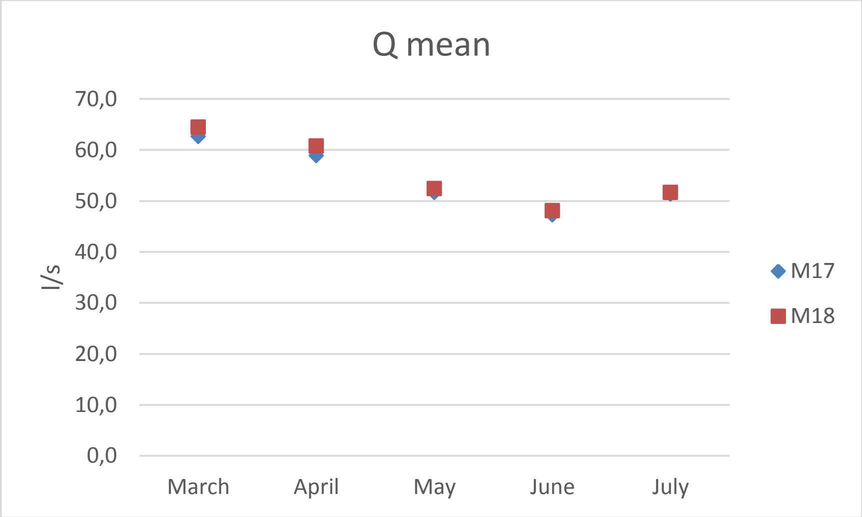
Attachment 7 Comparison of wastewater temperature between M11 and M12



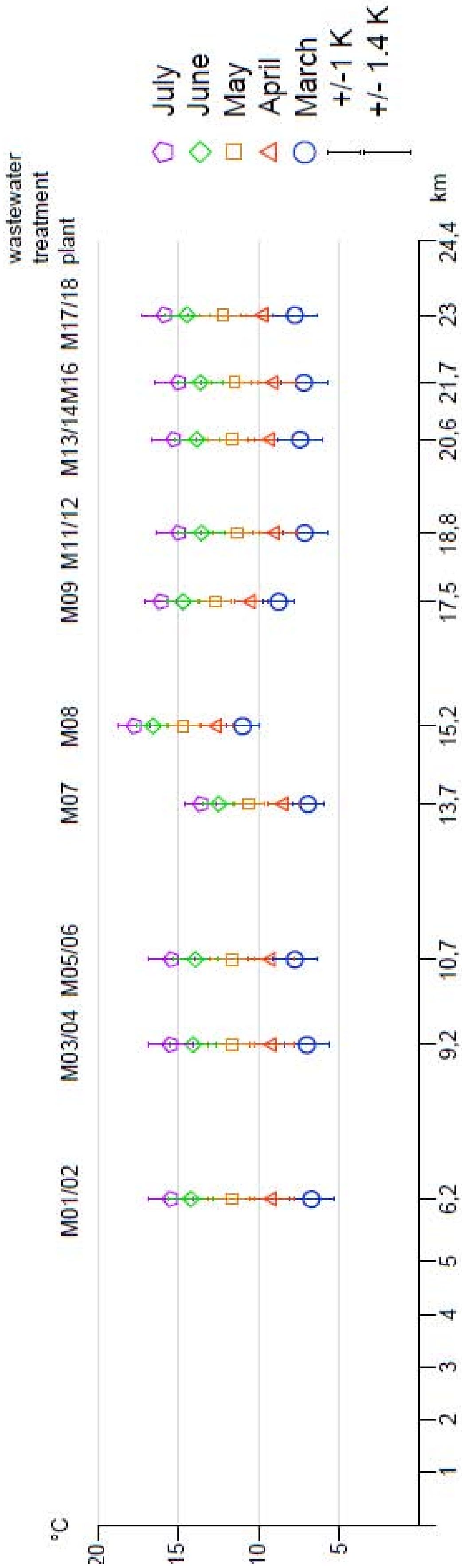
Attachment 8 Comparison of discharge between M11 and M12



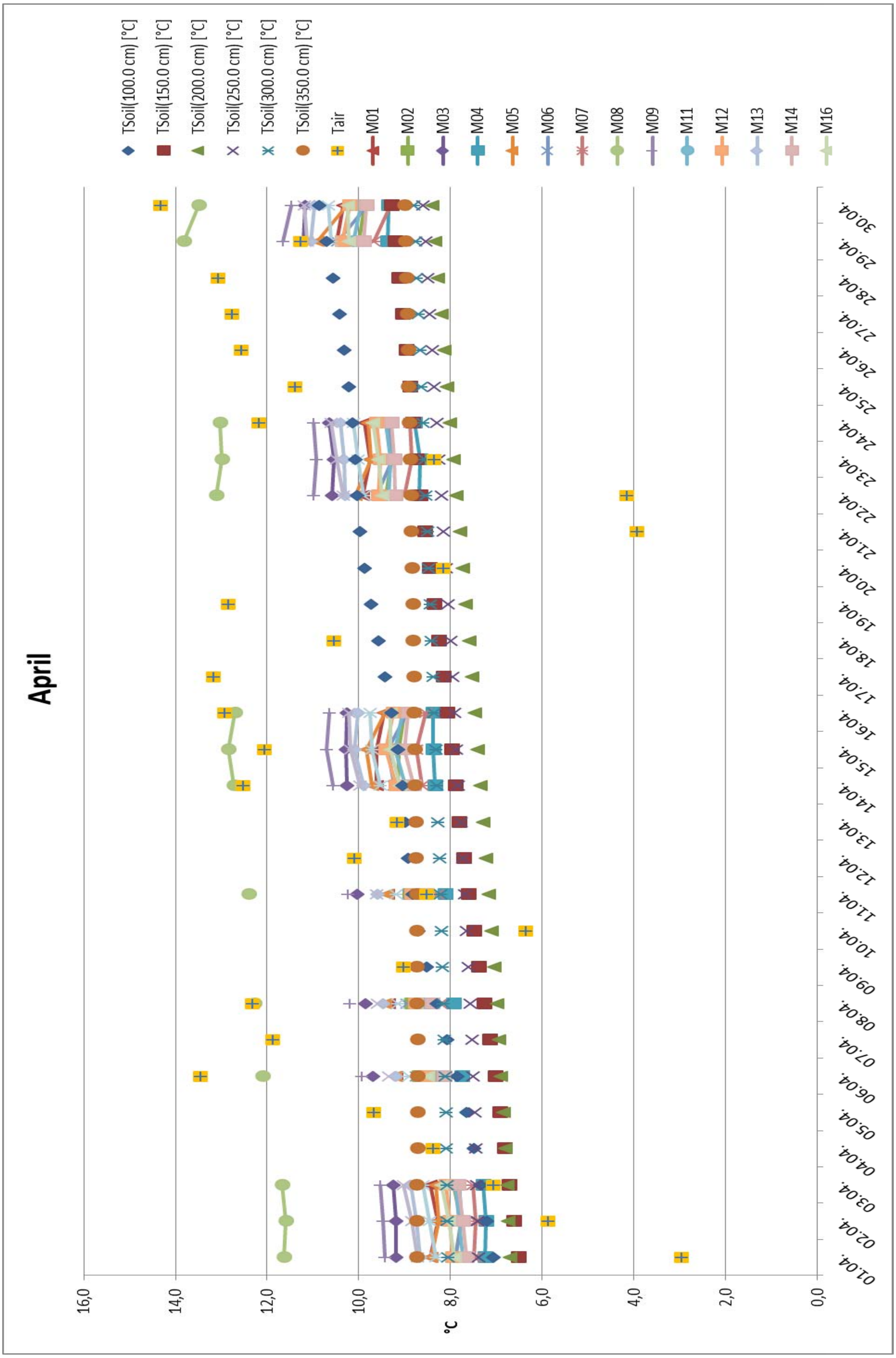
Attachment 9 Comparison of wastewater temperature between M17 and M18



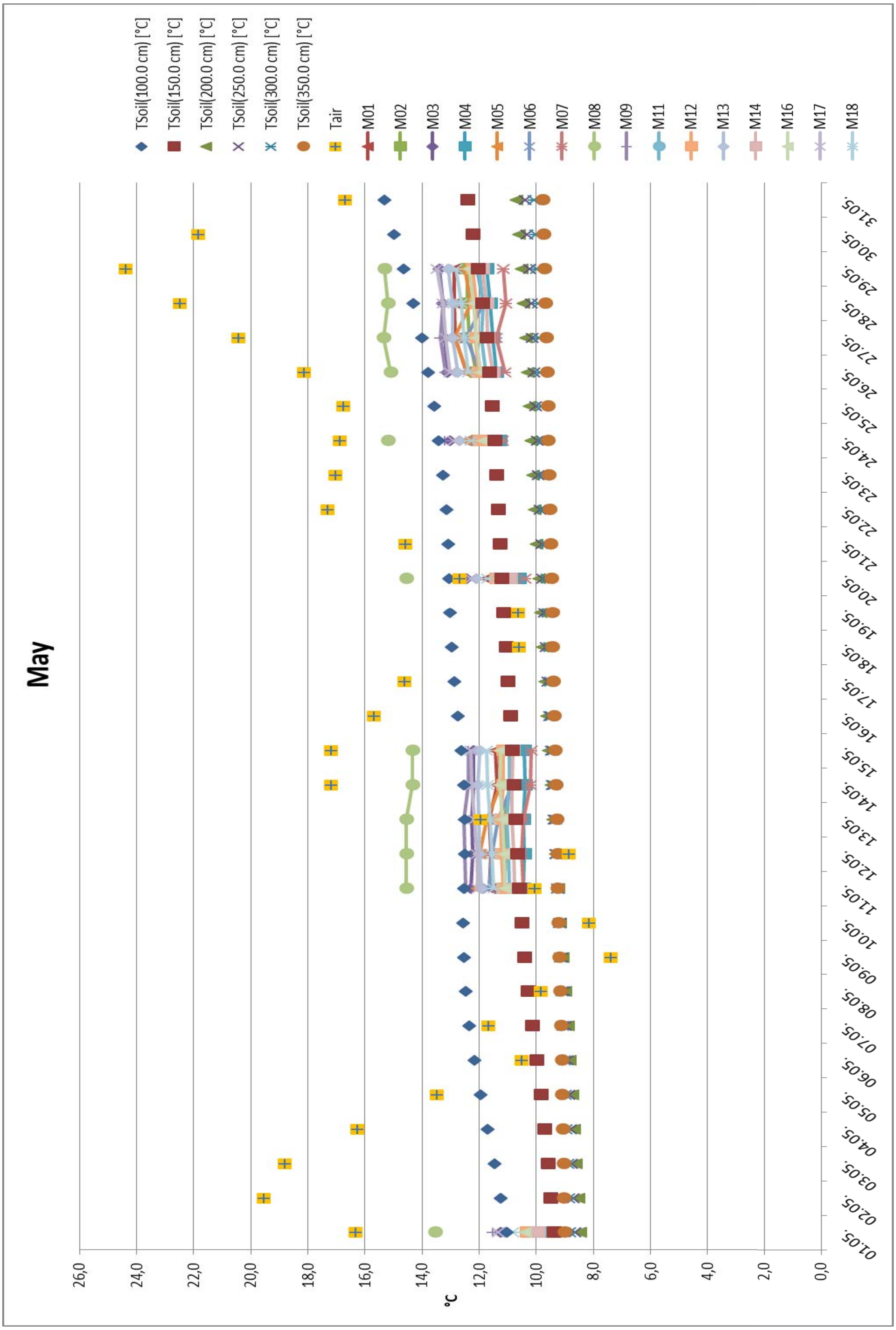
Attachment 10 Comparison of discharge between M17 and M18



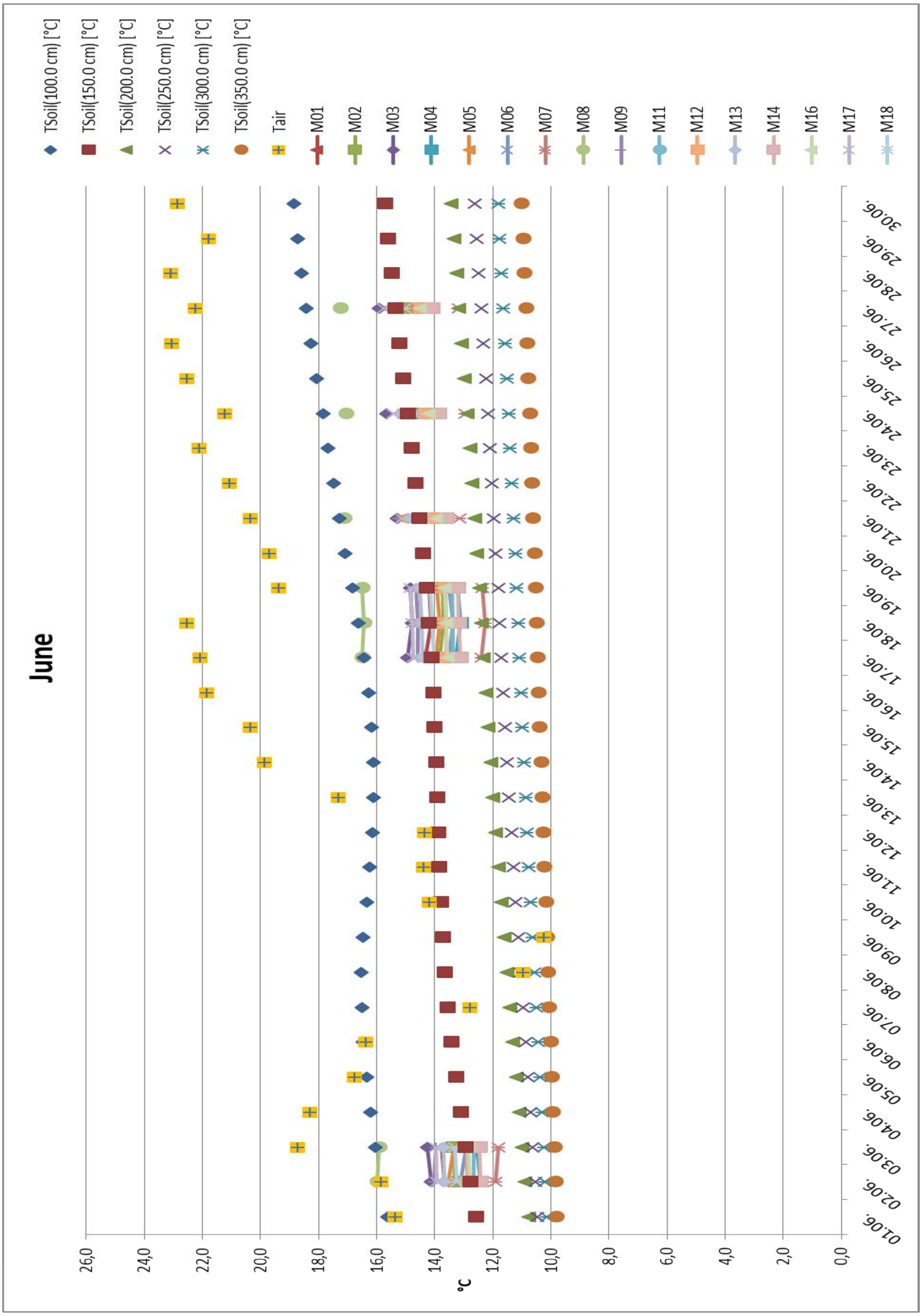
Attachment 11 Enlarged longitudinal profile of wastewater temperature development



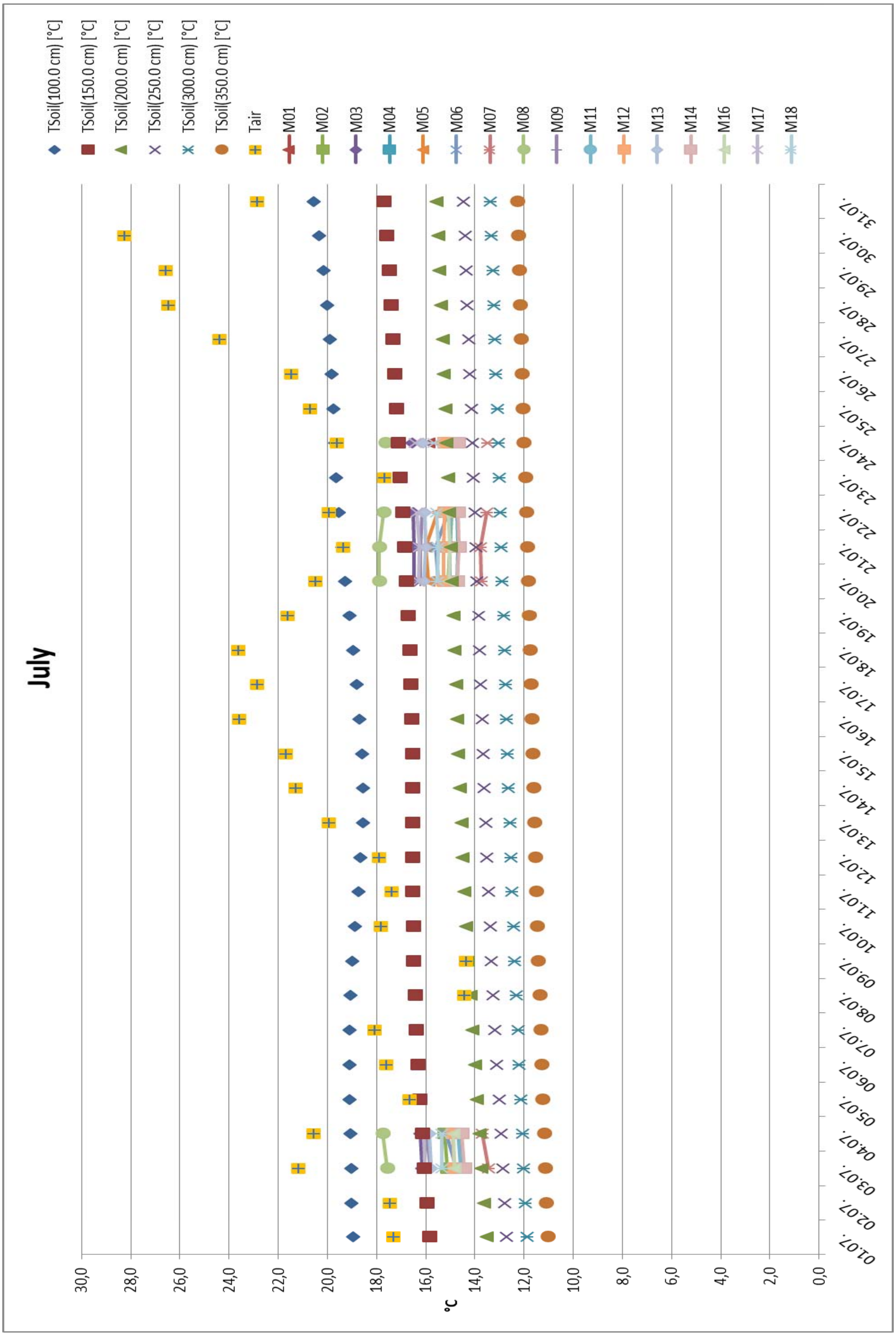
Attachment 12 Wastewater, soil and air temperature in April



Attachment 13 Wastewater, soil and air temperature in May



Attachment 14 Wastewater, soil and air temperature in June



Attachment 15 Wastewater, soil and air temperature in July

Attachment 16 Alligation alternate

Upstream measuring point	Month	Original T at upstream measuring point	Original T at M17/18	Calculated T at M17/18	T at upstream measuring point reduced by 0.1 °C	Calculated T at M17/18	T at upstream measuring point reduced by 0.5 °C	Calculated T at M17/18
M01/02	March	6.7	7.8	7.6	6.6	7.6	6.2	7.6
	April	9.2	9.7	9.7	9.1	9.6	8.7	9.6
	May	11.7	12.2	12.2	11.6	12.1	11.2	12.1
	June	14.2	14.5	14.4	14.1	14.4	13.7	14.4
	July	15.5	15.9	15.8	15.4	15.8	15.0	15.8
M03/04	March	7.0	7.8	7.6	6.9	7.6	6.5	7.5
	April	9.2	9.7	9.6	9.1	9.6	8.7	9.6
	May	11.7	12.2	12.1	11.6	12.1	11.2	12.0
	June	14.1	14.5	14.4	14.0	14.4	13.6	14.3
	July	15.5	15.9	15.8	15.4	15.8	15.0	15.7
M05/06	March	7.8	7.8	7.8	7.7	7.7	7.3	7.6
	April	9.2	9.7	9.6	9.1	9.5	8.7	9.4
	May	11.7	12.2	12.1	11.6	12.0	11.2	11.9
	June	14.0	14.5	14.3	13.9	14.3	13.5	14.1
	July	15.4	15.9	15.8	15.3	15.7	14.9	15.7
M07	March	6.9	7.8	7.3	6.8	7.3	6.4	7.1
	April	8.5	9.7	9.1	8.4	9.0	8.0	8.8
	May	10.6	12.2	11.5	10.5	11.4	10.1	11.3
	June	12.5	14.5	13.6	12.4	13.5	12.0	13.3
	July	13.6	15.9	15.1	13.5	15.0	13.1	14.9
M08	March	11.0	7.8	9.7	10.9	9.6	10.5	9.4
	April	12.6	9.7	11.4	12.5	11.3	12.1	11.1
	May	14.7	12.2	13.5	14.6	13.5	14.2	13.3
	June	16.6	14.5	15.6	16.5	15.5	16.1	15.3
	July	17.8	15.9	16.6	17.7	16.6	17.3	16.4
M09	March	8.8	7.8	8.4	8.7	8.3	8.3	8.1
	April	10.5	9.7	10.2	10.4	10.1	10.0	9.9
	May	12.7	12.2	12.5	12.6	12.5	12.2	12.2
	June	14.7	14.5	14.6	14.6	14.6	14.2	14.3
	July	16.1	15.9	16.0	16.0	15.9	15.6	15.7
M11/12	March	7.2	7.8	7.4	7.1	7.3	6.7	7.0
	April	9.0	9.7	9.3	8.9	9.2	8.5	8.9
	May	11.4	12.2	11.7	11.3	11.7	10.9	11.4
	June	13.6	14.5	13.9	13.5	13.8	13.1	13.6
	July	15.0	15.9	15.4	14.9	15.4	14.5	15.1
M13/14	March	7.4	7.8	7.5	7.3	7.4	6.9	7.2
	April	9.3	9.7	9.4	9.2	9.4	8.8	9.1

	May	11.7	12.2	11.9	11.6	11.8	11.2	11.6
	June	13.9	14.5	14.1	13.8	14.0	13.4	13.7
	July	15.3	15.9	15.5	15.2	15.5	14.8	15.3
M16	March	7.2	7.8	7.3	7.1	7.2	6.7	6.9
	April	9.1	9.7	9.2	9.0	9.1	8.6	8.8
	May	11.5	12.2	11.7	11.4	11.6	11.0	11.3
	June	13.6	14.5	13.9	13.5	13.8	13.1	13.5
	July	15.0	15.9	15.3	14.9	15.2	14.5	15.0

Curriculum Vitae

Personal Information

Name	Lena Simperler
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Date of birth	25. 02. 1990
Nationality	Austria

Education

07/2013 – 11/2013	Exchange semester at Lincoln University in New Zealand
10/2012 -06/2015	Master program "Natural resources management and ecological engineering" at the University of Natural Resources and Life Sciences, Vienna
08/2010 – 01/2011	exchange semester at the University of Copenhagen
2008 - 2012	Bachelor program "Environment and natural resource management" at the University of Natural Resources and Life Sciences, Vienna
2000 – 2008	BG/BRG Laa an der Thaya – high school graduation

Work experience

10/2014 – 01/2015	Internship at VATech-WABAG – Overseeing the operation of an enhanced primary treatment pilot plant
03/2014	Taking care of the conference booth from Miya Waters at the Water Loss Conference 2014 in Vienna
04/2014 – 12/2014	Internship at Ban Roean Ram – Center for Sustainable Development in Thailand
03/2014	Internship at UmweltbildungAustria – Grüne Insel
08/2006, 07/2007, 07/2008	Internship at Zurich insurance in Vienna

Other skills

Language skills	English (C1), Russian (A1)
Computer skills	Good knowledge of MS Office 2007 (Word, Excel and Powerpoint) Good ArcGIS-knowledge Basic AutoCAD-knowledge
Driving licences	Category B
Seminars	Participation in the GO EcoSocial training organized by Ökosoziales Studierendenforum

10. Affirmation

I certify, that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Vienna, 20th of May 2015,Lena Simperler