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ANALYSIS OF HEAT RECOVERY POTENTIAL FROM WASTEWATER: CASE STUDY HRADEC KRALOVE

MASTER THESIS

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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.

Prague, 20th of May 2018 Bc. Filip Nedorost

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Abstract

Heat recovery from wastewater has a great potential in the field of renewable energy. The energetic potential in wastewater is very large. 1.16 kWh of heat can be recovered from sewer system if the temperature of 1 m^3 of wastewater is reduced by 1 °C. An important factor needs to be taken into account: using energy contained in wastewater could have negative impact on the processes in the wastewater treatment plant as well as on the recipient. It is necessary to be especially careful when designing the optimal heat exchanger performance.

This study will describe the whole process of choosing the suitable sewer system parts for heat exchanger installations and the calculation of heat exchanger performance. The whole process could be divided into few steps. First of all it is necessary to predefine the spots in sewer system, where the heat potential is the highest. This step could be done with help of the SQUID. After the wastewater heat recovery site preselection, the measuring campaign and data analyzation should follow. Based on data analysis it is necessary to verify if the heat potential is high enough to install the heat exchanger. It is important to keep in mind that the heat exchanger installation should never negatively affect the processes which are running at the wastewater treatment plant. The treatment processes could be negatively affected by reducing wastewater temperature, under the level which guarantees the right wastewater treatment operating.

For optimal heat exchangers performance design the wastewater predicting software (TEMPEST) is applied. Based on the results, it is possible to define optimal heat exchanger performance and the number of days when the heat exchanger will be operating.

Suggestion of potential heat customers is a part of this thesis as well.

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1 Introduction

The threat of dangerous climate changes as part of ambitious global action, deep reductions in the EU's emissions have the potential to deliver benefits in the form of savings on fossil fuel imports and improvements in air quality and public health. Be able to face climate changes the European Union has committed to reduce CO_2 emission by 80% - 95% compared to the level in 1990. The energy sector produces the lion's share of man-made greenhouse gas emissions. Therefore, reducing greenhouse gas emissions by 2050 by over 80 % will put particular pressure on existing energy systems and new potential energy sources has to be developed. The energy infrastructure which will power citizen's houses, industry and services in 2050, as well as the buildings which people will use, are being designed and built now. The pattern of energy production and use in 2050 is already being set. [1]

Together with 195 countries, all the European Union states signed Paris agreement from year 2015, moreover all of the 27 EU states ratified the agreement as well.

The agreement sets out a global action plan to put the world on track to avoid climate change by limiting global warming to well below 2 °C. As a consequence, the extension of renewable energy supply is an imperative societal goal. Therefore, the search for additional sources of renewable energy is an ongoing process. In this context, wastewater attracts professional interest as it can be considered as domestic and inexhaustible resource of permanent availability [2].

With 50% of final energy consumption in 2012, heating and cooling is the EU's biggest energy sector. It is expected to remain so [3]. Reuse of generated heat and cold and increase the use of renewable energy are two of three main strategies in future decarbonisation of European energy system. According to a low–carbon heating and cooling strategy 78% of the total heat supply market comes from fossil sources [4]. This has to be changed. One of the huge heat potentials is hiding in urban sewer systems. It is striking that such a rich, local, renewable and relatively easy accessible heat resource has such a low utilization nowadays. At Figure 1 can be observed how big heat potential is just running away into the air and the Earth. There are only a few wastewater heat pump installations world-wide. In Europe wastewater heat pumps are operated for example in neighbouring Germany, Switzerland, and Norway; outside Europe example is heat recovery system from sewage in Vancouver in Canada. In the Czech Republic, wastewater as an energy source for the heat pumps has so far been neglected. The main arguments are the long payback period due to the high acquisition costs and possible impacts of the decrease of wastewater temperature on the wastewater treatment efficiency and operation costs [5]. Heat recovery from wastewater could help with decreasing fossil sources consumption. That means that thermal use of wastewater in a sewer goes hand in hand with decreasing CO_2 emissions.

Figure 1 – Wasting of the urban wastewater heat

What is more, almost half of the EU's buildings have individual boilers installed before 1992, with efficiency of 60% or less. 22% of individual gas boilers, 34% of direct electric heaters, 47% of oil boilers and 58% of coal boilers are older than their technical lifetime. [3]. Replacing those individual boilers with the effective wastewater heat exchanger will significantly decrease the electricity consumption and the associated CO_2 emission.

Fossil fuel supply sources are, on average, dominating alternatives in EU28 at current, where coal, oil products, and natural gas especially, represent 68% of the total supply to the building heat market (78% including electricity, which often is generated by use of fossil fuels). This indicates that the European building sector has an important role to play in the future decarbonisation of the European energy system, since there is plenty of room for improvements in this sector. One such improvement could be obtained by replacing some of the current fossil supply with recovered excess heat from energy and industry activities, as well as with renewable heat resources such as wastewater. [6]

Swiss researches reported that more than 15% thermal energy supplied to buildings was lost through the sewer system (up to 30% in case of low-energy buildings), hot water in buildings is using in everyday activities such as: showering, cloth/dish washing, cooking, body hygiene; percentage of consumption of drinking water during the day could be seen at Figure 2 . To recover this energy, various types of heat exchangers can be developed according to the area of use like domestic, sewage, filtered sewage, etc. [7]. Swiss study shows that up to 3% of buildings could be supply with the heat from wastewater [7]. According [8] the number is even higher up to 10% of buildings. It may look like it is not a big number, but when we realize that the heat source from sewers is for free and there are almost no maintenance costs, it worth to change the meaning about the wastewater. Wastewater should not be considered as waste but as a source of heat, energy, nutrients…

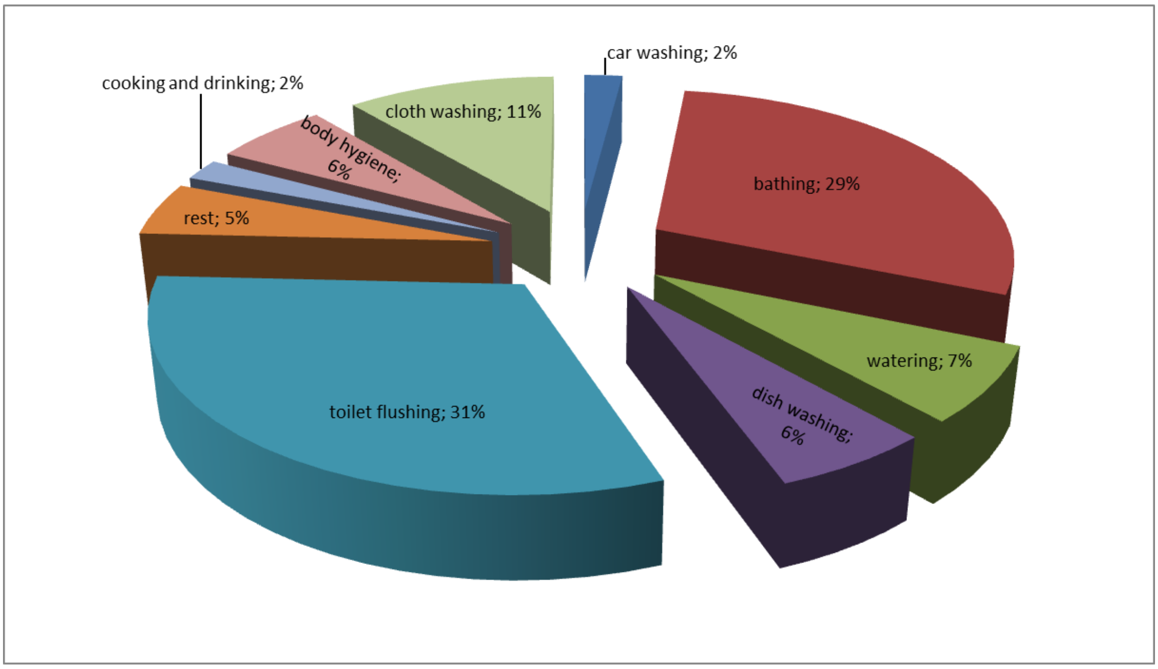


Figure 2 – Percentage of consumption of drinking water during the day **[9]**

Nowadays conception of urban drainage is still not hand in hand with the sustainable development. However it is for sure that to start using wastewater as a heat source in bigger scale is a step forward and hopefully next steps will follow soon.

A small obstacle may be a week regulations background. For example there are no standards or transcriptions for wastewater energy in Czech Republic.

2 Objectives

The sewer system is a dynamic system, where plenty of variable factors affects the wastewater temperature. Air temperature, soil temperature, ground water temperature, rainfall, size of residential and industrial, commercial and institutional area, are just a few factors, which affect the wastewater development in sewer system.

There is no preliminary process of strategic location identification and selection of heat recovery potential sites. Nowadays situation is comparable to that in the wind energy sector about 25 years ago. Following an initial first stage of practical experience, the standardization of components and interfaces of existing systems must come. First of all it is important to discover sites and locations with a high potential for heat recovery [10].

The barriers to use wastewater resources are lack of awareness and of information about the resource available; inadequate business models and incentives. Main objective of my thesis is to identify the possibility of heat exchangers installation in Hradec Králové.

The thesis interrelate more interrelated topics:

- testing a new device (SQUID) and suggestion the practical application of it
- detail wastewater temperature and discharge data analysis
- predicting wastewater temperature by mathematical modelling (TEMPEST)
- verification suitable sewer section for heat exchangers installations, designed in previous scientific work
- suggest a new suitable sewer sections for heat exchangers installations
- find an ideal heat exchangers performances based on balance between impact on the WWTP process and heat exchanger effectivity

New device named SQUID is going to be tested within this thesis. SQUID is floatable platform with different sensors and it is possible to use it for the preselection of hotter spots in sewer system and therefore identification of places where the heat exchanger installation could be possible. Another application could be the verification of the results of mathematical wastewater temperature predicting.

Data from measuring campaign in Hradec Králové from years 2013-2014 will be analyse in detail. Based on data analyzation and sewer system description the places for the heat exchanger installation will be defined. There are already proposals from previous research where to install the heat exchangers. The previous proposals will be assessed and new sewer sections suitable for the heat exchanger installation will be designed.

Next step will be to define the optimal heat exchanger performance. Optimal heat exchanger performance is based on minimal wastewater temperature at the inflow to the wastewater treatment plant. The boundary condition is the temperature - wastewater temperature cannot drop under 10 °C at the inflow to the WWTP, because of the wastewater treatment processes. Because of the sewer distance between heat exchanger installations and wastewater treatment plant in Hradec Králové is quite long (1,7 km), it is necessary to mathematically model the temperature development in this sewer section. One of the goals of my thesis is to verify the possibility of wastewater reheating in sewer system and calculate the limit temperature level of wastewater that could be cooled in the heat exchanger. The minimal wastewater temperature behind the heat exchanger will be defined by mathematical simulation with the TEMPEST (temperature estimation) model. Moreover an idea how to calibrate the TEMPEST model with the help of the SQUID will be described.

Based on known data from wastewater temperature discharge and temperature analysis and the TEMPEST model results, the suitable sections for heat exchangers and possible heat exchangers performance in Hradec Králové will be designed. The sewer sections, designed in previous scientific work, as a suitable for heat exchanger installation, will be verified What is more the heat exchangers operating possibilities will be mentioned. Optimal balance between heat exchangers performances and number of operating days will be calculated.

3 Fundamentals and technical background

3.1 Heat recovery background

3.1.1 European heat and cooling strategy

Heating and cooling put to use half of the EU's energy and the most of it is wasted. Nice example with heat wasting is waste water outlet. Developing a strategy to make heating and cooling more efficient and sustainable is a priority for the Energy Union. It should help to reduce energy imports and dependency, to cut costs for households and businesses, and to deliver the EU's greenhouse gas emission reduction goal and meet its commitment under the climate agreement reached at the COP21 climate conference in Paris. [3]

3.1.2 Legal situation

In few countries like, for instance, Switzerland and Germany wastewater as an energy source is already included in energy policymaking. [11].

In Austria, heat recovery from wastewater is stated explicitly in the new release of the Federal Law on the Increase of Energy Efficiency [12]. In Switzerland, the Association [13] supports wastewater heat recovery related initiatives.

In the Czech Republic there is no proper legal background or support for in sewer heat installations yet. Wastewater as a potential energy source is mentioned in the ČSN 75 6780 – Greywater and rainwater reuse inside buildings and adjoining estates and in Act number 185/2001 the waste act.

3.1.3 Wastewater as a renewable local energy source

It is possible to divide energy sources into primary and secondary. Primary sources are all energy sources that are extracted directly from nature, those origin is in natural forces. Secondary sources are mainly generated as consequence of transformation of primary energy sources into noble forms, industrial production or other human activity.

According to [14] renewable energy is generally defined as energy that comes from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat.

In general, the wastewater in literature is not considered as a renewable energy source. Heat energy that comes from wastewater could be tagged as pseudo renewable. In contrast with sunlight, wind, rain, tides, waves and geothermal heat, heat from wastewater comes from anthropological activity. There must be another energy source, which is warming the

water before it is used by human. Because of that energy from wastewater falls into the category of secondary sources.
On the other hand, after the wastewater enters the sewer system, it becomes source which is continuously replenished and therefore could be considered as a renewable.

What is for sure, heat from wastewater can be tagged as a local energy source. According to [15] the average water consumption in Czech Republic is around 100 l/person per day. When looking at the requirements regarding wastewater heat exchangers, a minimum discharge 10-15 l/s [16] [17] on dry weather days is necessary for the system to work economically efficiently. Easy calculation shows that the amount corresponds from 10000 to 15000 residents being connected upstream of the heat exchanger. That means each settlement with minimum of 10000-15000 residents could effectively use wastewater as a local energy source.
There are over 100 settlements fulfilling this requirement in Czech Republic and more than 50 in Austria.

3.1.4 *Wastewater heat exchangers and heat pumps*

Heat pump is a device comprised by two heat exchangers that transfer heat from a low-grade heat source (cold side) (e.g. ground water, surface water, soil, outdoor air, waste water, etc.) to a working fluid. By the application of higher grade form of energy (e.g. mechanical energy), it raises the temperature or increases the heat content of the working fluid before releasing its heat for utilization (hot side). Heat pumps are based on the Carnot cycle where the entropy of a compressed gas or refrigerant is higher that causes increase of temperature. The main components of a vapour compression cycle heat pump are: compressor, condenser, evaporator, and expansion valve. [18], [19]

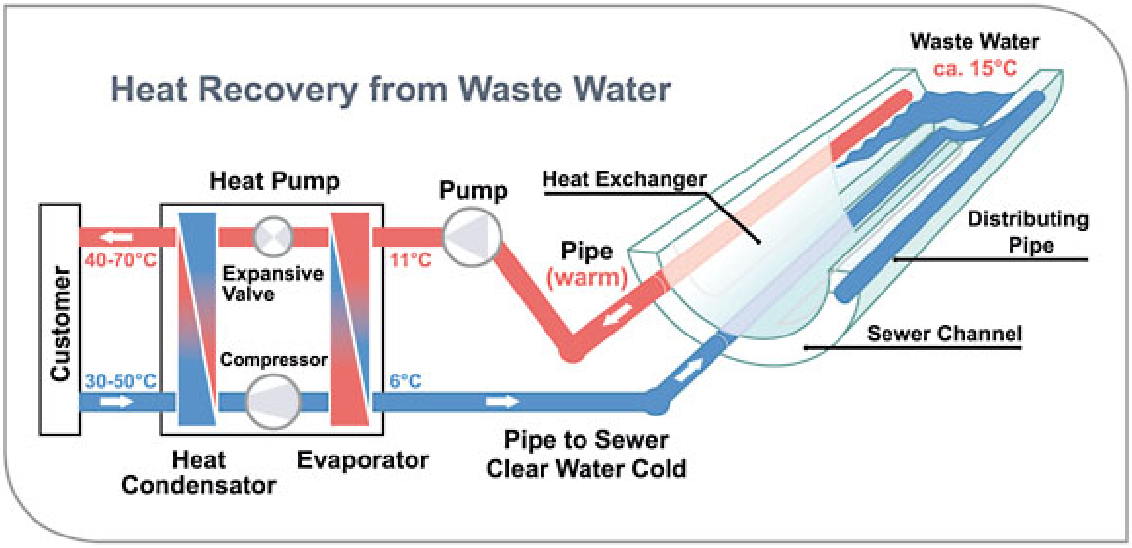


Figure 3 – Heat recovery from waste water **[20]**

As can be seen in Figure 3 the heat pump has no direct contact to wastewater. It only uses the heat from wastewater by heat exchanger.

Mechanical heat pumps exploit the physical properties of a volatile evaporating and condensing fluid known as a refrigerant. The heat pump compresses the refrigerant to make it hotter, and releases the pressure at the side where heat is absorbed. The working fluid, in its gaseous state, is pressurized and circulated through the system by a compressor. On the discharge side of the compressor, already hot and highly pressurized vapor is cooled in the heat exchanger, called a Heat condensator. The vapor is being cooled until it is condensed into a high pressure liquid with moderate temperature. The condensed refrigerant then passes through a pressure-lowering device. This may be an expansion valve. The low-pressure liquid refrigerant then enters another heat exchanger, the evaporator, in which the fluid absorbs heat and boils. The refrigerant then returns to the compressor and the cycle is repeated. [21, s. 98], [22]

Wastewater heat exchangers can be used in three different locations to recover heat from wastewater. Mainly, the wastewater heat exchanger may be inside the building to recover waste heat from domestic hot water, which is called domestic utilization. Wastewater heat exchanger can also be located inside or outside the sewage channel, which provides larger excess heat from wastewater to provide heating/cooling for multiple buildings. Apart from these two locations, wastewater heat exchanger can be installed downstream of a wastewater treatment plant to efficiently utilize the energy in the treated wastewater in larger scale. The heat recovery at the sewage treatment plant is technically easier since energy from the treated wastewater can be extracted more efficiently. [18]

Main installation locations for wastewater heat exchanger can be seen in Figure 4.

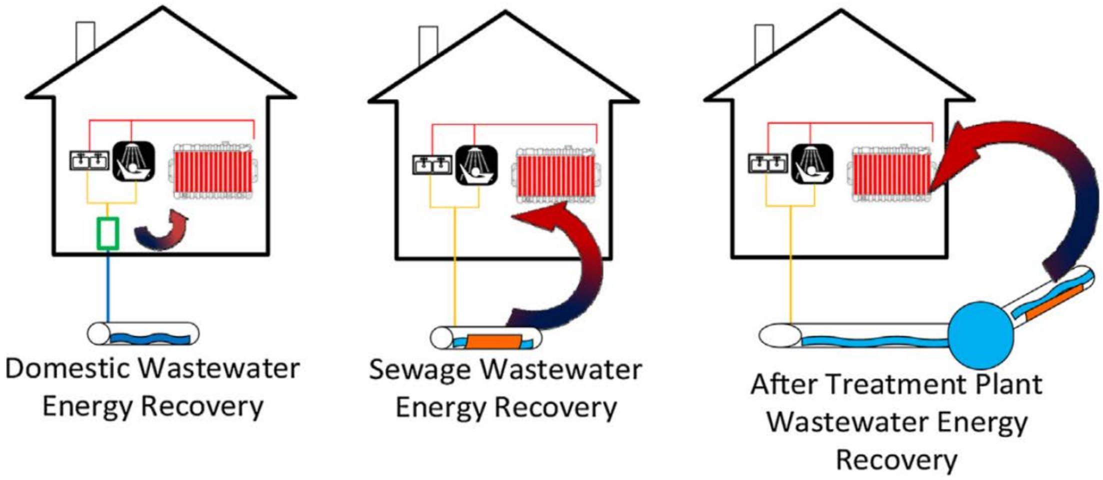


Figure 4 – Installation locations for wastewater heat exchangers **[18]**

In domestic utilization, water used by appliances such as washer and dishwasher, sink, shower, etc. contain a significant amount of heat energy. The aim of the wastewater heat exchanger in this system is to recover this heat to preheat the fresh water to be used as domestic hot water.

One of the most common applications of waste heat recovery from wastewater is the system installed in urban sewage channel. This kind of application will be researched in this thesis. Advantages of heat recovery from sewers are: sufficient quantity of water is continuously available, the energy source is relatively proximal to the consumers, the widespread sewer network in the cities, the heat quality that can be found in wastewater. The wastewater is transported through pipes tends in order to have a similar temperature as the ground. The heat is dissipated through the wall pipes [23]. It has been observed that after 10 km of transportation in main sewer pipes, wastewater has the same temperature as the soil. Therefore, if heat is to be recovered, the distance between the user and the heat source is important. [19]

There are more heat exchanger types in sewer. Heat exchangers can be shell and tube heat exchangers, spiral tube heat exchangers or plate heat exchangers mounted on pre-built pipes or pits which can be placed in the existing networks [19]. The sewage contains relatively high heat energy compared to the domestic system. However, recovering of the most of the heat energy inside the sewage channel may impede the efficiency of the treatment process downstream in the wastewater treatment plant. Therefore, the amount of energy recovered from sewage should be carefully optimized. It should not decrease the efficiency of wastewater treatment plant (more about this topic will be mention in chapter 3.1.7 Ecological consequences), but it should provide enough energy to increase the efficiency of wastewater heating pump system. [18]

3.1.5 Heat pump efficiency

Wastewater heat pumps work efficiently. The consumption of primary energy is lower by far than in traditional systems for the generation of heat and cold (energy in relation to the useful energy produced). Compared to a condensing gas heater, a wastewater heat pump (with peak load boiler) uses 10% less of primary energy, and compared to an oil-fired heater, even 23% less. Also, in comparison with other heat pump systems (groundwater, geothermal probes), wastewater installations perform well. The reason lies in the fact that the heat source exhibits favourable temperatures over the whole year. Wastewater systems achieve high annual coefficients of performance if everything is correctly planned and optimally operated. The highest COP value measured in Switzerland at an installation in Basel is more than 7. [7]. COP (coefficient of performance) is a ratio of heating or cooling provided and energy consumed. COP is dimensionless.

According to [24] heat pump which is using heat from wastewater could achieve COP values of 4.8. That means that for every unit of energy that is put into the heat pump 4.8 units of heat energy is generating.

[19] reflects a COP of 4,5 for a heat pump for heating.

3.1.6 *Heat distribution system*

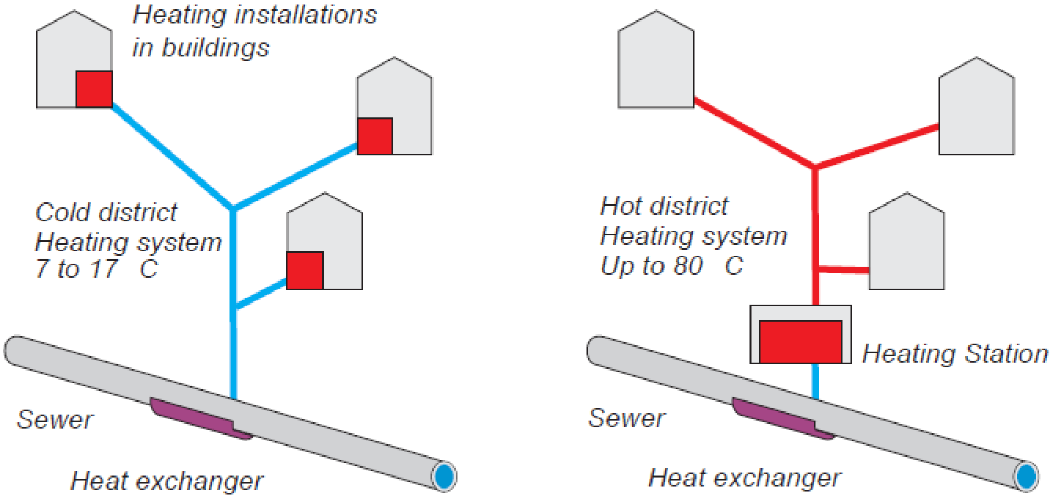


Figure 5 – Examples of heating distribution systems **[7]**

It is known that cold and hot district heating can be used. Cold district heating system transports heat energy on low temperature level of 7°C – 17°C in direction to individual buildings. After that the energy is processed in more decentralized heating facilities (heat pumps). On the other side, there is only one heat pump located close to the heat exchanger in case of hot district heating system. Then the heat energy is transported to individual consumers. High temperatures up to 80 °C are transported through the warm district heating system.

Both options are possible and both have pros and cons. Cold district heating system is better, when there is a large distance between the heat exchanger and heat user. More facilities need to be maintained in this case. That can lead to more maintains costs and maintains problems. On the contrary there are much higher capital costs in case of hot district heating system. Pipes must be well insulated to prevent large energy losses.

3.1.7 *Ecological consequences*

Wastewater treatment plants need the heat energy to perform necessary treatment processes. 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. [16] As mentioned above, there should be an optimization in recovery of heat from sewage water. To avoid hampering of the sewage treatment process, a wastewater heat exchanger can be installed after the treatment plant. These systems can achieve the highest amount of waste heat energy recovery from treated wastewater. Even though the amount of recovered energy is higher in contrast with domestic or sewage wastewaters heating pumps, one big disadvantage of these systems is that the treatment plants are usually far from the areas where heat or air conditioning is needed, and significant amount of the heat recovered from wastewater is lost during the transportation. If the treatment plant is close to the residential area, this method will be more appropriate, since it achieves large energy recovery and experiences less bio-fouling thanks to the treated wastewater [18]. What is more it is desirable not to discharge hot wastewater into the recipient.

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 of the wastewater temperature should be avoided unless sufficient dilution in the receiving water can be assured. [25]

According to [7] recommended values for the thermal use of raw wastewater are: the daily average wastewater temperature on entry to the sewage treatment plant should not be reduced to lower than 10°C. And the total cooling should be not more than 0.5 °C. Another scientist [26] suggests that, the sewage temperature should not drop below 6 °C and the inflow temperature at the wastewater treatment plant was set to a minimum of 11 °C. According to [19] the lowest possible temperature of wastewater delivered to wastewater treatment plant should be 12°C. All those three conclusions are in similar ranges and they do not differ too much from each other. In the case of this thesis, the minimal temperature at the inflow to the WWTP will be set up on 10 °C.

Another important aspect connected to ecology is CO_2 emission. In the Table 1 is comparison of relative CO_2 emissions of different energy systems.

Table 1 – Relative CO_2 emissions of energy systems **[7]**

Waste water heat pump, bivalent	22%
Combination heat pump – combined heat and power unit	41%
Gas heater with condensation	63%
Oil-fired heating	100%

Another ecological point of view is the SPI. Sustainable Process Index is an ecological footprint calculating instrument and it is compatible with life cycle analyses described in the [27]. SPI is a Life Cycle Impact Assessment tool for the evaluation of environmental impacts of processes, products or services which are essential part of any Life Cycle

Assessment (LCA) for evaluation the pressure on the environment [28]. In Fig. 5 the scheme for ecological evaluation by the SPI is shown.

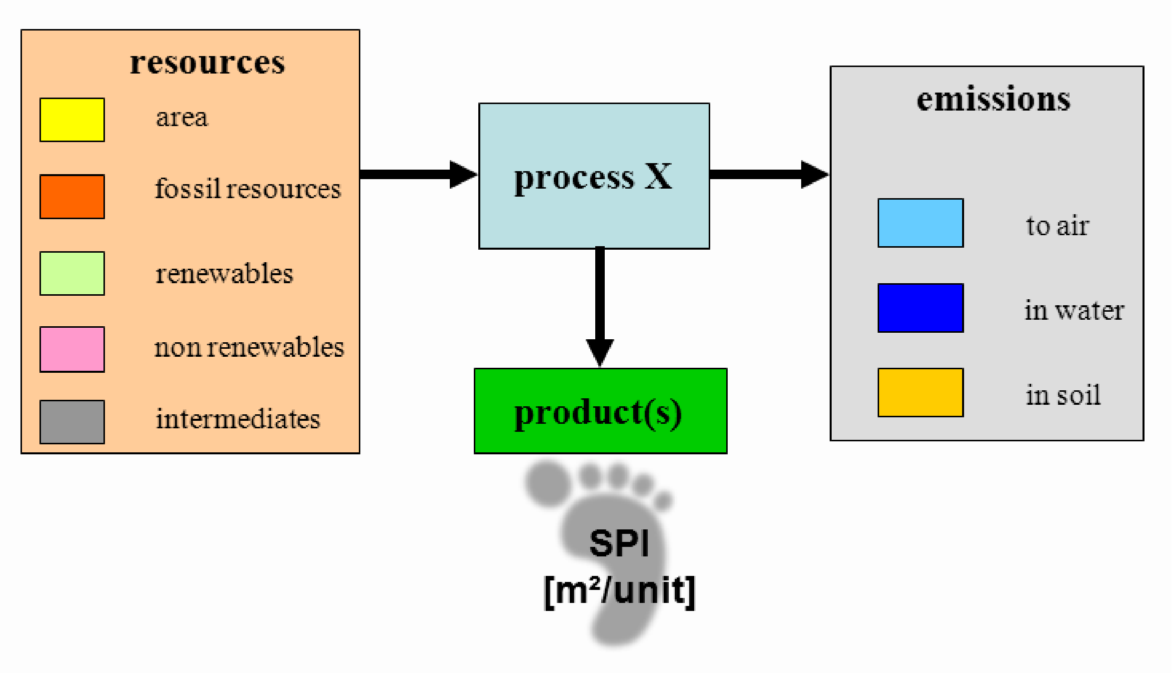


Figure 6 – SPI calculation methodology scheme **[29]**

Within this tool, it is possible to assemble entire life cycles in the form of process chains. The result is SPIfootprint, CO_2-life-cycle-emissions and the global warming potential (GWP) of the whole life cycle. [30]

[2] created research project for the ecological comparison of different heat producing technologies. A maximum external heat demand of 9057 MWh_{th}/a was taken in consideration for the ecological evaluation. Different scenarios were created for heat producing technologies, such as heat exchanger and heat pump operating with three different electricity mixes or heat from natural gas to provide the heat demand of 9057 MWh_{th}/a. The three evaluated electricity mixes are the EU electricity mix, AUT electricity mix and a mix based on renewable energy sources. The results are displayed in Figure 7.

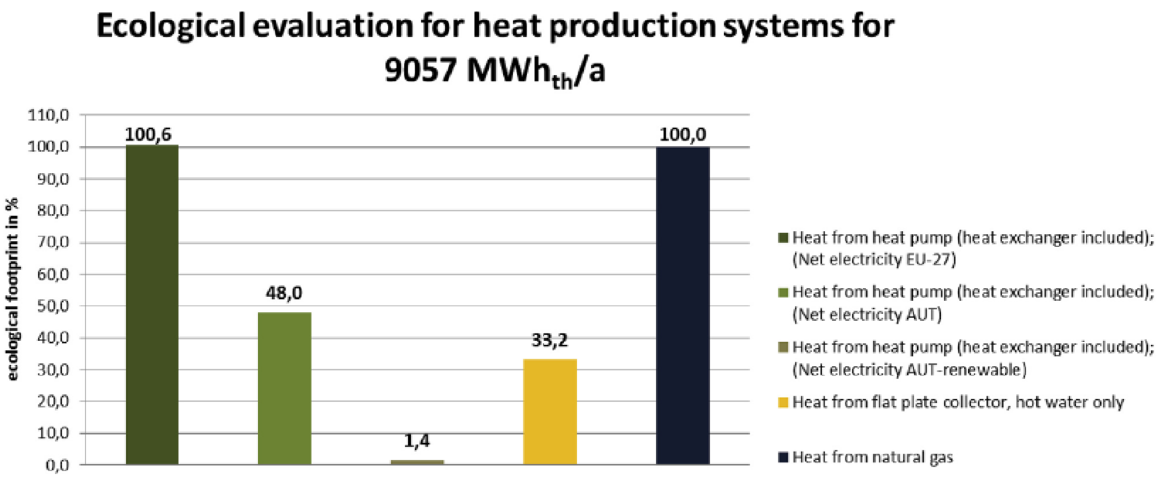


Figure 7 – Ecological evaluation for different heat production systems **[2]**

The heat pump driven by the EU mix generates roughly the same ecological footprint as thermal heat produced by using natural gas. An ecologically friendlier option is to use heat pumps with an average Austrian electricity mix or even better heat generated from solar heat collectors. By far the most sustainable option to produce the heat demand of 9057MWhth/a is using a wastewater heat pump supplied by electricity from renewable resources only. In result ecological footprint reduction is almost 99% in case of using mentioned process instead of run by natural gas. [2]

From the description above and Figure 7 it is possible to define that without another source of renewable electricity the heat pumps and heat exchanger are not ecologically friendly.

3.1.8 Economic consequences

Using local sources, as a heat from wastewater, of energy supplies support concept of smart energy system. Smart energy system leads to energy self-sufficiency. Nowadays energetic concept is without local control, unsustainable and based on fossil sources import or centrally produced energy import. Energy import caused drain on the budget. Heat from wastewater as a local energy source can reduce the energy import and lead to energy self-sufficiency.

As it is already mentioned in chapter 3.1.3, at least 10000-15000 residents should be connected upstream of the heat exchanger to ensure economic efficiency.

3.2 Selection of suitable heat recovery site

3.2.1 Heat recovery design parameters

The design parameters of heat recovery systems are: theoretically available heat (the flow rate and the temperature of wastewater, the temperature difference of the wastewater upstream and downstream of the heat exchanger), the geometry of the pipe (sewer diameter) , geometry of the heat exchanger, the viscosity of the wastewater, the velocity of the fluids in the heat exchanger, hydraulic conditions in sewer system, the fouling resistance caused by the formation of biofilm, the heat exchange coefficient and the heat transfer surface. [31] [5]

According to [17] there are the minimum requirements for this form of energy recovery to be factual: more than 10 l/s and a temperature above 10°C – 15 °C. What is more minimal sewer pipe diameter has to be 800 mm for an additional heat exchanger installation and 400 mm for prefabricated pipes. Wastewater flow velocity should be higher than 1 $m.s^{-1}$ this is because of the formation of biofilm on the wall of the heat exchanger. The biofilm leads to reduction of the efficiency of the heat exchange.

If we assume that the wastewater temperature do not decrease below 10 °C, the recovery heat wastewater potential is much higher than ground, air or groundwater heat potential, because in these cases the temperature of the heat resource is much lower.

The quantity of the theoretically available heat that can be recovered from sewer systems with heat exchangers is very large. As can be seen at calculation under, 1.16 kWh can be recovered if the temperature of 1 $m^3 \approx$ 1000kg of wastewater is changed by 1 K.

$$Q = c.m.\mathit{\Delta} t$$

$$Q - heat\ potential\ [kJ]$$

$$c - specific\ heat, c_{water} = 4.18\ {}^{kJ}\!/_{kg.°C}$$

$$m - mass\ [kg], m = 1000\ kg$$

$$\mathit{\Delta} t - change\ in\ temperature, \mathit{\Delta} t = 1°C$$

$$Q = 4.18 * 1000 * 1 = 4180\ kJ$$

$$1kWh = 3600kJ$$

$$Q = \frac{4180}{3600} = \boldsymbol{1.16kWh}$$

This calculation does not include losses; it is theoretical heat energy potential. The final heat potential is lower due to transport losses and thermal overdoses.

3.2.2 Potential energy consumers

There are many options where is possible to use the heat energy. The most common are space and water heating and cooling for the building sector in settlement areas. If there is no settlement area nearby the heat source, other options are considered. There are heating and cooling demands in forestry and agriculture. Thermal energy from wastewater can be applied in agriculture and forestry for dewatering as well as heating and cooling purposes.

Dewatering of agricultural and forest products can be considered. Wood chips, crops and spice plant can be dewatering. These processes represent heat sinks with heating requirements over varying periods. Whereas dewatering of wood chips can be carried out throughout the year, crops and spice plant drying are limited in time depending on harvesting dates. Another agricultural heat use, which can be considered is heating and cooling of barns or heating of greenhouses. Thermal energy from wastewater can provide the basic load for the heating system of greenhouses. Heating demand also exist e.g. in piglet breeding and poultry farming. Even more special is heat demand in aquaculture. Recirculation aquaculture systems feature heating demands depending on the kind of breed species (e.g. fish, micro-algae) and their temperature requirements. [32]

3.3 Wastewater discharge and temperature data

Two different types of sewer system are distinguished. Combined sewer systems collect storm water and wastewater from households and industries together in one single pipe system. Separated sewer systems on the other hand comprise two pipe systems: storm water and wastewater networks (sanitary sewers). To eliminate influences from storm water runoff on the wastewater discharge and temperature in combined systems, only days with dry weather are analysed. [31].

According to [12] days with elevated flow rates are excluded from the analysis to avoid distortion of results due to the influence of precipitation. Usually an increase in wastewater discharge rate, because of the raining event, leads to a consequent decrease of wastewater temperature. Another distortion of results could be caused by snow melting. It is a bit complicated to identify the days when the snow was melting. Therefore the days when the snow was melting were left as a part of analysis. Only a few days were identified as snow melting days, when the discharge was much higher and the temperature much lower in contrast with the other days.

3.4 Predicting of wastewater temperature development in sewer system

3.4.1 SQUID

Usually it is not well described how exactly the wastewater temperature in sewer system is changing during the transport to the wastewater treatment plant. The new easy technology named SQUID could easily reveal what exactly is happening in the sewers.

SQUID is a small floatable sensor platform in other words, sewer ball. The sewer ball consists of sensor which are measuring and recording: pH, temperature, redox and electrical conductivity. In the case of the wastewater heat recovery the most interesting is the temperature sensor. The temperature is measured with a PT1000 thermometer. The measurement range lies between about 0.5°C to 65°C.

3.4.2 Wastewater temperature predicting models

There are a few theories predicting wastewater temperature in sewer systems. In the case of the in sewer heat exchangers is important to define how the wastewater temperature will develop after cooling in the heat exchanger. It is important at the point of wastewater treatment plant. The wastewater temperature at entry to the wastewater treatment plant should never drop under values between 10°C. The reason is described in detail in chapter 3.1.7. Therefore if the wastewater in heat exchanger is cooled below this value it is important to see if there is a possibility for wastewater reheating from ambient conditions in sewer system.

For example [8] suggest using simply method called Alligation alternate. Based on easy equation it is possible to dedicate the wastewater temperature at the WWTP inflow. 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. [25]

Simple model discovered by Abdel-Aal et al is a bit more sophisticated. The model consists of energy balance equations between in-sewer air and wastewater, as well as wastewater and the surrounding soil [33]

Modelling software named TEMPEST is much more sophisticate and applicable. The interactive simulation program TEMPEST (temperature estimation) has been developed to calculate the dynamics and longitudinal spatial profiles of the wastewater temperature in the sewer. The program is based on a new model of the heat balance in sewers and for a summary of the model equations see. Applications range from simple steady state estimates of the changes of the wastewater temperature in a single sewer line to full scale simulations of the dynamics of the wastewater temperature in successive sewer lines with lateral inflows. [34] . Within this thesis the TEMPEST software will be applied. The possibility of wastewater reheating after leaving the heat exchanger will be modelled within the case study in sewer system in Hradec Králové.

[35] used the TEMPEST software for modelling the wastewater temperature development due to wastewater discharge Q = 0.04m^3/s. cooling down to 5°C. Favourable and unfavourable conditions in sewer system for wastewater temperature reheating were simulated. Favourable conditions: reinforced concrete pipe, saturated sandy soil, soil temperature 12 °C. Unfavourable conditions: concrete pipe, not saturated clay, clay temperature 8 °C.

Result in favourable conditions are the temperature after 2,5 km increase from 5 °C to 6,5 °C and after 10 km to 10 °C. Quite contrary in unfavourable conditions the wastewater temperature reheating is much slower and lower after 10 km wastewater is reheated from 5°C to 5,25 °C.

Same temperature predicting will be applied in the Hradec Králové case study. Wastewater in three different sewers is cooled and mixed in one main sewer. After mixing the wastewater reheating will be modelled and observed.

4 Material and methods

The thesis considers more interrelated topics. The first part of the study focuses on the spatial and temporal data analysis of wastewater discharge and temperature in Hradec Králové sewer system. The second part deals with the possibility of SQUID application for wastewater temperature development predicting. The third part is interconnection of results from the previous researches from BOKU and ČVUT and their extension. The final part is about the evaluation of potential impact of the heat exchanger installation on the wastewater treatment process. The potential impact is validating by the wastewater temperature predicting model TEMPEST.

4.1 Process of the selection of suitable heat recovery site

The basic prerequisites for the suitability of in-sewer heat recovery are existing heat demand and available heat potential.

[12] defined key methodological steps to evaluate the suitability of heat recovery site in a sewer system.

- Preselection of a suitable heat recovery site:
    - Identification of a potential heat customer
    - Identification of a suitable heat recovery site
- Processing of wastewater discharge and temperature data
    - Collecting of wastewater discharge and temperature data
    - Preparation of collected wastewater discharge and temperature data
- Assessment of the potential heat recovery site
    - Estimation of the available heat potential
    - Estimation of the potential impact on WWTP inflow temperature
- Decision making
    - Comparison of heat demand and heat supply
    - Appraisal of the potential impact on WWTP inflow temperature

The following chapters are built up on the scheme mentioned above. Each of the methodological steps are described in chapters Material and methods and Results and discussion. Some of the steps were done in previous research the rest was created as a part of this thesis. The results from previous researches will be verified and together with my new findings are giving a comprehensive view on potential of using the wastewater as an energy resource in Hradec Králové.

4.2 Preselection of a potential heat recovery site

Suitable heat consuming buildings are selected according to following criteria: owner, proximity to suitable sewer and heat utilisation. For selected buildings a heat pump system is designed and capital expenditures and operational costs are calculated [36].

Based on above mentioned criteria [37] defined the sewer sections in Hradec Králové suitable for heat exchangers installations. They are displayed in Figure 8.

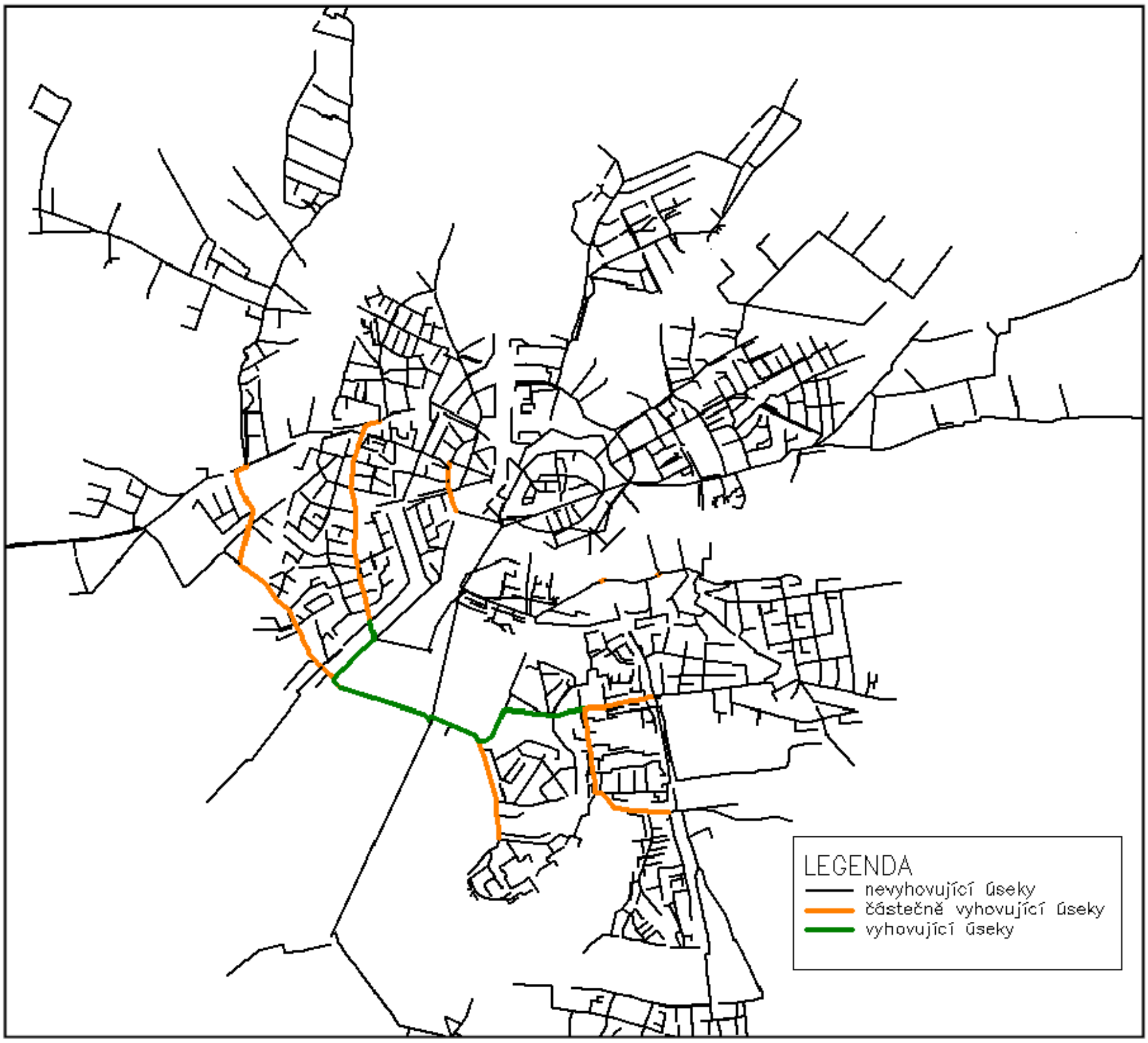


Figure 8 – Scheme of Hradec Králové sewer system with highlighted sections suitable for heat exchanger installations **[38]**

In Figure 8 the sewer sections suitable for heat exchanger installations are highlighted in green and partly suitable sewer sections are highlighted in orange.

Among others in the framework of this master thesis the proposal suitable sections are going to be verified and new suggestions for suitable sewer sections will be suggested.

4.2.1 Criteria influencing the preselection of suitable heat recovery site

4.2.1.1 Theoretically available heat

Theoretical available heat in the individual sewer system can be calculated as:

$$W_{WT} = c * \rho * Q * \Delta T$$

$c - specific\ heat\ capacity\ of\ wastewater$
$(for\ waste\ water\ 0 - 20°C\ the\ value\ is\ 4{,}19\ {}^{kWs}/_{kg\ *\ °C})$

$\rho - wastewater\ density\ (for\ watewater\ 0 - 20°C\ the\ value\ is\ 1\ {}^{kg}/_{l})$

$Q - wastewater\ discharge\ \left({}^{l}/_{s}\right)$

$\Delta T - the\ difference\ between\ temperaturesupstream\ T1\ (°C) and$
$downstream\ T2\ (°C) orf\ the\ heat\ exchanger$

4.2.1.2 Sewer diameter

This criteria takes into account the possibility of the installation of the heat exchanger and its accessibility for the maintenance and biofilm removal.

4.2.1.3 Hydraulic conditions (hydraulic capacity of the sewer, pressurized flow)

Heat exchanger should not substantially decrease the hydraulic capacity of the sewer and should not be installed in overloaded sewers.

4.3 Processing of wastewater discharge and wastewater temperature (data analysis)

4.3.1 Area and measuring campaign description

The data used for the analysis and evaluation are taken from measuring campaign conducted between March 2013 and February 2014 as part of research project Acquisition of thermal energy from sewage water in sewerage networks, TACR (technological agency of Czech Republic). The wastewater discharge and wastewater temperature were measured in the city of Hradec Králové during the medium-term monitoring campaign. City of Hradec Králové is drained by the combined sewer system. Combined sewer systems are sewers that are collecting rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. Sewer system in Hradec Králové is divided into eight catchment areas (A, 1A, B, C, 1C, D, E, F and those are drained by 8 trunk sewers. In seven of them the wastewater discharge and wastewater temperature were measured. Catchment area F is aside from all the others and is not drained by a main sewer. No measuring was carried in catchment area F, but there is known average wastewater temperature and discharge. In the cases of all the other catchment areas, the measurement tool was always installed to the closure profile of each catchment area. This is schematically displayed in the Figure 9. Wastewater from each catchment area is brought to main sewer collector and then drains away to the wastewater treatment plant.

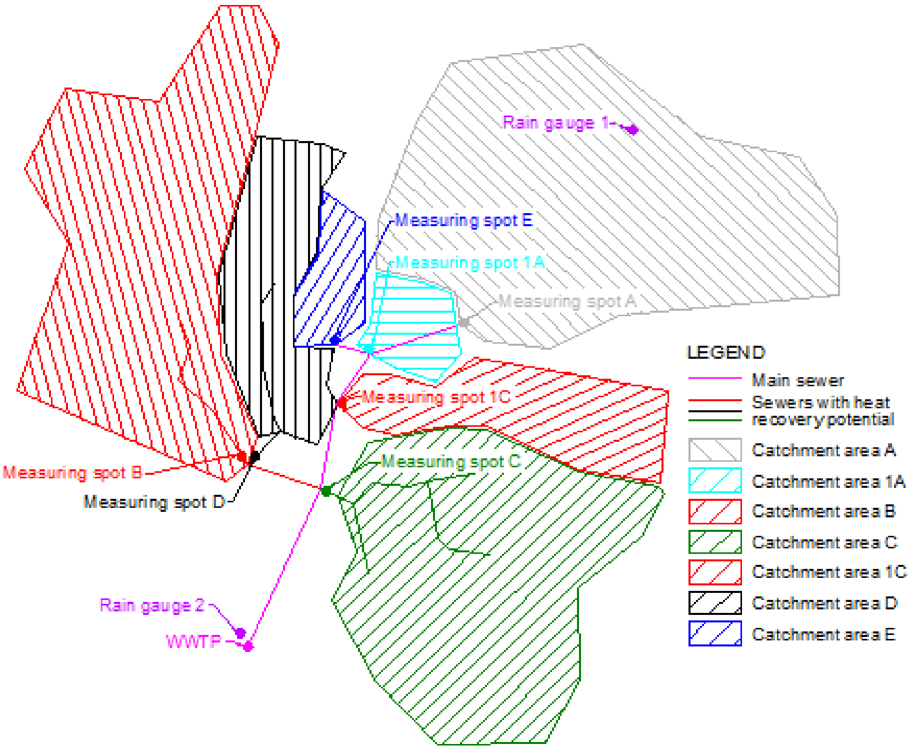


Figure 9 – Scheme of Hradec Králové urban drainage system

It can be also observed from Figure 9 that not only information about wastewater has been measured. Two rain gauges have been installed as well for dry weather day be detected. Rainy days are excluded from the analysis because rainy days are not a normal operating state. This is detailly described in chapter 3.3. In this thesis temperature and discharge data from 7 measuring sites and data from wastewater treatment plant will be analysed.

4.3.2 *Monitoring process description*

In this chapter the measuring sites and measuring tools will be described. In seven closure profiles different measuring tools for measuring temperature, flow or wastewater level have being installed. Measurement was supplied with two rain gauges and the data from WWTP were provided by Královéhradecká provozní a.s.

At approximately one-month intervals the measuring sites and measuring tools have being controlled and collected data have being downloaded. Downloaded data are raw data. In case of wastewater level and discharge, in each measuring site the calibration was necessary.

What is more during each control processes the temperature sensors have being cleaned and reference temperature has being measured each month at each measuring site. Temperatures before cleaning, after cleaning and temperatures from reference measuring were compared. Based on this, the temperature drift has been described. And raw data from temperature sensors have being adapted. The temperature modification based on temperature compares was necessary at measuring spot C. Data from measuring site 1C were excluded from analysis. Values from thermometer which has been installed at measuring site 1C did not correspond with the reference values at all. Raw values from all the other measuring spots were same as values from reference measuring and can be considered as responsible.

4.3.3 *Data preparation*

4.3.3.1 *Rainfall data*

In order to eliminate the influence of rainwater temperature on wastewater temperature only days with dry weather flow were used for further analysis. Two rain gauges were used to identify the rainy days. Afterwards the rainy days are excluded from temporal and spatial analysis. Days when at least one of the rain gauges recorded precipitation higher than 1 mm are considered as rainy days.

4.3.3.2 *Temperature data*

Temperature raw data are compared with the reference measuring values. Except measuring site C and 1C all the other measured values (from A, 1A, B, D, E) are corresponding with the reference values. Temperature data from wastewater treatment plant are provided by WWTP operator.

Temperature differences from reference measurement have been recorded during each terrain control by reference thermometer at all the measuring sites. The terrain control has being done approximately in one month intervals. Except the measuring site C and 1C, all the results correspond with the reference measurements.

In the case of measuring site C the temperature differences were not so big and it was possible to define the right value. It is important to mention that the temperature differences were a bit different in every control day. For example temperature recorded at measuring spot C 2.1.2014 was the same - 15,9 °C - before and after the temperature sensor cleaning, but reference temperature was 14,1 °C in the same day. The recorded temperature between 21.12.2013 and 20.1.2014 had to be lowered by 1,8 °C. The recorded temperature before 21.12.2013 and after 20.1.2014 had to be adapted by reference measuring from 9.12.2013 respectively 7.2.2014. The same operation has been done through observed period.

In case of thermometer 1C the measured and reference values were different and there is not possible to find any trend between measured and reference values. Thus the temperature results from measuring site 1C are excluded from the data analysis.

4.3.3.3 Discharge data

At measuring sites, where only the wastewater level has being measured, the reference discharge measuring was necessary. There were two discharge calibration methods applied. At measuring site where the wastewater level was high enough the hydrometric flow measurement has been applied. In cases, where the hydrometric method was not possible, the tracer method substituted.

Based on results from measuring methods described above and known geometry of the sewer the reference manning factor was calculated. Manning factor was calculated from Cheesy equation. This is the case when only wastewater level was measured.

In cases where beside the wastewater level the waste water velocity was measured as well, discharge was calculated from continuity equation. From known geometry of the sewer and measured wastewater level is possible to calculate the discharge cross-sectional area.

Based on those measured and calculated values the measuring were calibrated and raw data transferred to real discharges.

4.4 Predicting and description of wastewater temperature in sewers – TEMPEST mathematical modelling

4.4.1 TEMPEST

TEMPEST is in-sewer wastewater temperature predicting model. It consists of balance equations for mass, heat and momentum for sewer lines. 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. Based on this, a plenty of input data are needed for the model. Concretely there are 27 values behind the model such as: Soil thermal diffusivity, soli density, Friction coefficient of the pipe, air hydraulic radius, reaction enthalpy,… When the software tool is applied the amount of input data decreases drastically to 15 parameters. The rest of the values are included as default values in the computer application or calculated through other parameters. Parameters which are necessary to know about the modelled sewer 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. [34]

4.4.2 SQUID

SQUID is a small floatable sensor platform in other words, sewer ball. The sewer ball consists of sensor which are measuring and recording: pH, temperature, redox and electrical conductivity. SQUID was developed in Switzerland in year 2017 and it was my pleasure to be one of the first persons using and testing the SQUID.

Firs necessary step was to calibrate all the SQUID sensors (temperature sensor, pH sensor, OPR sensor and sensor for measuring Electrical conductivity).

The most valuable measured physical quantity for my thesis is the temperature. The temperature sensor has been calibrated and also the SQUID has been tried within field testing. Based on the SQUID measurements the hot spots in sewer system can be identified and the preselection of potential heat recovery sites can be specified.

5 Results and discussion

5.1 Preselection of a potential heat recovery site

5.1.1 SQUID – device testing and possibility of application

As a first step for preselection of potential heat recovery site could be use of the SQUID. SQUID is displayed in Figure 10

From the temperature development is possible to define the spots with higher temperatures and with higher potential for heat exchanger installations. Therefore SQUID could be used as a preselection tool for marking sections with higher heat potential. What is more the SQUID could be used for calibration and verification of the TEMPEST model results. This possibility is described in chapter 5.4.2.4

One part of my thesis is about the SQUID device testing. Summary of the results is described in this chapter. Testing was divided into two main parts. First was about laboratory testing and calibration and second was about field testing.

Figure 10 – SQUID during the laboratory testing and calibration. (SQUID is just the ball in the beaker)

5.1.1.1 Temperature calibration curve – laboratory testing

Experimental run 1

Experimental setup:

Date: 07.11.2017

Duration: 45 minutes

Reference sensor: Metrohm Titrando 808 with PT1000

Goal: Definition of temperature calibration curve

Sample: Tempered tap water (drinking water)

Method: Sample was gradually warmed up by adding warm water with a temperature of about 50°C. After each addition the sample was thoroughly mixed and measured. Thirteen reference points within the temperature range from 8 to 44°C were used for SQUID temperature calibration.

Results

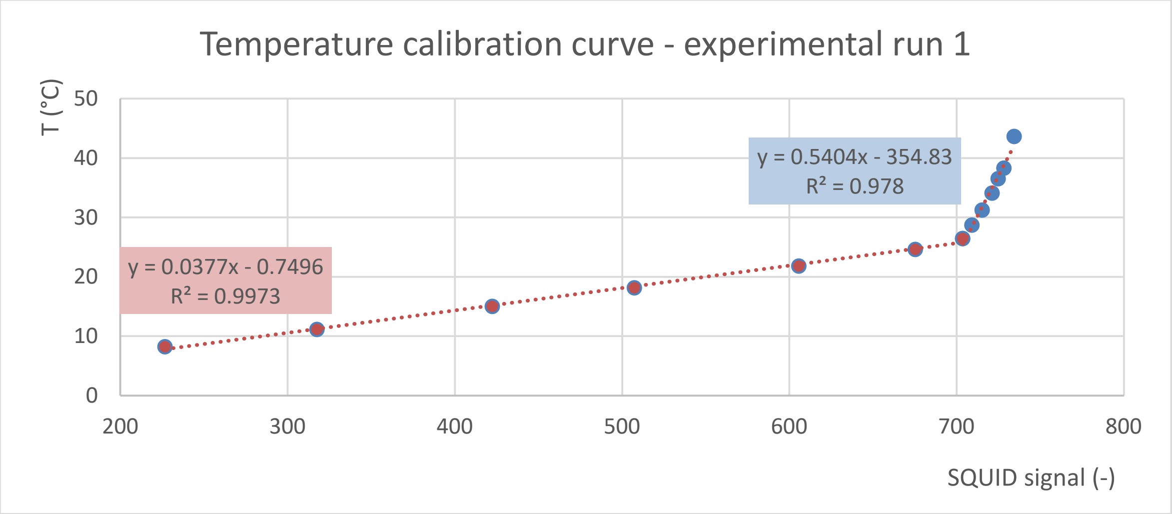


Figure 11 – The result of the temperature calibration

Observations

The experiment provided a well-defined linear correlation between SQUID and reference measurement, but two different calibration functions are observed, one for temperatures up to 25°C and another one for 25-45°C. The correlation coefficient can be considered very satisfying in both cases ($R^2 \geq 0{,}98$).

Experimental run 2

Experimental setup

Date: 09.11.2017

Duration: 1 hour 30 minutes

Reference sensor: WTW Multi 3430 with temperature sensor PT100 (due to higher capacity for data storage)

Goal: verify the results from experimental run 1

Sample: Tempered tap water (drinking water)

Method: An electrical heater was used to heat the sample. The experiment started with a water temperature of 7°C and finally a temperature close to 50°C was reached. The reference sensor was set-up to measure and store data in 10 seconds step (same as SQUID).

Results

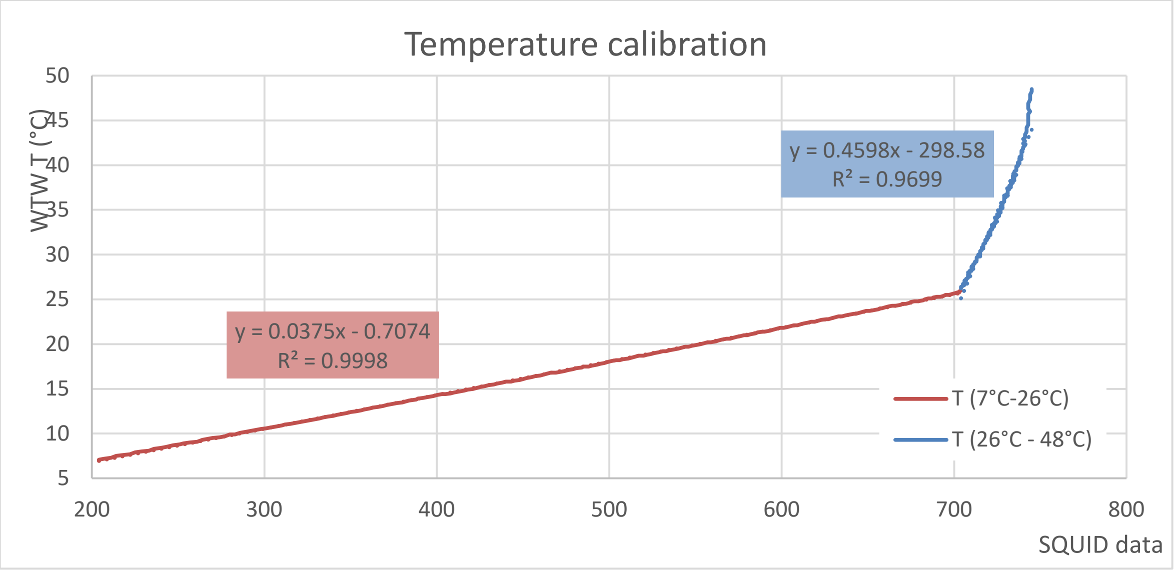


Figure 12 – Second experiment of temperature calibration

Observations

The results from first experimental run could be reproduced. The first calibration curve covers the range up to 26°C, the second the one from 26°C to 48°C. Calibration functions from 7 to 26°C from experimental run no.1 and experimental run no.2 are very similar. Small deviations between experimental run no.1 and no.2 can be observed for the calibration functions from 26 to 48°C.

Experimental run 3

Experimental setup

Date: 09.11.2017

Duration: 10,5 hours

Reference sensor: WTW Multi 3430 pH sensor with temperature compensation

Goal: Verify the calibration curve and test SQUID in loger time trial

Sample: 6 °C tempered tap water (drinking water)

Method: The experiment is performed at room temperature (SQUID and reference sensor was permanently submerged in the sample solution). Reference sensor (WTW) was set up to measure and store data in 10 seconds steps (same as SQUID).

Results

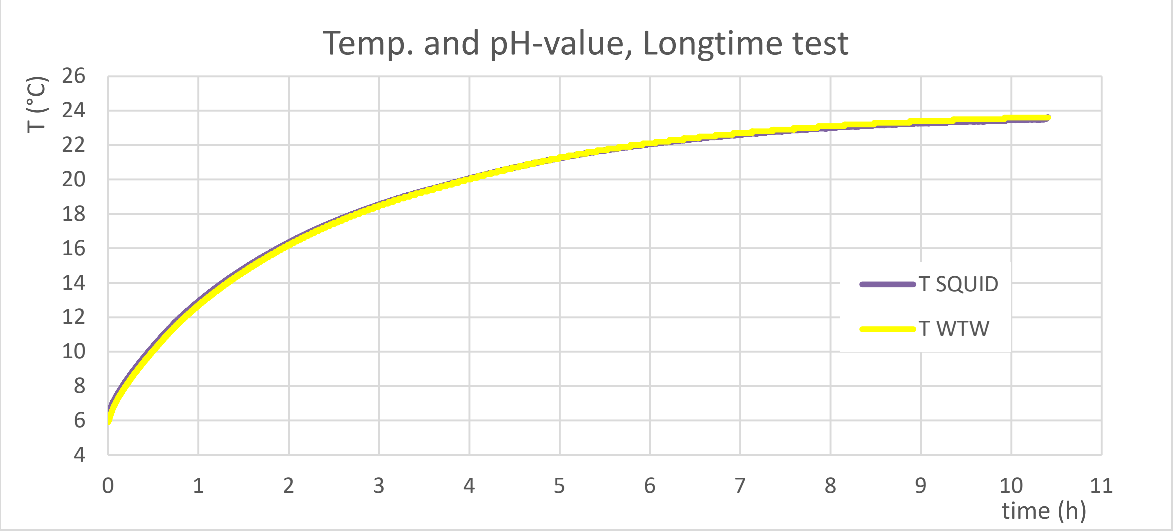


Figure 13 – Long-time SQUID test and temperature calibration verification

Observations

Sample temperature constantly aligns with room temperature. In the process, both temperature curves remain almost congruent. This seems to prove the accuracy of the calibration curve from temperature trials. However, sample temperature remained below 26°C, so that only one of the temperature calibrations curves was relevant for this measurement. Anyway it is not expected that the wastewater temperature in sewer system will be higher than 26 °C and therefore the calibration curve supposed to be sufficient.

5.1.1.2 Field testing

Introduction

Aim of field trial: Observation of SQUID performance (sensors, practical handling) under in-sewer wastewater flow conditions
Location: Main collector of a combined sewer system in an Austrian rural area (dominance of residential wastewater)
Testing date: 29.11.2017
Reference measurement: WTW Multi 3430
Wastewater level and flow measurement: Nivus PCM Pro
Method: Three experimental runs were carried out during the field testing. SQUID's deployment points in the sewer system were two different pre-defined manholes, collection point was at the inflow of the related wastewater treatment plant (WWTP). For the first trial SQUID was placed in a manhole only 110 m upstream of the WWTP. For the second and third trial a manhole at a distance of about 1.117 m upstream of the WWTP was chosen.
Weather conditions: Air temperature during the trials was around 5 °C. In the morning light rain, during the trials no precipitation occurred (consequently, dry weather flow conditions could be assumed).

Experimental run 1

Experimental setup

Trial 1 was a short distance test run.
Trial duration: 13:53 - 13:55 (duration: 110 sec)
Manhole A description:
- Distance to WWTP: 110 m
- Sewer cross-section DN 1100
- Manhole depth: 1,65 m
- Wastewater flow: 160 l.s-1
- Flow velocity: 0,7 m.s-1
- Wastewater level: 0,29 m

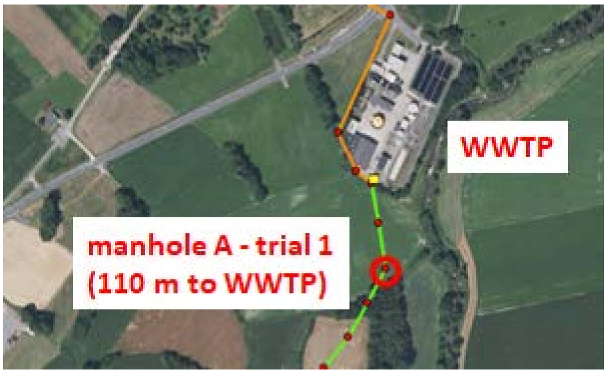


Figure 14 – Overview of experimental run 1

Results

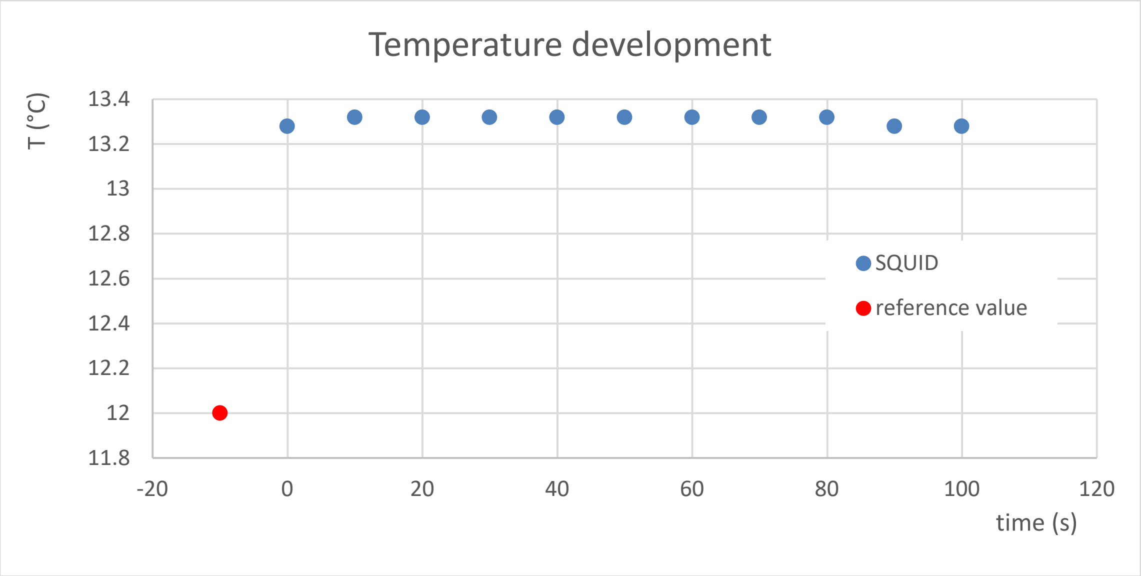


Figure 15 – Wastewater temperature development – experimental run 1

As it can be seen in Fig. 3, wastewater temperature remains relatively constant around 13,3 °C along the flow path. Although lab testing provided a very promising correlation between SQUID and reference temperature measurements, the field testing difference between SQUID and reference values is around 1,3°C.

Experimental run 2

Experimental setup

After the short distance test run in trial 1, trial 2 can be considered as the actual testing of SQUID.
Trial duration: 15:06 - 15:24 (duration: 18 min)
Manhole B description:
- Distance to WWTP: 1.117 m

- Sewer cross-section Egg shaped 800/1200 (from manhole B to confluence, DN 1000 from confluence to WWTP)
- Sewer depth: 2,57 m
- Wastewater flow: 130 l.s-1
- Flow velocity: 1,1 m.s-1
- Wastewater level: 0,31 m

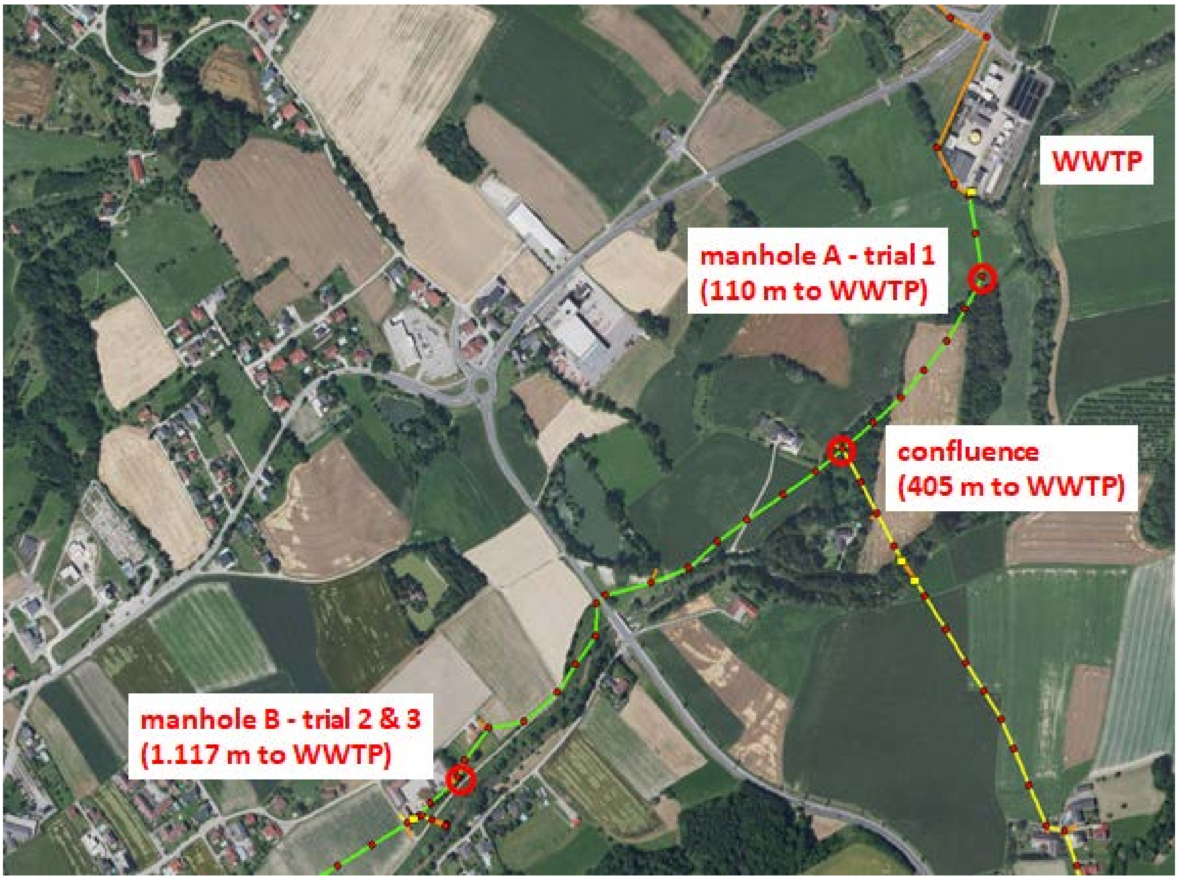


Figure 16 – Overview of experimental run 2

Results

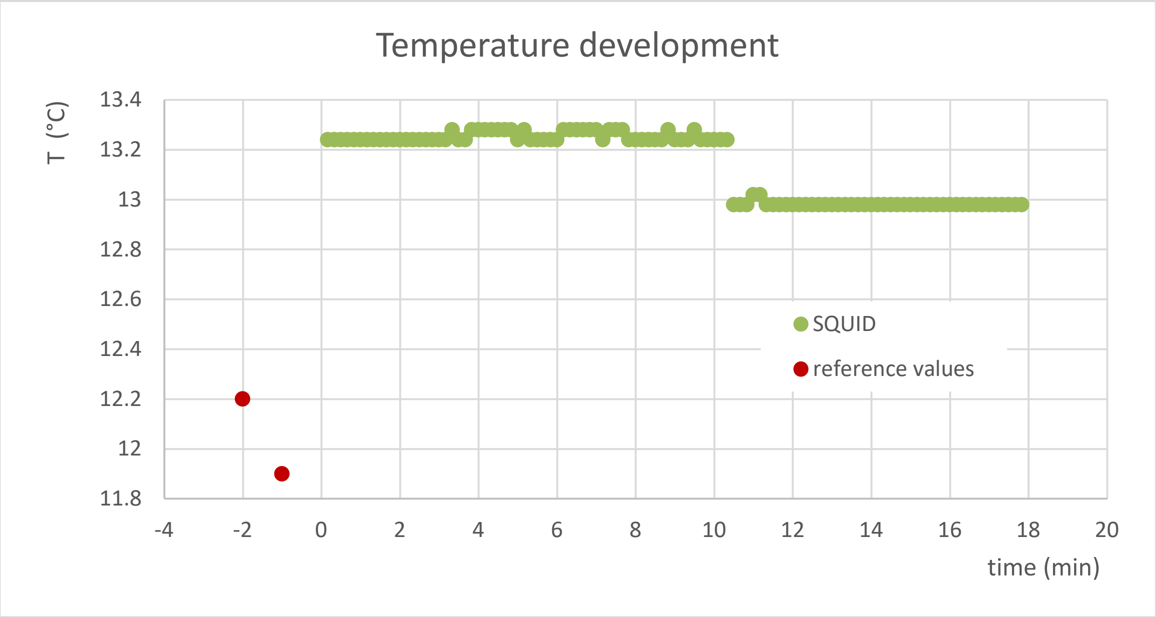


Figure 17 – Wastewater temperature development - experimental run 2

Temperature patterns in. Figure 17 remain very constant around 13,2 °C during the first ten minutes of the trial. Then a sudden drop of temperature appears, which can be explained by the confluence of a second collector at a distance of 405 m from WWTP. Afterwards the wastewater temperature again remains rather constant at the slightly lower temperature level of about 13,0 °C. The gap between SQUID measured temperature and the reference values is around 1,3 °C.

Experimental run 3

Experimental setup

Experimental run 3, was a repetition of experimental run 2 (SQUID deployment at manhole B and extraction at the inflow of the WWTP).
Trial duration: 15:44 – 16:02 (duration: 18 min)

Results

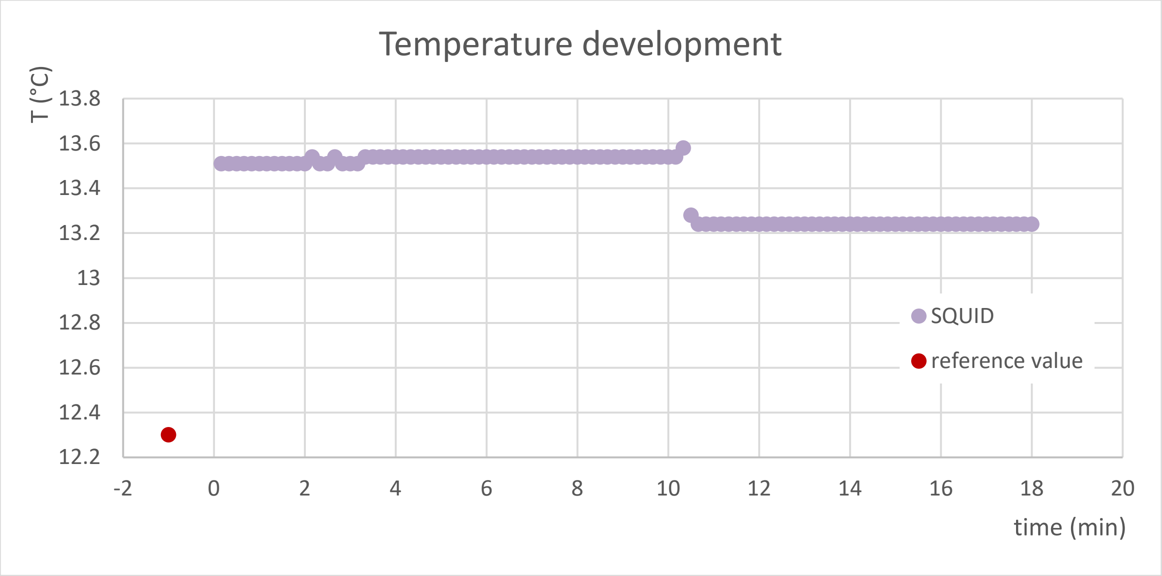


Figure 18 – Wastewater temperature development - experimental run 3

As one can see in Figure 18, the wastewater temperature remains very constant along the flow path. Before the confluence (clearly visible) it is around 13,5 °C, after it around 13,2 °C. The reference measurement made before deploying SQUID to the sewer was 12,3 °C and thus significantly lower (1,2 °C) than the values obtained with SQUID.

Temperature development comparing

In the following Figure 19 the wastewater temperature patterns of all three trials are being displayed. The reference values measured are not considered.

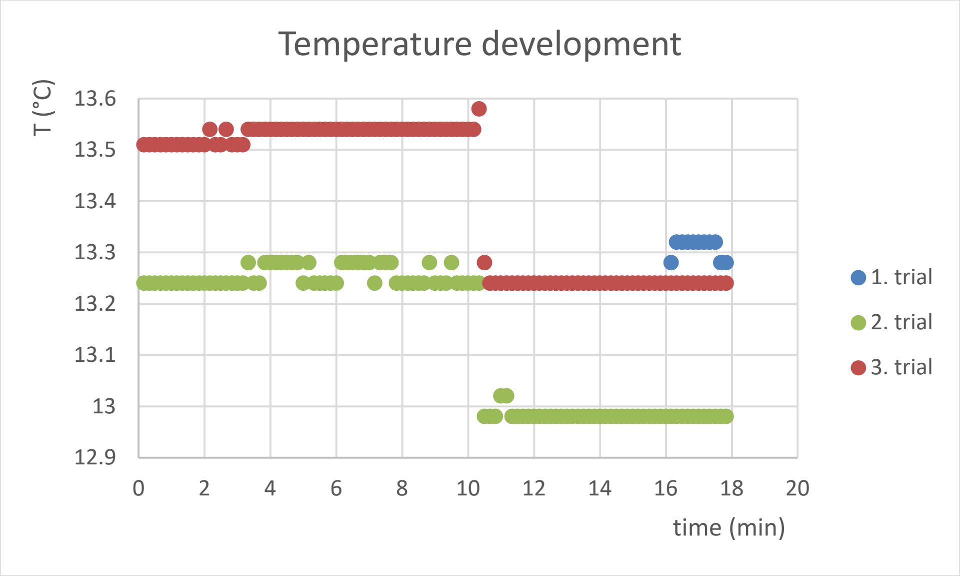


Figure 19 –Temperature development comparing

Apart from slightly different temperature levels, which can be explained by the different day times the trials took place, the patterns of trails 2 and 3 appear identical. In both trials, the confluence can be identified easily. However, despite very promising lab trials the gap between SQUID and reference temperatures is rather significant (the latter are around 1,2 °C lower) and thus not very satisfying for both trials. Otherwise, the clear detection of the confluence is a promising result.

It can also be considered as a very interesting observation, that in-sewer wastewater temperature remains constant along a flow path of more than 1.100 m.

It is obvious that the SQUID could be applied for a preselection of heat exchanger installation suitable parts of the sewer system. What is more another realistic SQUID application seems to be a verification of the mathematical modelling results.

5.2 Selection of a potential heat recovery site

5.2.1 Criteria influencing the possibility of the heat exchanger installation

The result of [36] research was the definition of sewer system sections in Hradec Králové, which are suitable or at least partly suitable for heat exchanger installation. From those result only one (east heat exchanger) from three considered heat exchangers will be judged. The other two (north and west) heat exchangers are designed to be in the main collecting sewer built approximately 25 m underground. Previous research did not think about placing heat exchanger into the main collector. All three heat exchangers are displayed in Figure 20 –

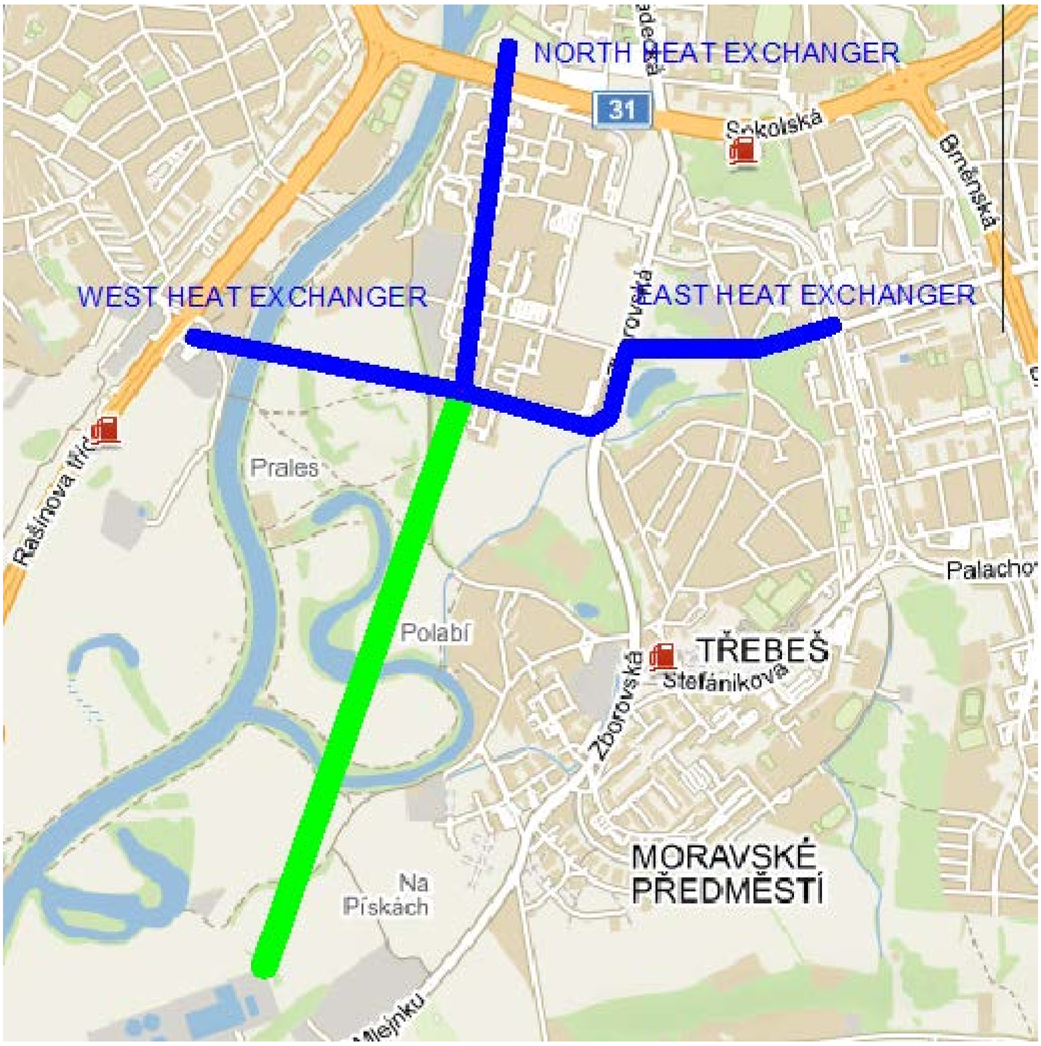


Figure 20 – Map where three considered heat exchanger are displayed. Section with cooled wastewater is represented by green colour.

5.3 Processing of wastewater discharge and temperature data

5.3.1 Collecting of wastewater discharge and temperature data

5.3.1.1 Description of individual measuring sites

Measuring spots are displayed in the Figure 9.

Measuring spot A		
Sewer type	combined	
Profile characterization	Shape	Circle, DN 1500
	Material	Concrete
Measuring tool	Wastewater discharge	Sigma 950
	Wastewater temperature	Fiedler pt100
Measured Quantities	Wastewater level, discharge and velocity	3 minutes
	Wastewater temperature	3; 6 minutes

Measuring spot 1A		
Sewer type	combined	
Profile characterization	Shape	Circle, DN 400
	Material	Concrete
Measuring tool	Wastewater discharge	Ultrasonic sensor U3000
	Wastewater temperature	Fiedler pt100
Measured Quantities	Wastewater discharge	3 minutes
	Wastewater temperature	3; 6 minutes

Measuring spot B		
Sewer type	combined	
Profile characterization	Shape	Circle, DN 1500
	Material	Concrete
Measuring tool	Wastewater discharge	Ultrasonic sensor U3000
	Wastewater temperature	Fiedler pt100
Measured Quantities	Wastewater discharge	3 minutes
	Wastewater temperature	3; 6 minutes

Measuring spot C		
Sewer type	combined	
Profile characterization	Shape	Circle, DN 2200
	Material	Concrete
Measuring tool	Wastewater discharge	Nivus – preasure and velocity sensor
	Wastewater temperature	Fiedler pt100
Measured Quantities	Wastewater level and velocity	3 minutes
	Wastewater temperature	3; 6 minutes

Measuring spot 1C		
Sewer type	combined	
Profile characterization	Shape	Circle, DN 1200
	Material	Concrete
Measuring tool	Wastewater discharge	Sigma 950
	Wastewater temperature	Fiedler pt100
Measured Quantities	Wastewater level and velocity	3 minutes
	Wastewater temperature	3; 6 minutes

Measuring spot D		
Sewer type	combined	
Profile characterization	Shape	Circle, DN 2000
	Material	Concrete
Measuring tool	Wastewater discharge	Fiedler – ultrasonic level sensor
	Wastewater temperature	Fiedler pt100
Measured Quantities	Wastewater level	3 minutes
	Wastewater temperature	3; 6 minutes

Measuring spot E		
Sewer type	combined	
Profile characterization	Shape	Crone profile (400x200)
	Material	Concrete
Measuring tool	Wastewater discharge	Fiedler – ultrasonic level sensor
	Wastewater temperature	Fiedler pt100
Measured Quantities	Wastewater level	3 minutes
	Wastewater temperature	3; 6 minutes

Measuring spot inflow to WWTP		
Measured Quantities	Discharge	1 minute
	Temperature	1 minute

Rain gauge 1		
Recording interval	No rain	1 hour
	rain	1 minute

Rain gauge 2		
Recording interval	No rain	1 hour
	rain	1 minute

Table 2 – Measuring sites and device description

5.3.1.2 *Scope of data analyzation*

Because of another source of space heating in the Hradec Králové, it is expected that the heat gained from the wastewater could be used for heating water. Despite the hot water demand is yearlong, data within period March 2013, October 2013 – February 2014 will be analysed. It is expected that those six months are the coldest. Within those months (October – March) the impact of the heat exchanger installation on the wastewater treatment plant processes will be the most significant.

5.3.2 Preparation of collected wastewater discharge and temperature data

The data analysis is based on data recorded during 182 days in March 2013, October 2013, November 2013, December 2013, January 2014 and February 2014. 38 days from 182 were excluded from the analysis because of the rainy weather or high discharge rate due to preceded precipitation.

Final analysis has being created from 144 not rainy days. At 8 measuring sites the temperature and discharge have being recorded in 1, 3 or 6 minutes steps. Based on recorded values the hourly mean values have being calculated and use for future calculations.

	October		November		December		January		February		March	
Measuring site	Q (l/s)	T (°C)	Q (l/s)	T (°C)	Q (l/s)	T (°C)	Q (l/s)	T (°C)	Q (l/s)	T (°C)	Q (l/s)	T (°C)
A	x	●	x	●	x	●	x	●	x	●	x	●
1A	x	●	x	●	x	●	x	●	x	x	x	●
B	●	●	●	●	●	●	●	●	●	●	●	●
C	●	●	●	●	●	●	●	●	●	●	●	●
1C	●	x	●	x	●	x	x	x	x	x	x	x
D	●	●	●	●	●	●	●	●	●	●	●	●
E	x	x	●	●	●	●	●	●	●	●	●	●
WWTP	●	●	●	●	●	●	●	●	●	●	●	●

● - Months and measuring sites where the data were sufficient for the data analysis.

x – Months and measuring sites where the data are not complete.

Table 3 – Summary of measuring site, where the data analysis was possible

Unfortunately the wastewater discharges data from measuring spots 1A, A and also 1C were not sufficient for data analysis. In case A and 1C the measuring tool has been destroyed during the measuring campaign and in case 1A it is not possible to calculate accurate values.

Thermometer at measuring site 1C has being tagged as unreliable. In each controlled measurement the temperature from 1C thermometer was different than value from reference measuring tool.

Other gaps in measuring are not so significant. These are caused by low battery or easily fixed problem which has being fixed within next control. This is for example gap in data at measuring site E in October.

5.3.3 *Analysis of dry weather conditions*

In this chapter will be described monthly results of the analysis. The output is the chart displaying daily temperature and discharge development during the individual moth. The presented result is after exclusion the rainy days.

Only a few charts will be presented in this chapter. All the charts are possible to find in the appendix.

5.3.3.1 *Discharge*

Figure 21 represents the mean hourly discharge of all days without precipitation in March 2013 at measuring site B. In total 27 days are displayed in this chart. Each daily curve is displayed with its own trend line. What is more the maximal and minimal discharge wrapping curves are displayed in all the charts below this paragraph. The wrapping curves represent the maximal/minimal discharge, which have being measured in a specific hour of the day. Daily and hour values are in the vicinity of an average value with a scattering of +/-10 l/s. This can be caused by snow melting or by uneven flow of infiltrated/inflow water.

Almost on each of the displayed days it is possible to define the same trend which is the best observable at the mean Q line. The similar trend can be observed in each dry weather day during the analysed time period at all the measuring sites. To demonstrate this trend Figure 22 is attached. In the Figure 22 is displayed the mean hourly discharge in March from measuring site E. When comparing those two charts the only difference is amount of the discharge. The trend lines are almost equal. This trend is not accidental. It is caused by diurnal cycle. Diurnal cycle will be detail described in chapter 5.3.3.3. Only one measuring site which does not show the same trends is displayed in the Figure 23 – Mean hourly discharge Q at WWTP in March where the measuring site at the inflow to the wastewater treatment plant is displayed. The discharge here is much higher than in other measuring sites. Also the scattering is much greater. In compares fluctuation of individual days is smaller than in other measuring sites. It is caused by different time demands to reach wastewater treatment plant. This different time demand reduces the discharge fluctuation.

Few more charts from all the measuring sites and months are displayed in the appendix. It is not necessary to display all of them, because in total it is more than 30 very similar charts.

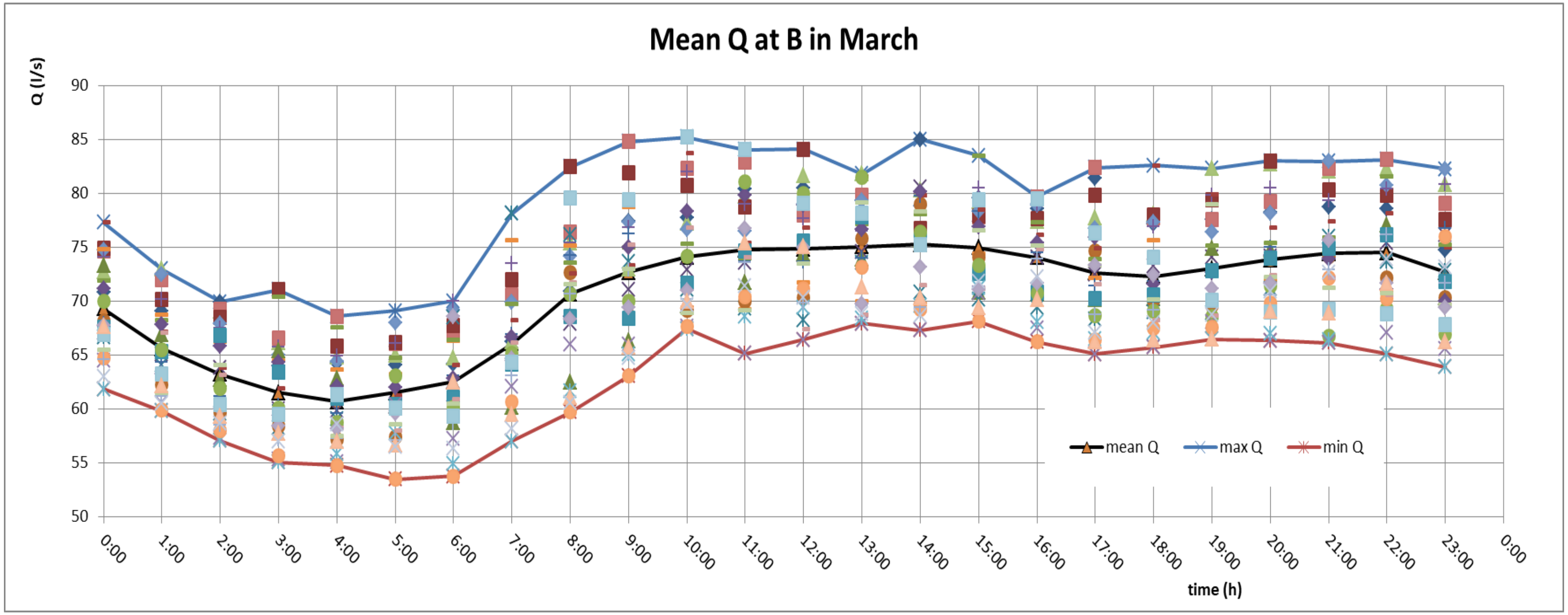


Figure 21 – Mean hourly discharge Q at measuring site B in March

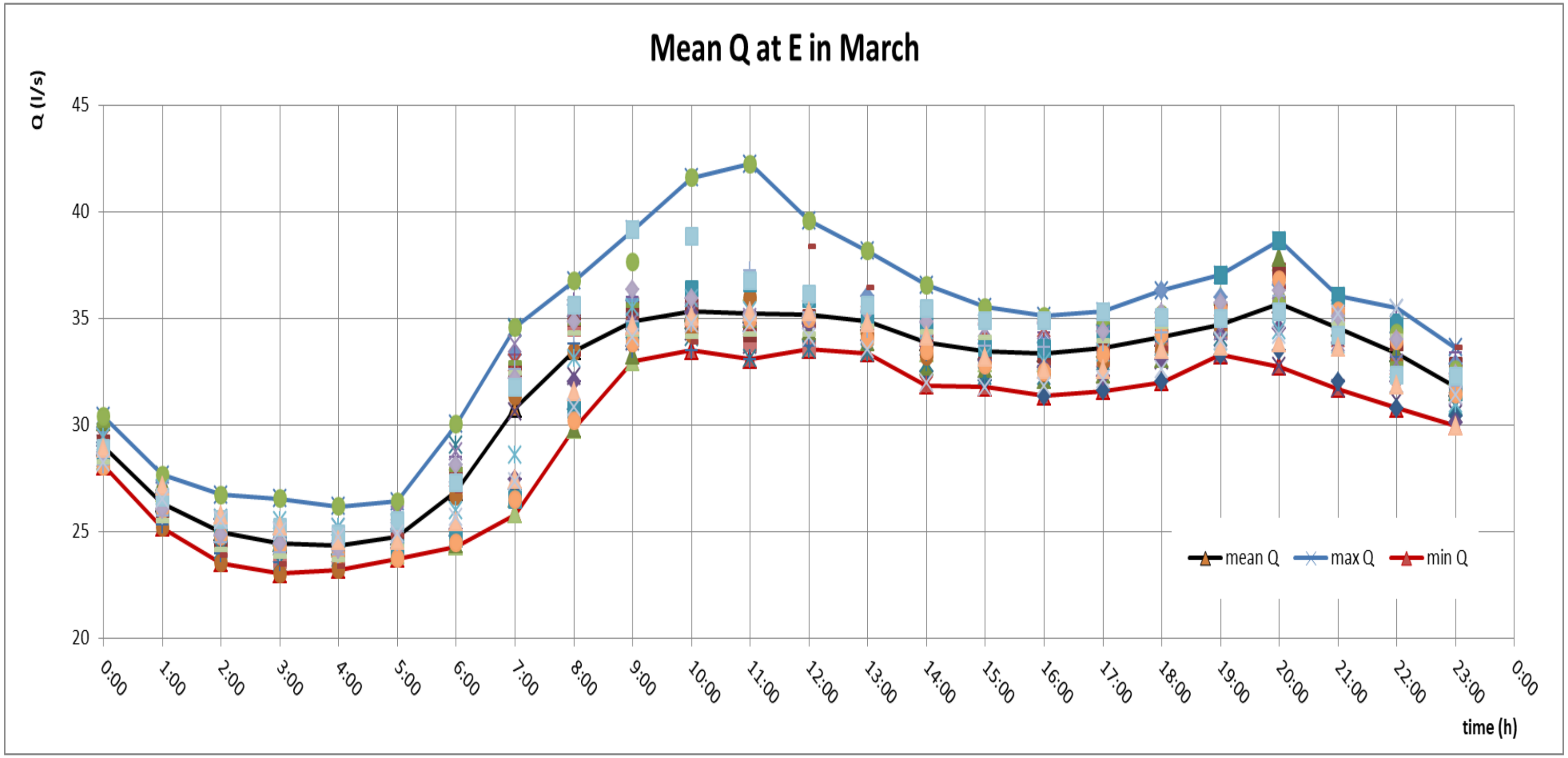


Figure 22 – Mean hourly discharge Q at measuring site E in March

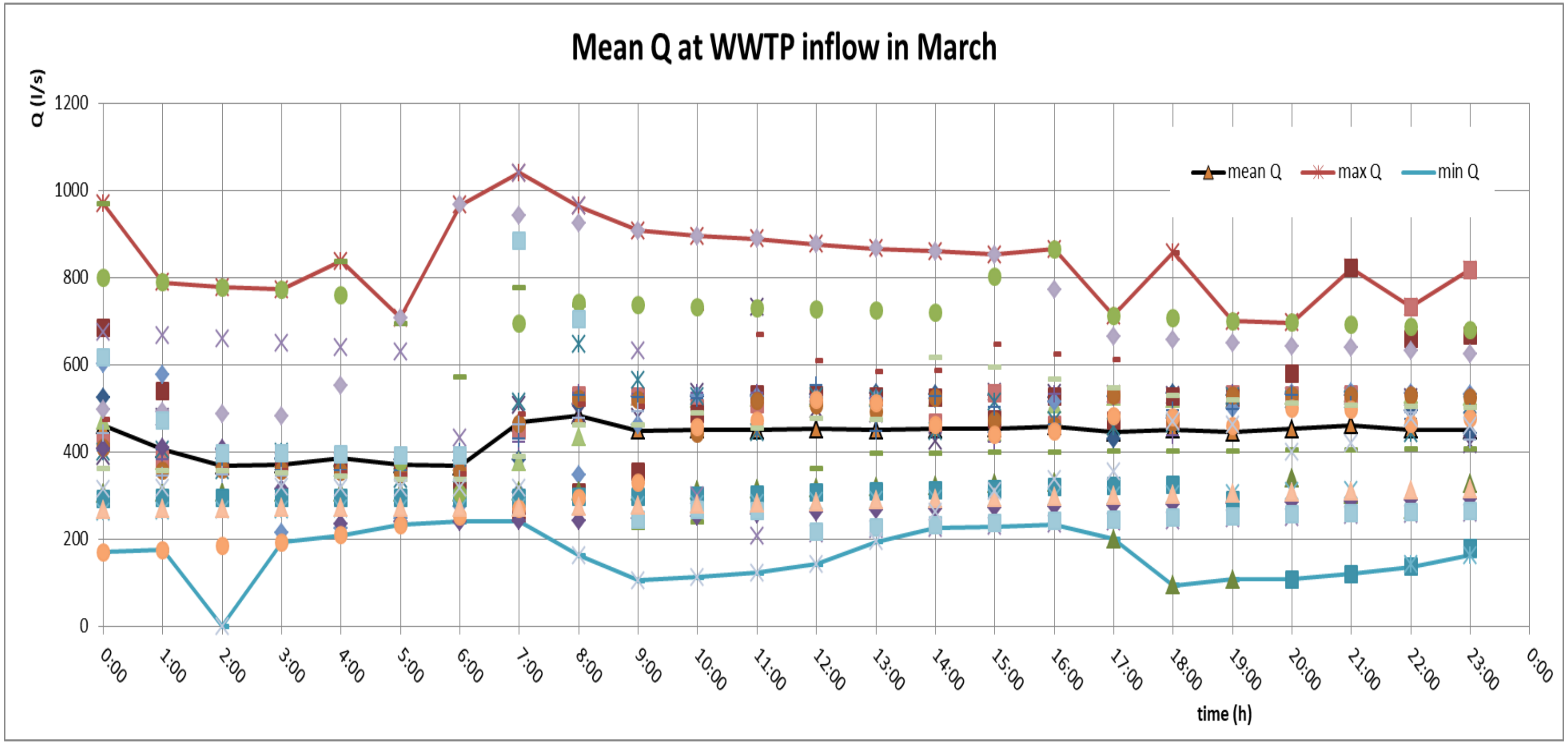


Figure 23 – Mean hourly discharge Q at WWTP in March

5.3.3.2 Temperature

In contrast to the discharge the temperature development does not represent such significant trends. Anyway it is possible to define them. Those trends can be observed between the individual months and also between the individual measuring sites. Trends in wastewater temperature are hand in hand with the trends in wastewater discharge. One trend which can be observed is that the wastewater temperature is higher in the evening. Those trends are characterized in detail in chapter 5.3.3.3.

For comparison three charts are attached: Figure 24, Figure 25, Figure 26. Those charts are displaying the daily wastewater temperature development in March at three different measuring sites. Same as in the case of discharge, the three trend lines are representing mean, maximal and minimal measured temperatures. The other trend lines are representing wastewater temperature development day by day and hour by hour.

An interesting finding is that the temperature at the same time at measuring site B displayed in Figure 24 is by 2,5 °C lower than at measuring site E displayed in Figure 25. It is probably caused by infiltration/inflow waters. Infiltration/inflow water have a lower temperature than wastewater and it could be the reason why the wastewater temperature in sewer B is cooler.

Another very interesting observation is that in all of the measuring sites: A, 1A, B, C, D, E the trend in temperature development is with minor inequalities almost similar. On the other hand the trend in temperature development at WWTP is exactly the opposite. This phenomenon can be observed in each of the analysed months. More about this will be described in the chapter 5.3.3.6.

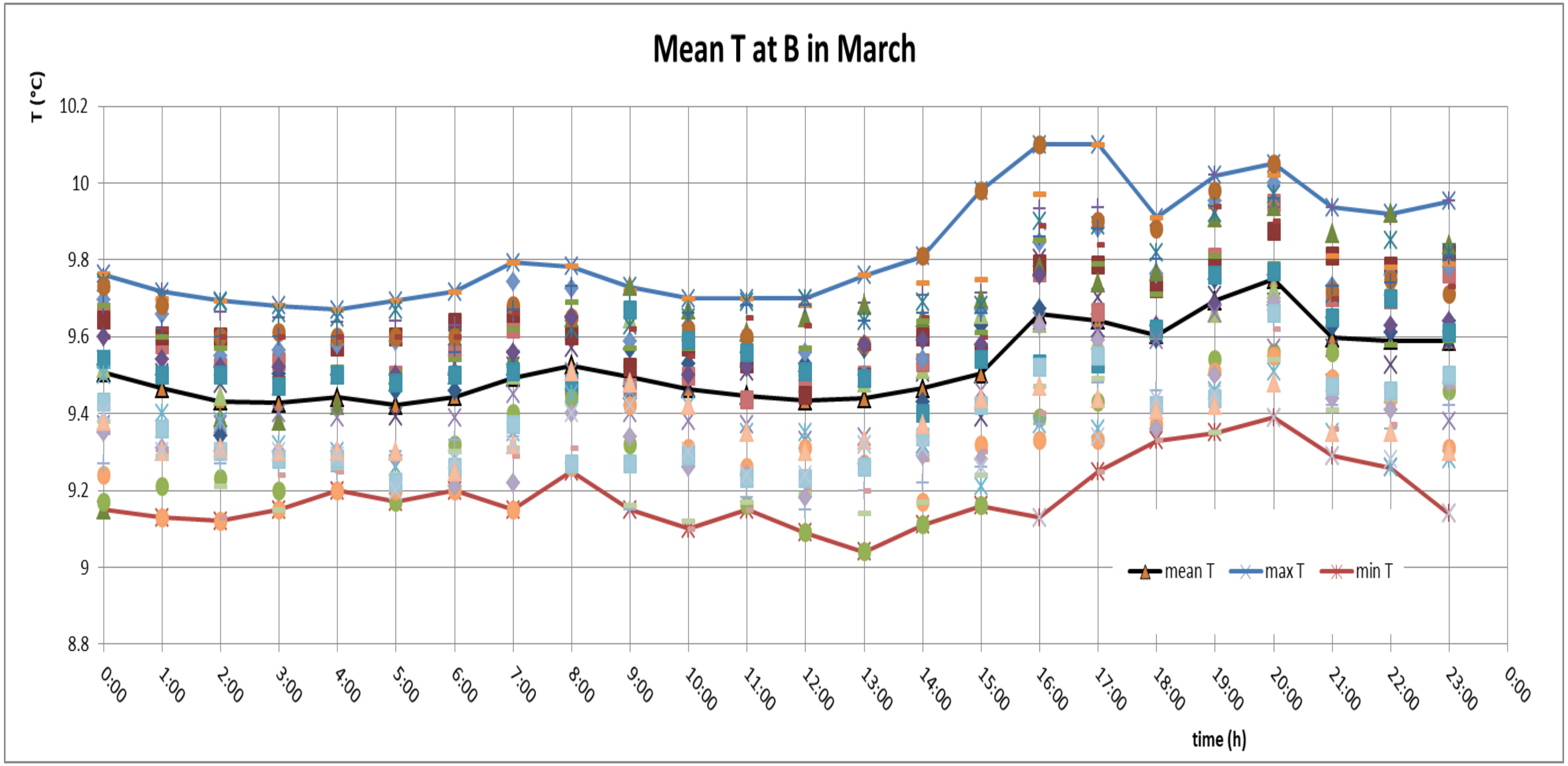


Figure 24 – Mean hourly temperature T at measuring site B in March

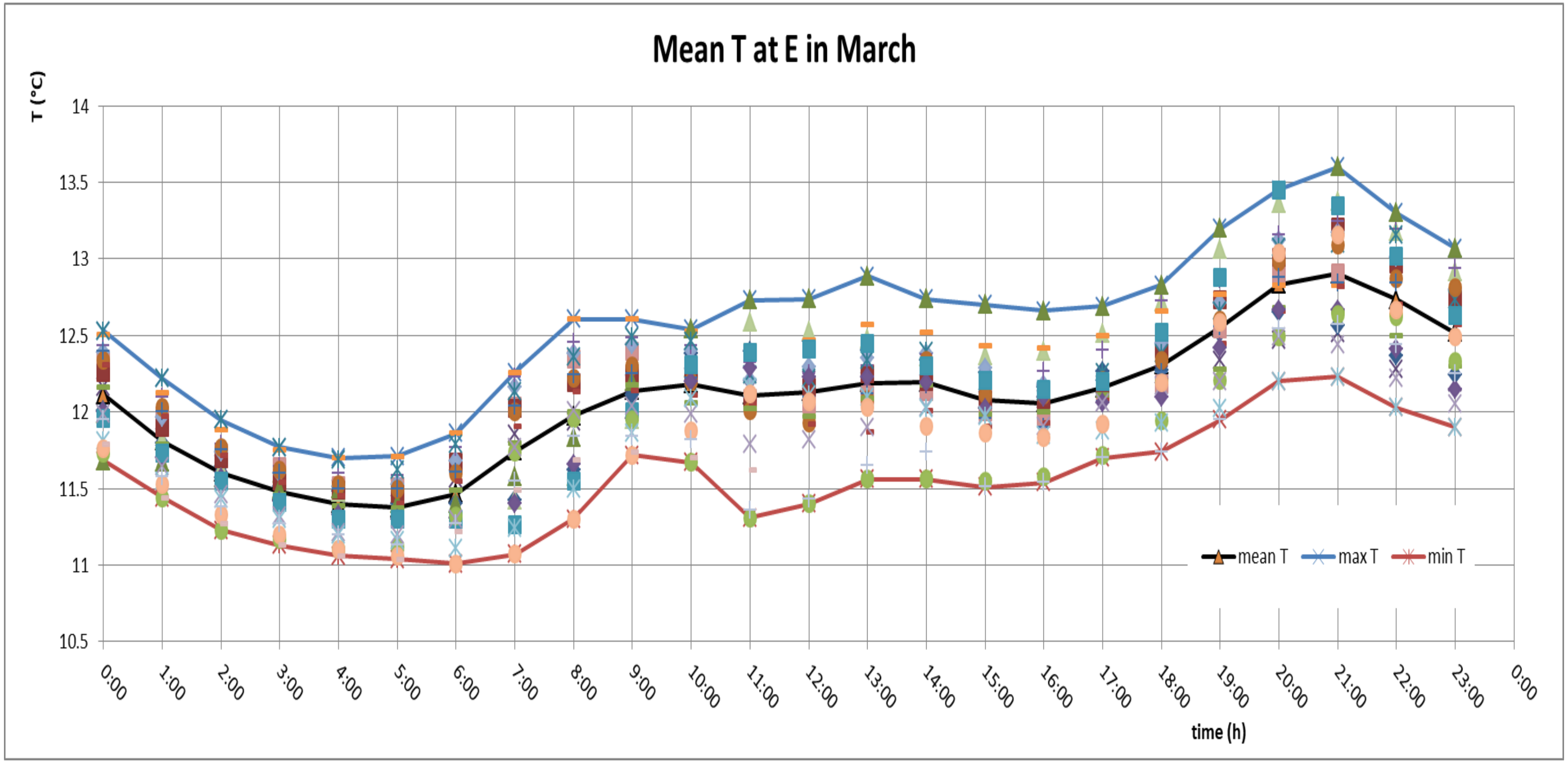


Figure 25 – Mean hourly temperature T at measuring site E in March

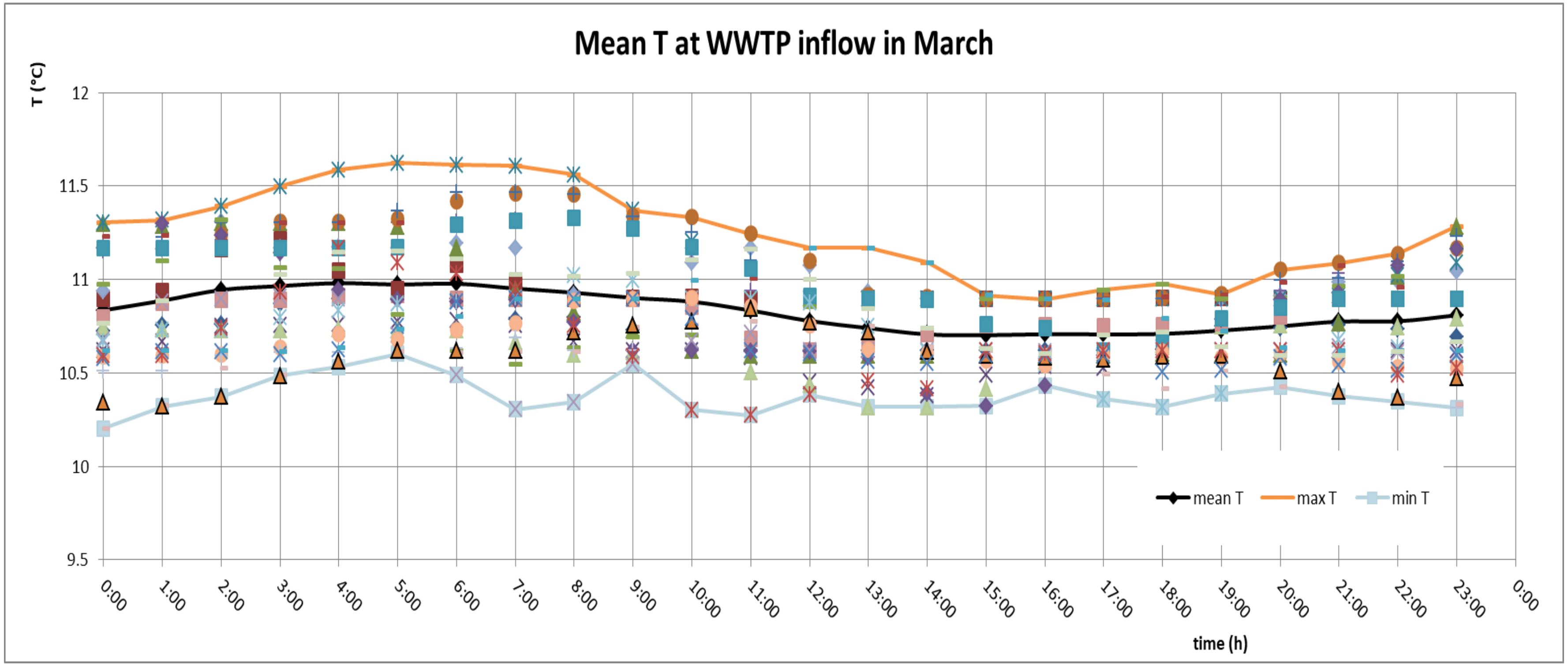


Figure 26 – Mean hourly temperature T at measuring site WWTP in March

5.3.3.3 Analysis of the diurnal cycle at measuring sites

Wastewater temperature and discharge in sewer system are developing according to some trends. Those trends are similar each day, each month and also can be observed in different measuring sites. It is possible to define daily periodicity which is caused by human acting. For explanation of this trend Figure 27 is attached.

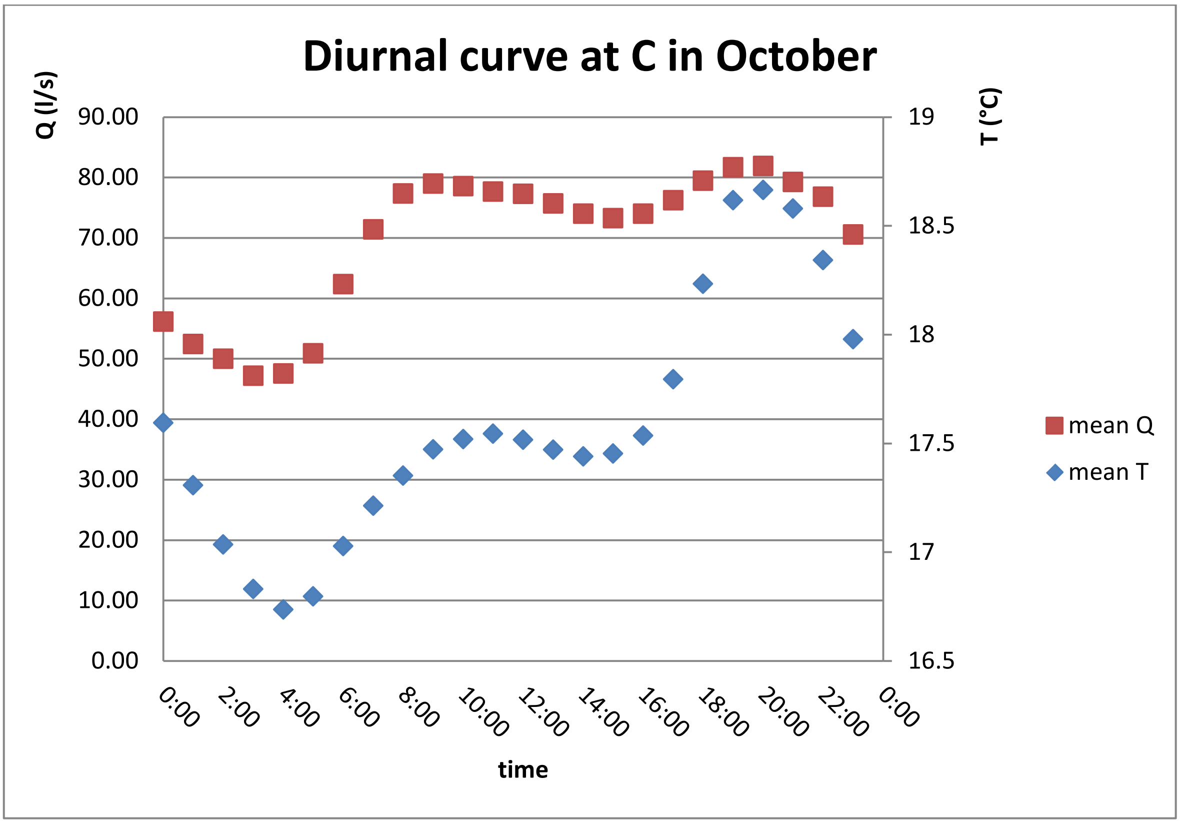


Figure 27 – Diurnal curve at measuring site C in October

Diurnal curve in Figure 27 represents pattern of dry weather wastewater temperature and discharge development during the day in combined sewer system. The chart in Figure 27 is created from mean hourly values in October 2013. From 31 days in October, 8 days have being excluded because of the rain. From the remaining 23 days the mean values representing each hour during the day have being calculated and are represented by curves in Figure 27.

In this case of diurnal curve at measuring site C in October displayed in Figure 27 wastewater temperature and discharge have similar behaviour. At measuring site C, similar temperature and discharge development can be observed in each of the months. Both curves start with a decline from midnight to approximately 4 A.M. At this time the lowest point in the curve is reached. From around 4 or 5 A.M. to approximately 8 A.M. a relatively steep increase occurs, which is followed by the first peak of the day at 9 A.M. After the first peak is reached the values are slowly decreasing until 3 P.M. From 3 P.M. until 7 P.M. steep increase can be observed. This increase is much more significant in case of temperature. The second higher peak of the day can be defined around 7 P.M. and 8 P.M. At this time the temperature and the discharge are reaching the highest daily values as well. After reaching the second peak there is a relatively fast decrease and diurnal cycle is repeated.

All what is described in paragraph above has an explanation. The wastewater temperature and discharge development during the day correspond with the human being. The pattern can be explained by higher water consumption at the moments of the peaks in the morning and in the evening. The use of warmer water (showers) is also in connection with this. Another explanation of lower wastewater temperatures during the nights could be the wastewater and infiltrate/inflow dilution. The infiltrate/inflow water has a constant temperature (lower than wastewater) and constant inflow. During the night time the wastewater discharge from human activities is much lower and it is diluted with the infiltrate/inflow water with constant discharge and temperature. During the daytime wastewater consumption and temperature stay approximately constant (dishwashers, washing machines, toilet flushing) and during the night a decrease in discharge and temperature is recorded.

For comparison three more diurnal curves are attached Figure 28, Figure 29, Figure 30 from October from different measuring sites.

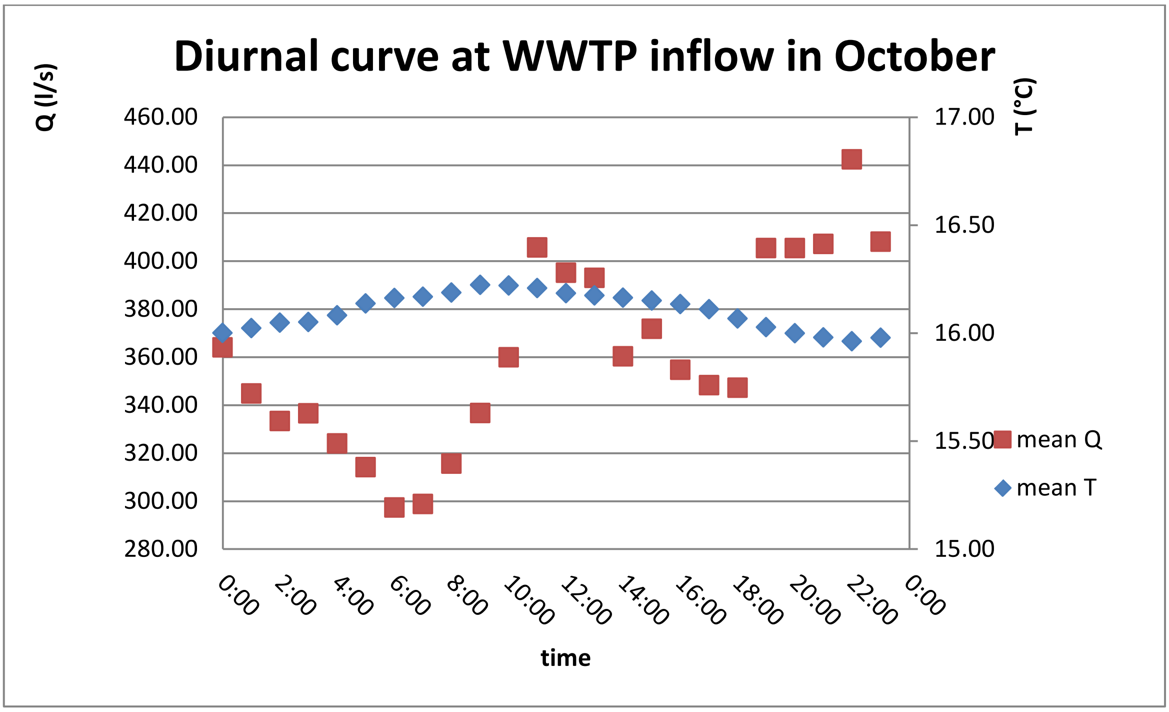


Figure 28 – Diurnal curve at measuring site WWTP in October

During dry weather days inflow to the WWTP is not so fluent as in cases of the other measuring sites. More and bigger shock changes into the wastewater discharge can be observed at the WWTP. For example between 10 A.M. and 11 A.M. the discharge stepped up by 45 l/s from 360l/s to 405 l/s. Even higher jump growth by 60 l/s was recorded between 6 P.M. and 7 P.M.

Quite contrary to the discharge, the temperature at the inflow to the WWTP is almost constant. In October the temperatures fluctuated within the range of values 16 °C and 16,2°C. This range 0,2 °C compare to the other measuring sites is quite small. For example at measuring sites C, D, B in Figure 27, Figure 29, Figure 30 the range was higher than 1,5 °C.

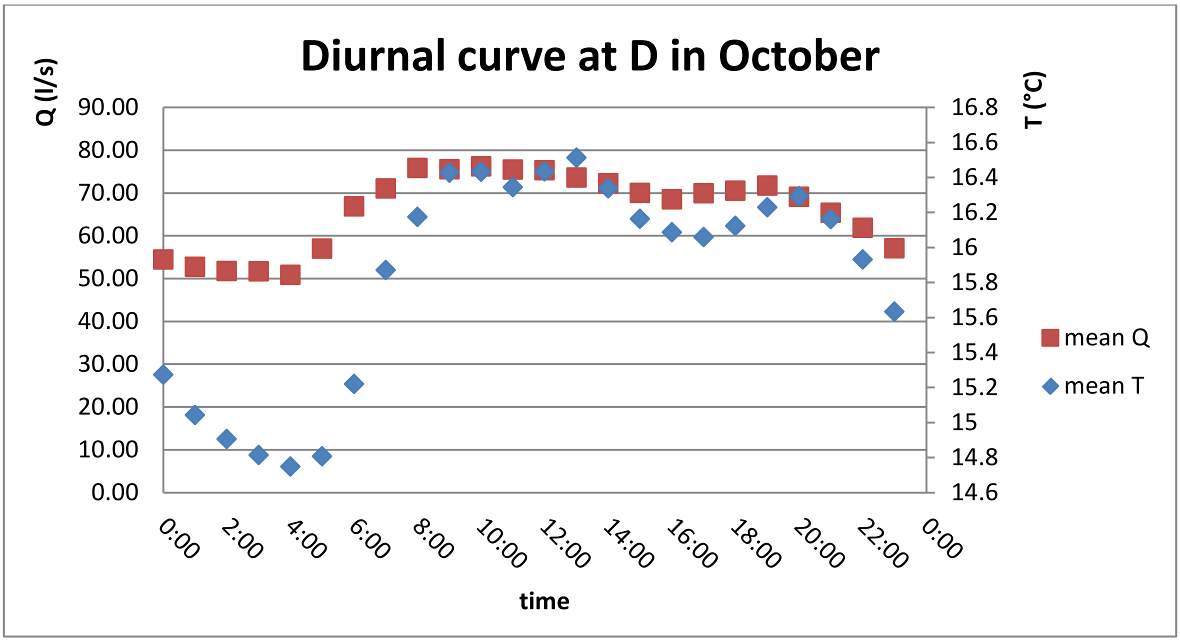


Figure 29 – Diurnal curve at measuring site D in October

It the Figure 29 the temperature and discharge trends are similar as in Figure 27.

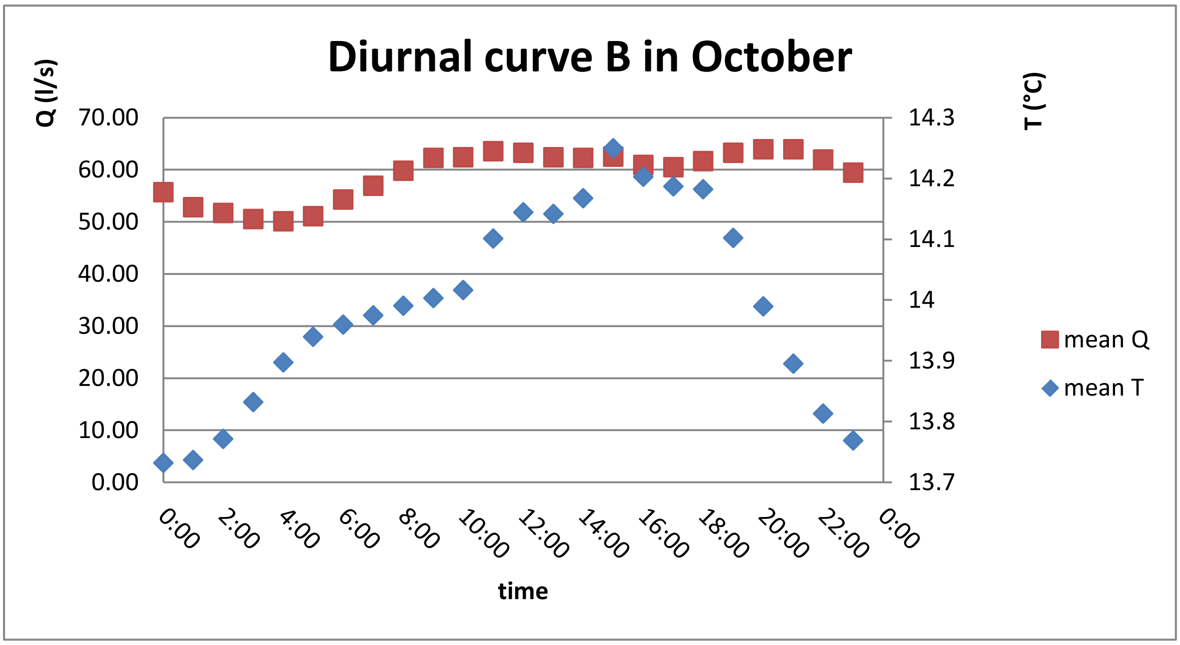


Figure 30 – Diurnal curve at measuring site B in October

For compares the diurnal curve at measuring site B in October does not correspond with the discharge. The wastewater temperature is slowly growing from midnight till 4 P.M. and after reaching the daily maximum at 4 P.M. the wastewater temperature is decreasing slowly until midnight.

5.3.3.4 Analysis of the wastewater temperature development over the individual months

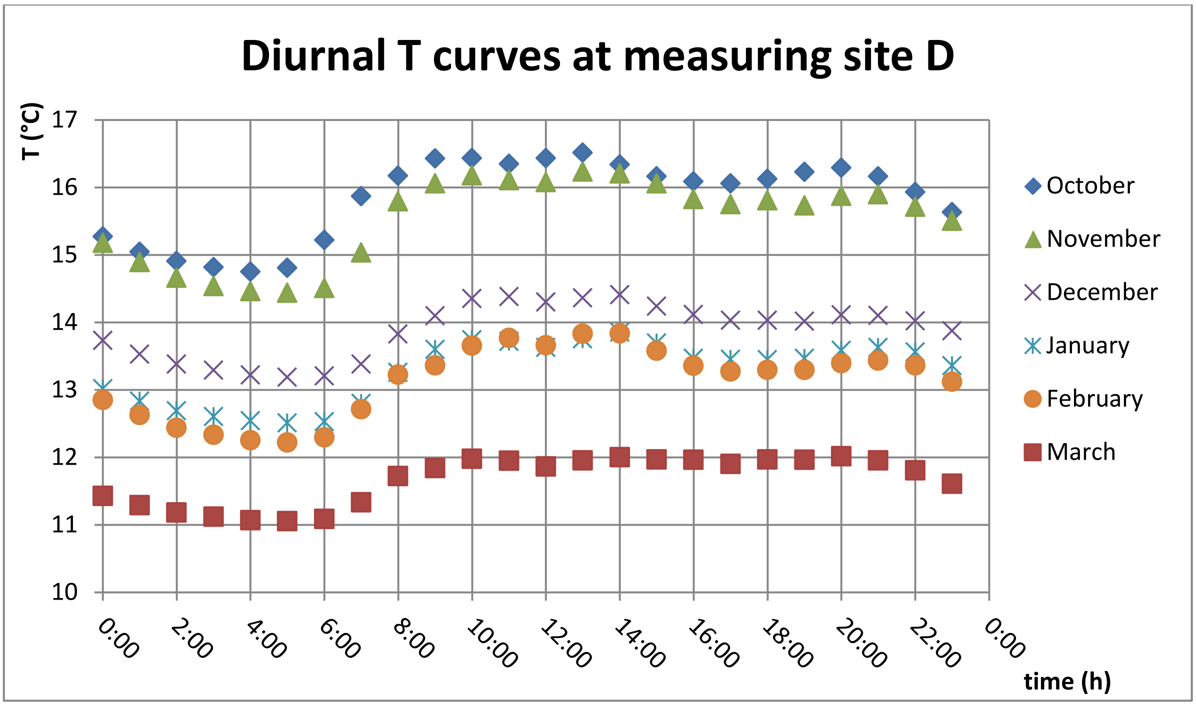


Figure 31 – Diurnal temperature curves at measuring site D

In Figure 31 wastewater temperature development during the monitored moths is displayed. From the Figure 31 it is possible to observe that the wastewater temperature is decreasing from October to March. This phenomenon is not random. The same temperature development was recorded in all the measuring sites A, 1A, B, D, E, WWTP except C. At measuring site C the temperature in February was lower than temperature in March.

In general the lowest temperatures were recorded in March.

5.3.3.5 Analysis of the wastewater discharge development over the individual months

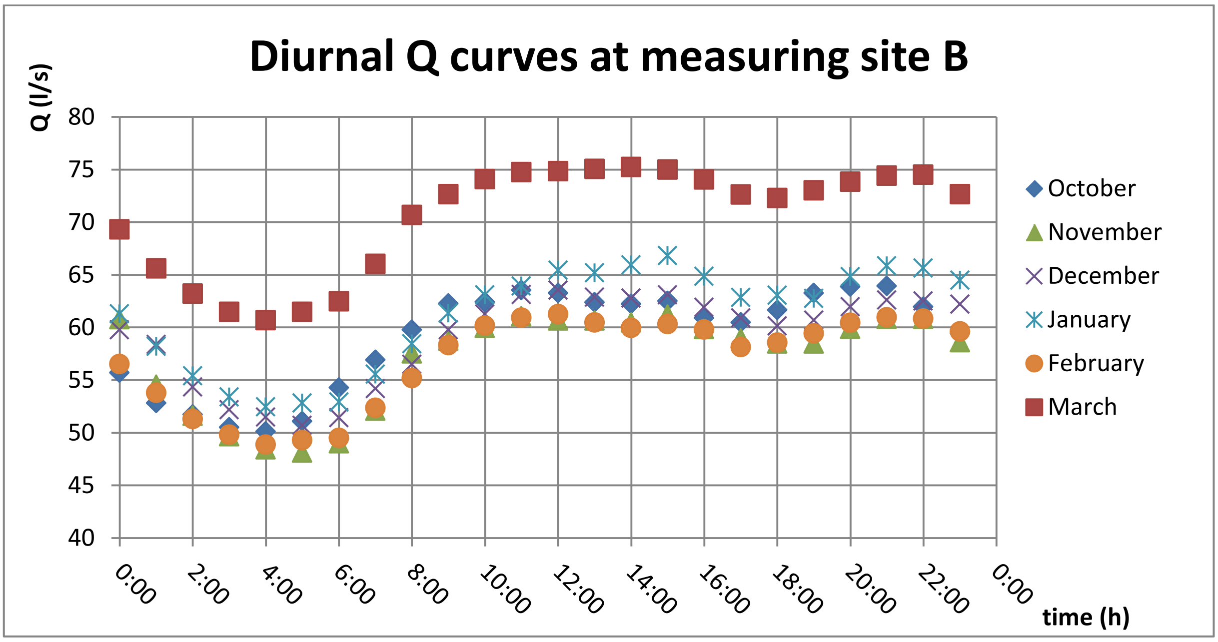


Figure 32 – Diurnal discharge curves at measuring site B

In Figure 32 the diurnal discharge curves during the monitored period are displayed. At all the curves the typical diurnal development, which is described in the chapter 5.3.3.3, is distinct. Comparing to temperature there is no trend with decreasing or increasing discharge over the measured period. Individual monthly diurnal curves intertwine with each other. This phenomenon can be observed at each of the measuring sites. Another phenomenon which can also be observed at the measuring sites B and D is that the March discharge curve is much higher than all the others. The reason why is this happening could be that data in March are measured in the year 2013. All the others months follow up without gap in the end of the year 2013 and the beginning of the year 2014. At two other measuring sites C, E where the data were sufficient to complete the discharge analysis the March discharge curve merges with the others.

Another explanation for the phenomenon of higher discharges in March could be snow melting. Hradec Králové is situated in the foothills of the Krkonoše Mountains and the March wastewater discharge can be affected by snow melting.

5.3.3.6 Analysis of the diurnal curves from different measuring sites

This analysis will be demonstrated on month February.

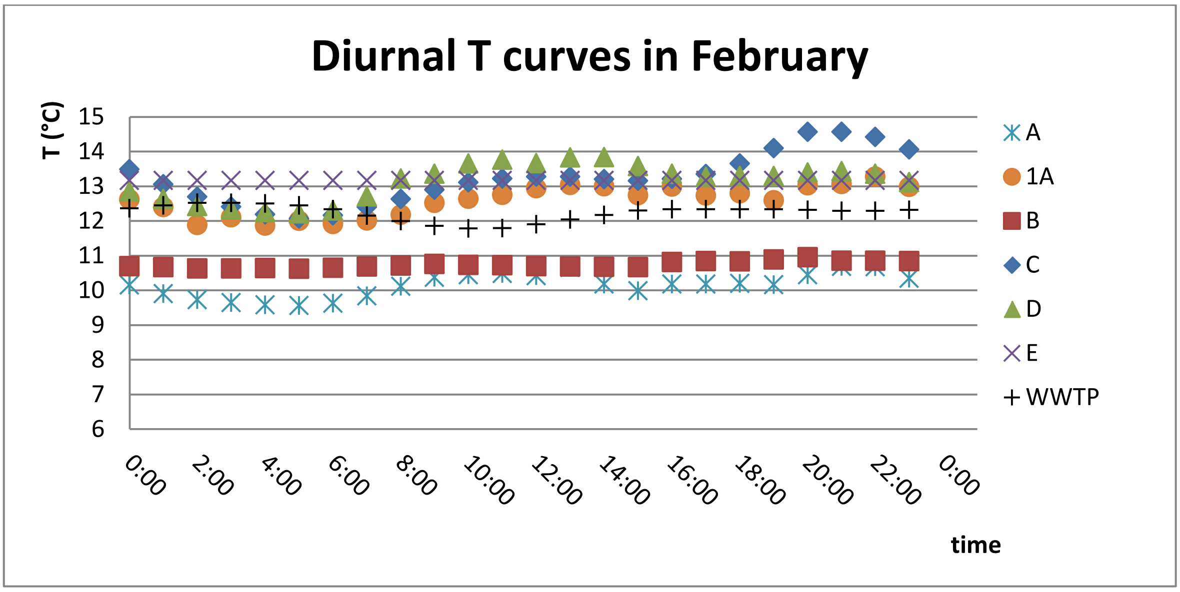


Figure 33 – Compares of diurnal temperature curves at different measuring sites in February

From Figure 33 can be observed that the temperature at each of the measuring site is different. The lowest is always at measuring sites A and B. Temperatures at the other measuring sites 1A, C, D, E are a little bit higher and go through each other. Temperature at the inflow to the WWTP is in the middle of the values. That makes sense because the measuring at the WWTP connecting the wastewater from all the other sewers and measuring sites.

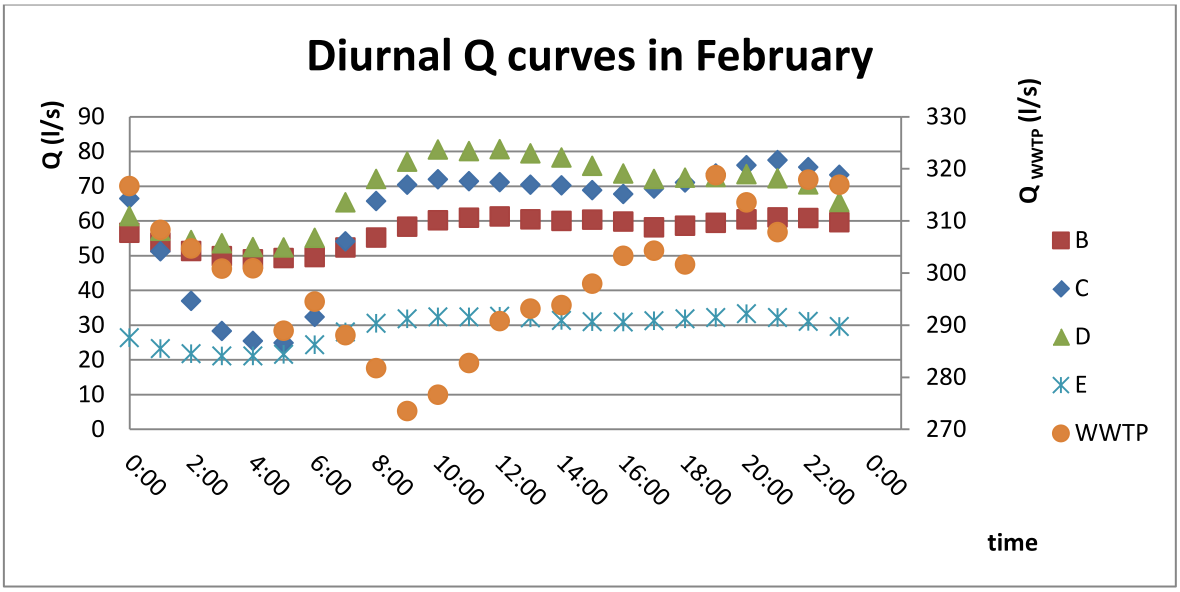


Figure 34 – compares of diurnal discharge curves at different measuring sites in February

In the Figure 34 diurnal discharge curves in February are displayed. For better clarity the wastewater discharge is displayed on the minor axis. The WWTP discharge development is strange and does not correspond with the other curves development. This can be caused by discharge delay. Similar discharge developments are observable in each of the analysed months.

5.3.3.7 Changes over time in wastewater temperature at different measuring sites

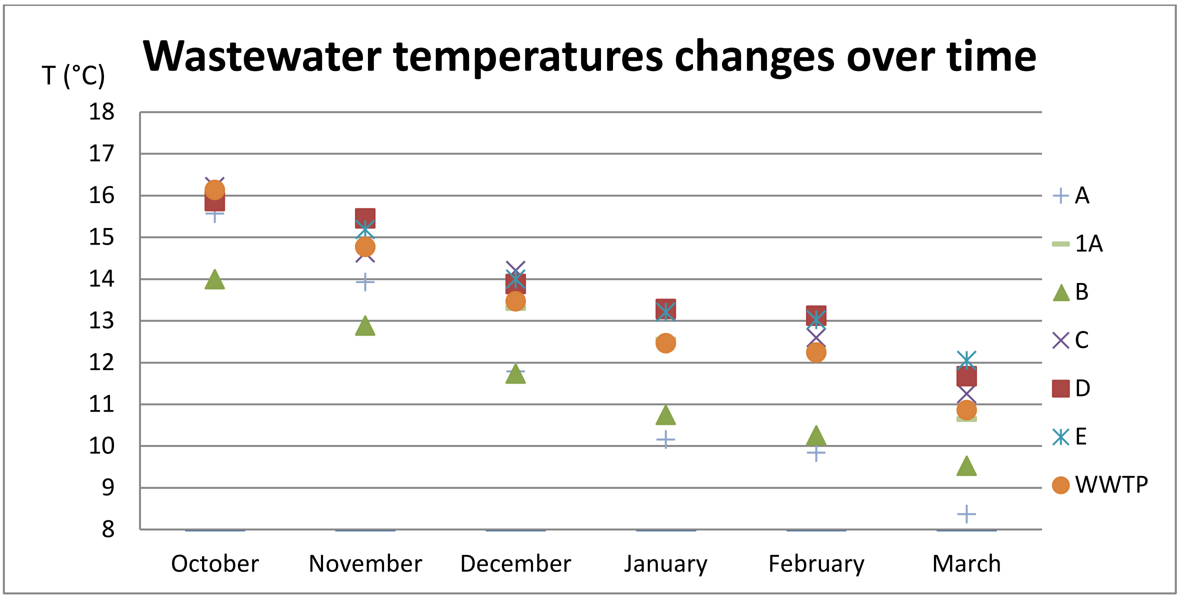


Figure 35 – Wastewater temperatures changes over time at different measuring sites

A chart, which is possible to get the most information from, about the whole analysis, is displayed in Figure 35. The summary results of the whole analysis are displayed in this chart. Temporary development, trends and measuring from different measuring sites can be compared. In each month the mean value from October to March at each measuring point are displayed.

Probably the most interesting finding from chart in Figure 35 is that the wastewater temperature development has from October to March a decreasing tendency at all of the measuring sites. Based on this information it is possible to mark the March as the coldest wastewater month of the observed period.

It could be interesting to compare wastewater temperature development and the outside air temperature development. Measuring the outside air temperature was not a part of the measuring campaign. Outside air temperature data were gained from [39]. It is important to highlight that the individual months from October 2013 to February 2014 are following each other. Data from March 2014 were not possible to use because they were not sufficient for the analysis. The data in March are from the year 2013. It is important to mention that the March 2013 was colder than all the other observed months.

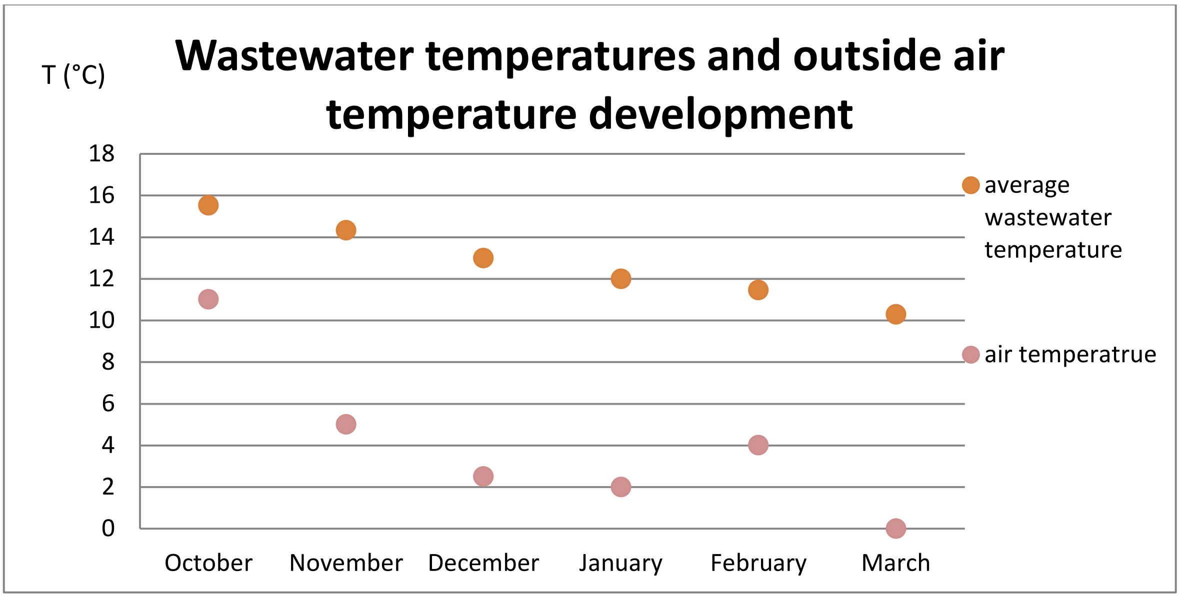


Figure 36 – Outside air temperature and average wastewater temperature development in Hradec Králové **[39]**

It is interesting to see that there are similar trends in wastewater temperature and outside air temperature development over the individual months. The differences in case of wastewater temperature are not so marginal as in case of air temperature. For example the outside air temperature between January and February grew up by 2°C quite contrary the wastewater temperature at the same period lightly decreased or stayed constant at most of the measuring sites. In general it is expected that the wastewater temperature correspond with the outside air temperature with a delay. That means if the outside air temperature decrease the wastewater temperature should decrease as well but after some time period. This period is probably much shorter than one month, because in this case it is not possible to observe this phenomenon.

5.3.3.8 Changes over time in wastewater discharge at different measuring sites

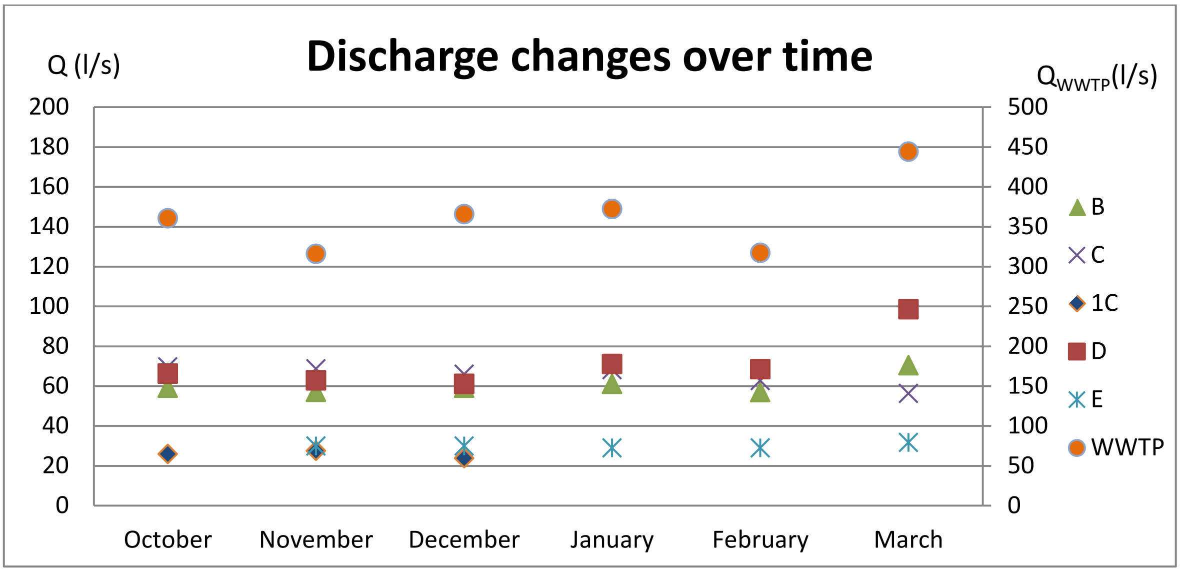


Figure 37 – Wastewater discharge changes over time at different measuring sites

In Figure 37 discharges at different measuring sites during the measured period are displayed. All the displayed values are connected to the main “y” axis on the left side of the chart. Only values from WWTP are related to axis on the right side because the discharges here are much higher. Such adjustment of the chart was made in order to improve clarity of the chart.

From Figure 9 is possible to see that all the sewers are connected to one main sewer and this is transporting the wastewater to the treatment plant. That means WWTP line in Figure 37 supposed to be the summary of all the other lines. It is important to mention that not all the results from measuring sites are displayed in chart in Figure 37. For example lines from measuring site A and 1A are not displayed, because only the wastewater temperature were analysed at those spots.

When looking in detail at the chart in Figure 37 in general it is possible to identify that the WWTP discharge almost correspond with the characteristically trends of the others. Just in December the WWTP discharge was higher than in November, the same effect was not possible to define at the other measuring sites. Discharges between November and December at other measuring sites stayed equal.

5.4 Assessment of the potential heat recovery site based on wastewater temperature predicting

Subchapters below are hand in hand with each other. Designed potential of available heat cannot negatively affect the WWPT inflow temperature.

5.4.1 Estimation of the available heat potential

From the Figure 20 is obvious that three heat exchangers could be installed. For easier orientation, within this thesis the heat exchangers will be named north, west and east heat exchanger.

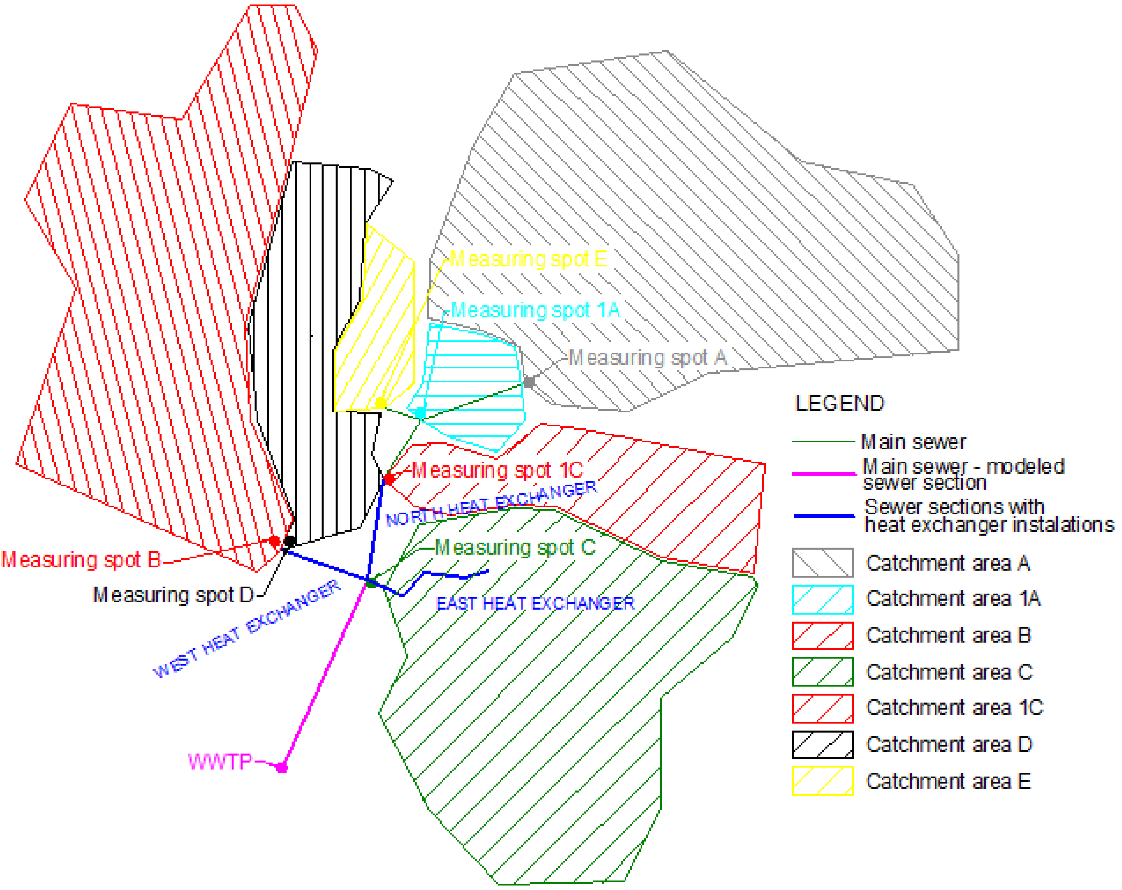


Figure 38 – Scheme of the heat exchangers installations

The north heat exchanger is collecting wastewater from catchment areas: A, 1A, 1C and E therefore the discharge is higher than in other heat exchangers. West heat exchanger is supplied by wastewater from catchment areas B and D. These two heat exchangers are supposed to be in the main wastewater collectors 25 - 28 m underground. East heat exchanger is supposed to be installed in sewer system draining the catchment area C, which is not the same deep (is common sewer system). The sewers at north and west heat exchangers installations are collecting wastewater from smaller sewer branches (two or more). Mixing equation is applied to calculate the final wastewater discharge and temperature.

$$Q.t = \sum_{i \to n} (Q_i . t_i)$$

$$Q = \sum_{i \to n} Q_i$$

The same equation is applied when the wastewater from all three heat exchanger is mixing.

Conditions in all three exchangers are different. The main different is in discharge. In Table 4 are displayed average discharge values representing measuring period from the whole observed period (March, October, November, December 2013 and January, February 2014). The average discharges are possible to consider as dry weather average discharges during the whole year.

Table 4 – Average wastewater discharges in the individual heat exchangers

average discharges (l/s)						
A	1A	E	1C	B	D	C
57.1	46.6	29.8	25.7	60.6	71.4	65.2
north exchanger				west exchanger		east exchanger
159.2 l/s				132.0 l/s		65.2 l/s

For better imagination the average wastewater temperatures from measuring campaign are displayed in Table 5. The year average temperatures will be higher because these values are representing the winter period only (October - March).

In case of heat exchanger installations the average temperature is not the most important factor. Much more important is the minimal wastewater temperature.

Table 5 – Average wastewater temperatures in individual heat exchangers

average temperatures (°C)						
A	1A	E	1C	B	D	C
11.6	13.4	13.5	14.0	11.5	13.9	13.7
north exchanger				west exchanger		east exchanger
12.9				12.8		13.7

The heat exchanger performance will be designed basing on minimal wastewater temperature after mixing from all three branches. The maximum cooling effect of the heat exchanger installations should not cool down the wastewater under 9,8 °C. In this case the sufficient wastewater temperature at the wastewater treatment plant will be guaranteed most of the time. The heat exchanger operating hours will be optimal, more about this topic is written in chapter 5.4.2.4. Wastewater temperature development and guarantee of right wastewater treatment plant operation will be described in the following chapter 5.4.2. How the temperature 9,8 °C was calculated will be described in the same chapter.

Heat exchanger performance will be designed basing on the theoretically available heat in the individual sewers.

$W = c.\rho.Q.\Delta T$

$W - theoretically\ availabele\ heat\ (kW)$

$\rho - wastewater\ density\ (1\, {}^{kg}/_{l})$

$c - specific\ heat\ capacity\ of\ wastewater\ (c = 4{,}19\ kWs.kg^{-1}.{}^{\circ}C^{-1})$

$Q - wastewater\ discharge\ \left({}^{l}/_{s}\right)$

$\Delta T - the\ difference\ between\ wastewater\ temperatures\ upstream\ T_1({}^{\circ}C) and$

$downstream\ T_2\ ({}^{\circ}C)\quad \Delta T = T_1 - T_2$

c and ρ are constant. Q and T_1 are variables. T2 is variable as well, but the temperature T2 is related to the boundary condition of minimal temperature at the inflow to the WWTP.

5.4.2 Estimation of the potential impact on WWTP inflow temperature

The heat exchangers should be designed so they do not affect the WWTP treatment processes at any way. To better description how the wastewater is developing in sewer system, the TEMPES have been applied.

5.4.2.1 TEMPEST model set up

The wastewater temperature development was modelled in sewer section between heat wastewater treatment plant and the spot where all three sewer branches with heat exchanger could be installed. The temperature development has been modelled by software TEMPEST.

First of all it was necessary to calibrate the model. From Figure 38 is obvious that all three sewers where the heat exchangers could be installed are connected in one point. The main sewer collector from this point to WWTP is 1725 m long.

Based on known discharges and temperatures at the inflow to the WWTP and at the above mentioned spot, where all the sewer branches are connected into the one main sewer collector, it was possible to calibrate the model.

For the calibration three different time periods have being used.

First 10.12.2013 – 17.12.2013

Second 1.1.2014 – 3.1.2014

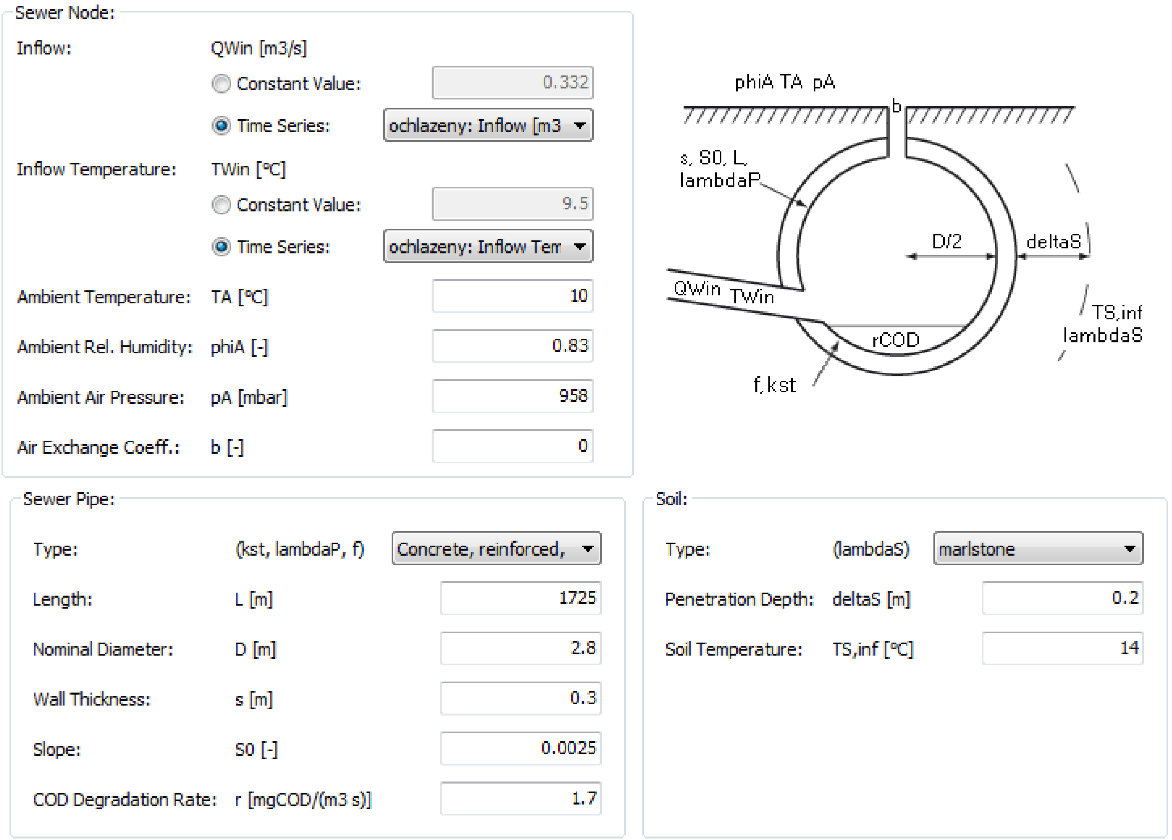
Third 1.2.2014 – 4.2.2014

These periods have been chosen because of many reasons. The first reason is that during these periods there is no power cut in measuring campaign. Data from all the measuring sites are available and responsible. What is more there were no rain recorded during this period. The third reason was that these periods were colder periods during the year. That means the potential negative impact on WWTP inflow temperature is higher than in warmer periods.

5.4.2.2 TEMPEST model input data

In Figure 39 the TEMPEST input mask is displayed. All the data which are necessary to know for predicting and modelling wastewater temperature development are displayed in the input mask. The information displayed in Figure 39 represents the real conditions in the sewer. The first input information is about sewer node. Wastewater discharge and temperature are entered as a time series. Because the modelled part of the sewer is built 25 – 28 meters underground, there is a minimal impact of the ambient weather conditions. Therefore the air exchange coefficient b [-] equals 0. Ambient Temperature, Rel. humidity and Air pressure are represented by average values in Hradec Králové area during the measuring campaign. The second inputs characterize the sewer pipe. In this case the sewer is made of reinforced concrete with wall thickness circa 0,3 m. Pipe diameter is 2,8 m and slope 0,0025. As it was already mentioned the sewer length is 1725 m. The last the most important inputs are about the sewer surroundings. The sewer was excavated in marlstone. And probably the most important factor is the marlstone temperature 25 m under the surface. Temperature in tunnel 25 m underground is constant during the whole year. There is no direct contact with ambient weather and the temperature is circa 14 °C.

The known wastewater discharge and temperature from WWTP were compared with results calculated with TEMPEST. All above mentioned input parameters have been adjusted basing on the calibration results. It is expected that the input data except the inflow discharge and temperature series are almost invariable during the whole year. This expectation has been verified during three different calibration experiments in December, January and February.


Sewer Node:

Inflow:	QWin [m3/s]		
	○ Constant Value:	0.332	
	● Time Series:	ochlazeny: Inflow [m3	
Inflow Temperature:	TWin [°C]		
	○ Constant Value:	9.5	
	● Time Series:	ochlazeny: Inflow Ter	
Ambient Temperature:	TA [°C]	10	
Ambient Rel. Humidity:	phiA [-]	0.83	
Ambient Air Pressure:	pA [mbar]	958	
Air Exchange Coeff.:	b [-]	0	

Sewer Pipe:

Type:	(kst, lambdaP, f)	Concrete, reinforced,
Length:	L [m]	1725
Nominal Diameter:	D [m]	2.8
Wall Thickness:	s [m]	0.3
Slope:	S0 [-]	0.0025
COD Degradation Rate:	r [mgCOD/(m3 s)]	1.7

Soil:

Type:	(lambdaS)	marlstone
Penetration Depth:	deltaS [m]	0.2
Soil Temperature:	TS,inf [°C]	14

Figure 39 – TEMPEST input mask

5.4.2.3 *TEMPEST model calibration results*

Comparing the wastewater temperatures modelled with TEMPEST and temperatures measured at the WWTP it is possible to say that in case of all calibration experiments the wastewater temperature in sewer stays almost constant. There are only small changes in temperature development at the spot where the wastewater from all three heat exchanger is collected and at the WWTP inflow.

After successful model calibration and input data adjustment the modelling temperature development simulation could start. Unfortunately because of the gaps in data it was not possible to model a longer time period than 7 days. Anyway 7 days period should be sufficient and responsible for the purpose of this calibration. It was important to define if there is a possibility of the wastewater reheating in 1,725m long main wastewater collector, after it is cooled down in the heat exchangers.

The results from the modelling are displayed in Figure 40, Figure 41, Figure 42

The temperature lines displayed in all the charts are representing the temperature courses in usual conditions without heat exchangers. The other lines represent the temperature courses after wastewater cooling in the heat exchangers. The lines described as “development in the mixing point” represent the temperature courses at the beginning of the modelled part of the sewer system just after the collecting of wastewater from all there sewer branches. The other lines in charts represent the wastewater temperature course right in front of the WWTP.

From the charts in Figure 40, Figure 41, Figure 42 it is possible to observe that there are no significant changes in the wastewater temperature developments. In all the modelled results the temperature developments at the beginning of the modelled part and in front of the WWTP are almost the same. In general it is possible to observe that the wastewater temperature is reheated by 0,1 – 0,2 °C in 1725 m of sewer.

From the trends in Figure 40, Figure 41, Figure 42 it is still posible to observe the typical diurnal curves. The most critical are the nights. The limitation for heat exchanger installation is the wastewater discharge. Smaller night discharge causes that the wastewater needs to be more cooled than in case of higher daytimes discharges.

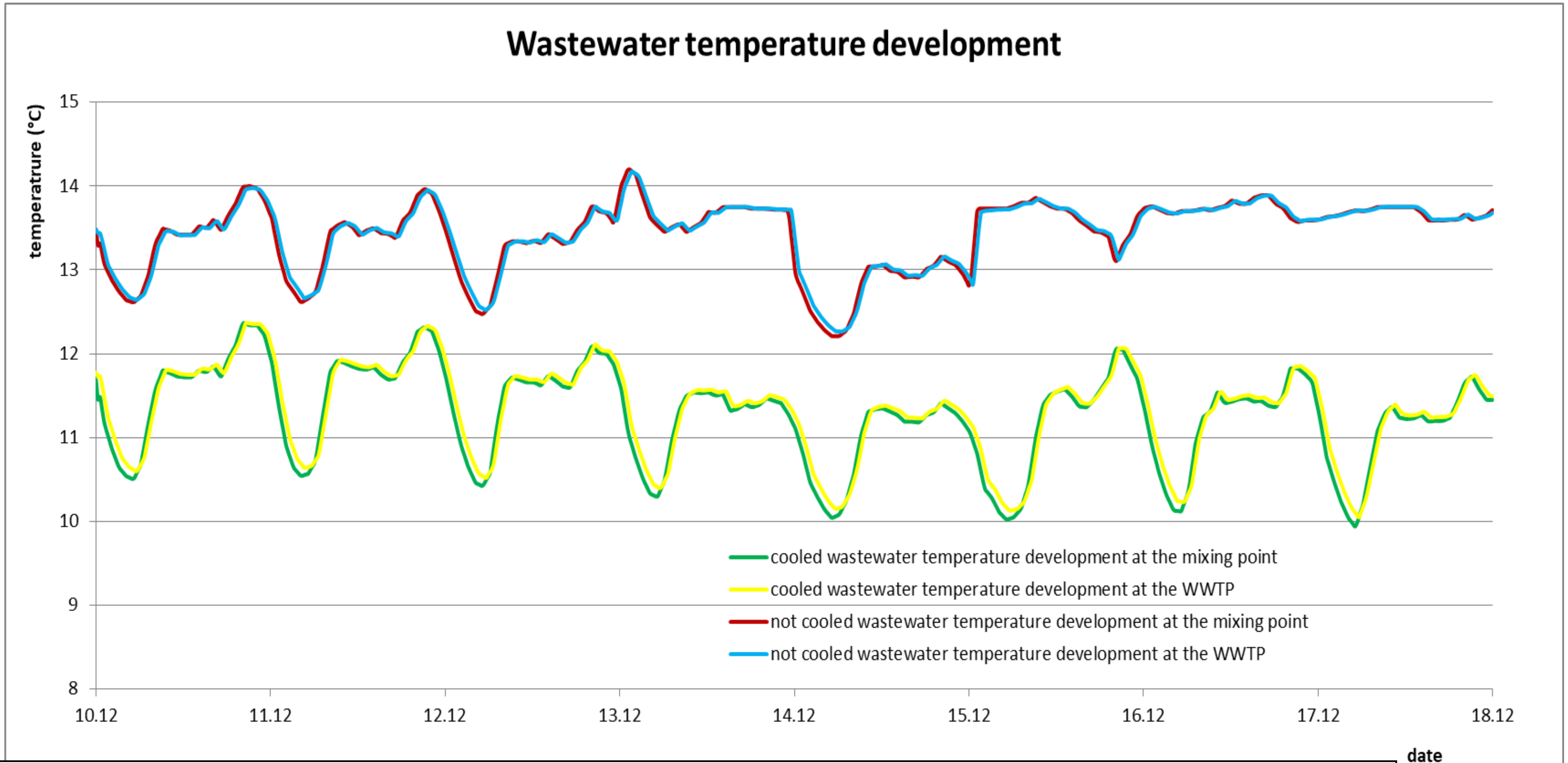


Figure 40 – Wastewater temperature development in the modelled part of the sewer

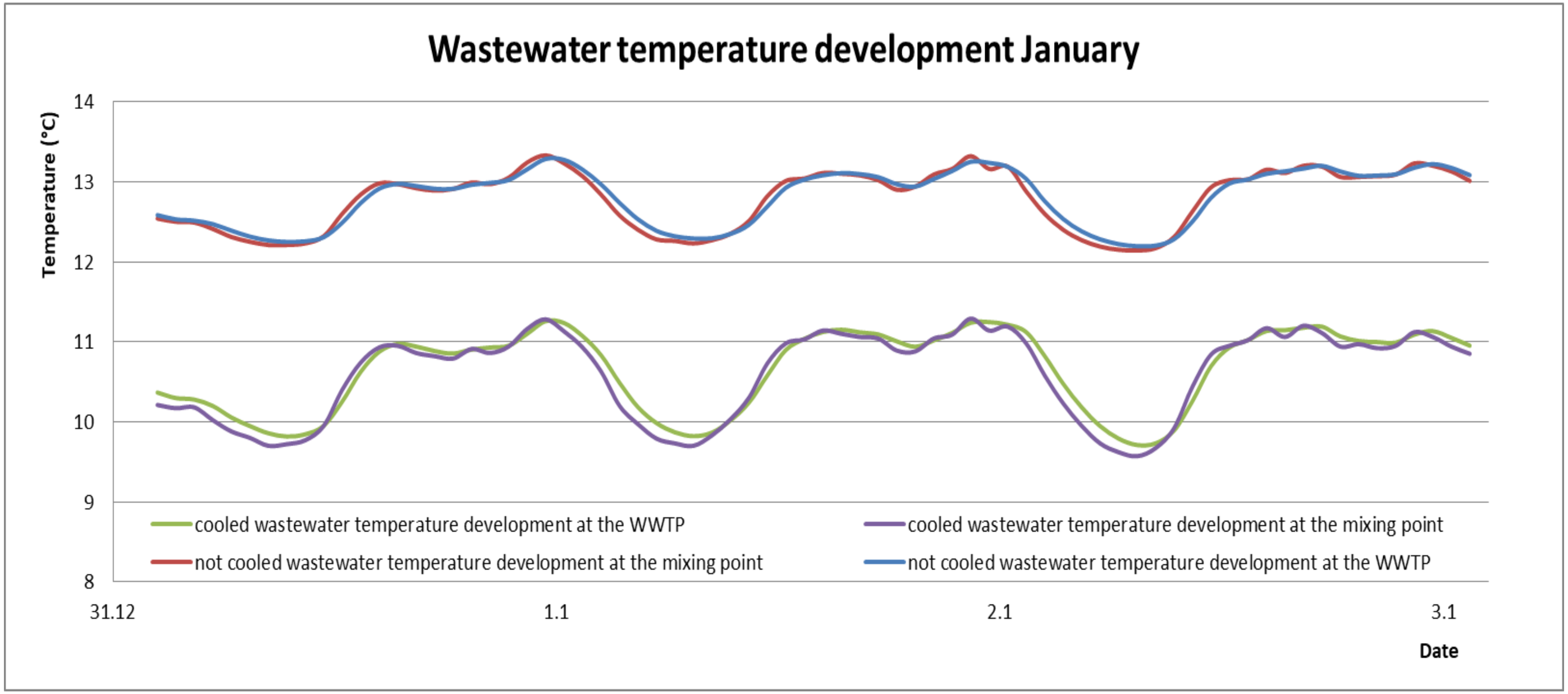


Figure 41 – Wastewater temperature development in the modelled part of the sewer

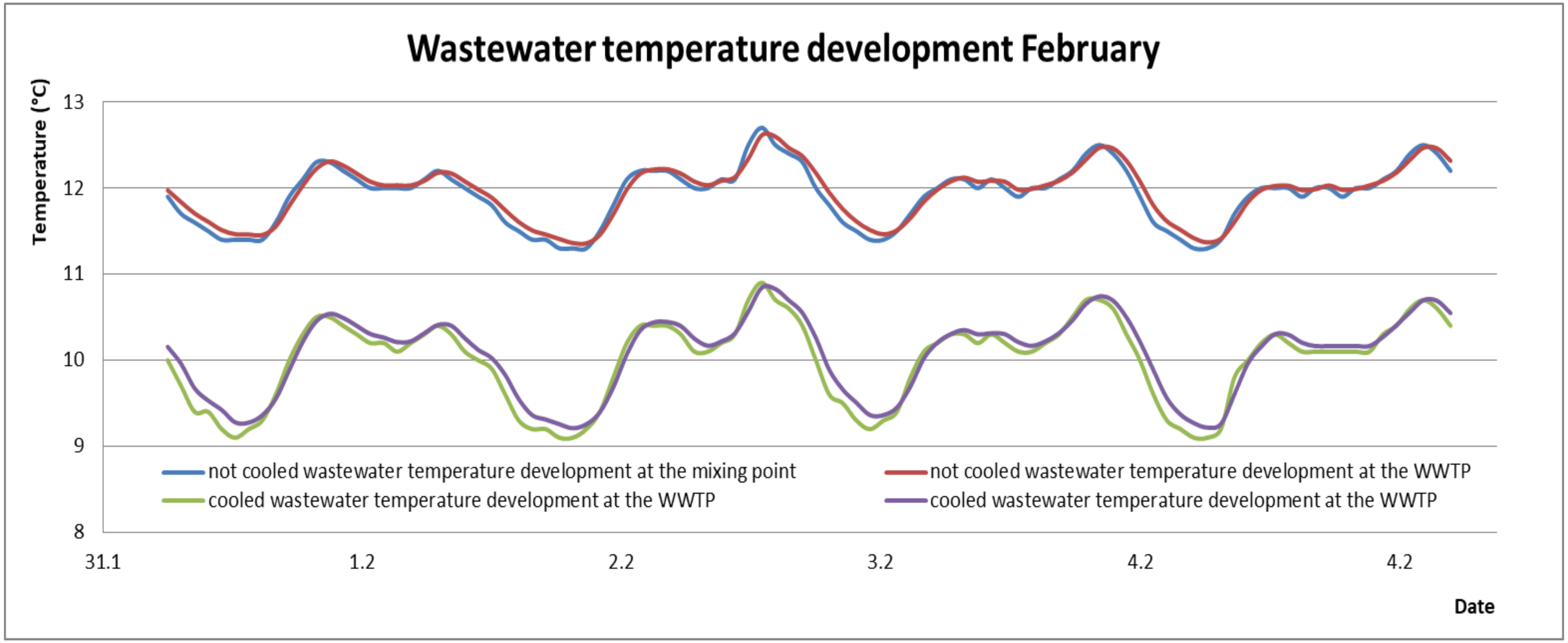


Figure 42 – Wastewater temperature development in the modelled part of the sewer

5.4.2.4 Possibility of TEMPEST model results verification

When looking at the TEMPEST model results in chapter 5.4.2.3 and the results from the SQUID device testing in chapter 5.1.1 arise the idea, if there is a possibility of using the SQUID for TEMPEST model results verification.

Unfortunately it was not enough time to find a solution how to do this kind of testing. The biggest problem is that the main sewer collector in Hradec Králové is 25 – 28 m underground and the entrance to this collector is allowed only in the presence of mining office.

Another problem is how to get the SQUID from wastewater. It will be quite difficult to catch the SQUID in front of the pumps which are pumping the wastewater towards the WWTP. And the SQUID is probably not able to survive the transport through the pump.

The complexity of the Hradec Králové situation does not mean that this approach cannot be used in a different sewer system in another city.

6 Conclusion and outlook – comparison of heat demand and heat supply

With regards to potential problems related to the issue of the ownership of wastewater it is better to supply with the heat from heat exchange only buildings and objects with the same owner as wastewater treatment and sewer system operator. In case of Hradec Králové the urban drainage operator is the city of Hradec Králové. Based on this information all the supplied buildings should be operate or owned by Hradec Králové as well.

Heat subscriber building should not be far away from heat exchanger.

Good heat customers are for example: schools, kindergartens and another civic amenity close to heat exchanger.

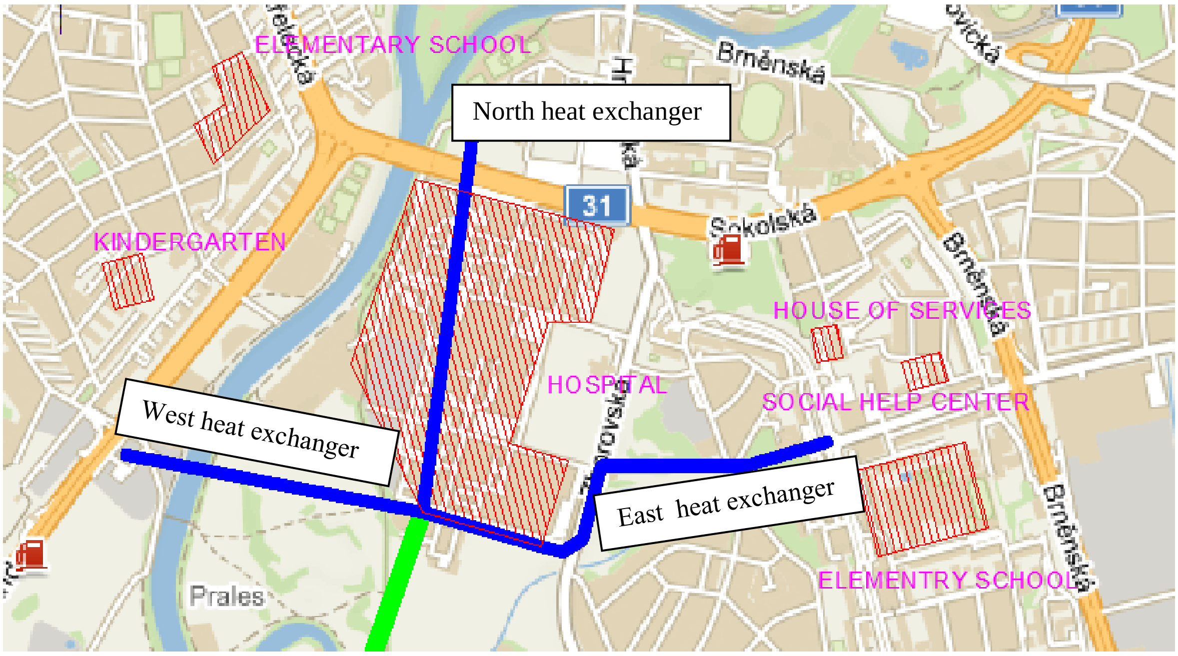


Figure 43 – Map with highlighted potential heat customers

In Figure 43 objects are highlighted and described, which can be marked as a potential heat customer. Except the Hospital, all the other buildings are under the administration of the Hradec Kálové city. In case of the Hospital the owner and administrator is Czech state. The Hospital has such advantages as geography position regarded to possible heat exchanger installations, that it worth it to create an agreement between Hradec Králové region (hospital runner) and Královehradecká provozní (urban drainage runner).

Based on TEMPEST simulation the minimal wastewater temperature, which the wastewater can be cooled to, was set at 9,8 °C. This temperature guarantees that in most of the time wastewater will reach the WWTP inlet with minimal temperature equal 10 °C.

Wastewater temperature 9,8 °C was determined as a boundary condition. After wastewater cooling under this temperature level the heat exchanger has to be shut down. Based on data from measuring campaign and the analysis, it was possible to define days when the boundary condition has not been met. In these days the heat exchangers are not running. Unfortunately data are not responsible enough to calculate not running days in case of north heat exchanger. North heat exchanger is different from the other two because into this heat exchanger four catchment areas are drained. It was not possible to combine data from these catchment areas and calculate the exact wastewater discharge and temperature.

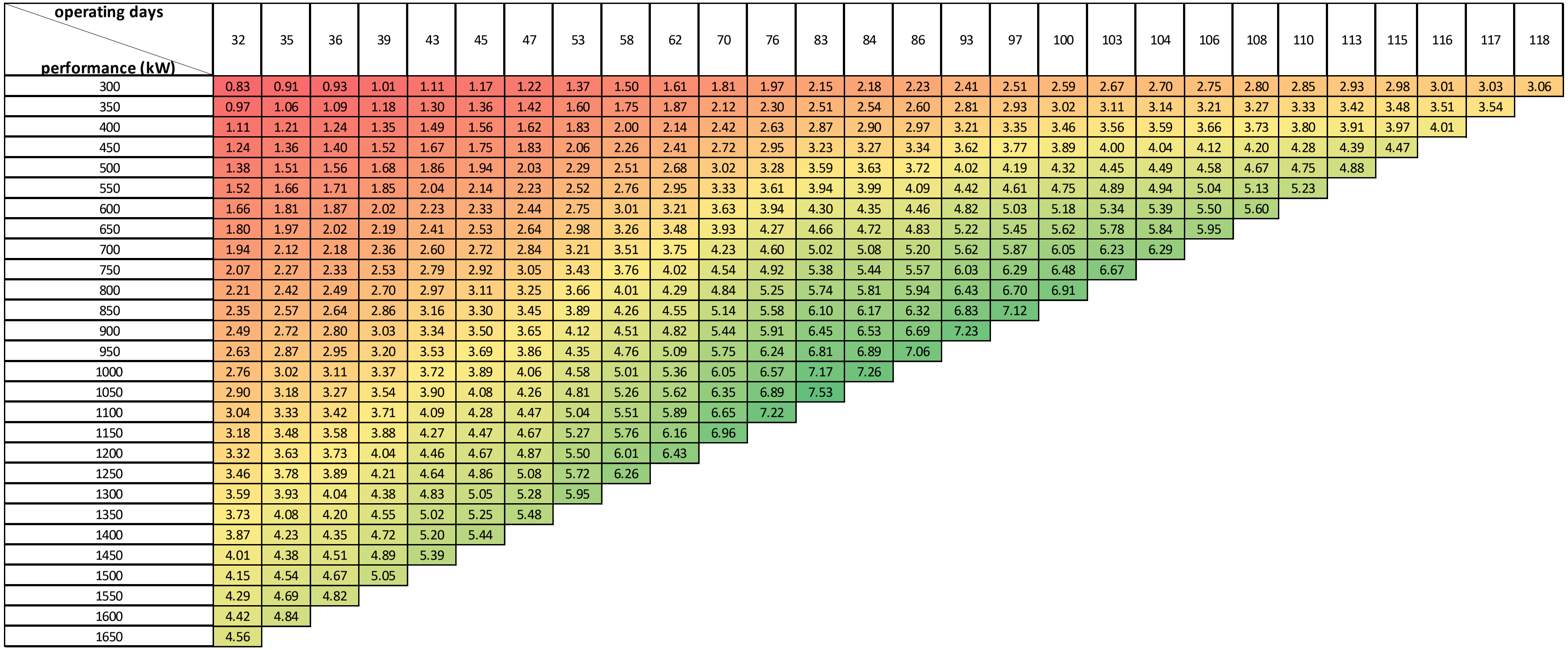
The other heat exchangers (west and east) are characterized in tables bellow. There are calculations of yearly heat exchanger effectivity (TJ/year, terra Joules per year) in tables. Based on heat exchanger performances and number of operating days, it is possible to define the most optimal combination. In Figure 44 and Figure 45 the east and the west heat exchangers are characterized. It is important to mention that the heat exchanger optimization is only for the data from measuring campaign. It was in case of east heat exchanger 124 days and west exchanger 116 days. The calculation is based on the assumption that the heat exchanger will be operating during the summer period (April-September) and during the rainy days as well. During the reported rains the discharge in sewer system is growing up but the wastewater temperature is not decreasing dramatically. Based on high wastewater discharge it is possible to say that the heat exchangers could work in rainy days as well.

The results from Figure 44 serve to identification of the optimal east heat exchanger performance. East heat exchanger optimal performance will be in range between 700 – 850 KW, for this performance range is possible to calculate the operating days during the year and the total produced heat. It will be 335 – 318 operating days and the yearly annual of removed heat: 21,1 – 24,3 TJ/year. The heat which could be delivered to the customers will be much lower.

The same analysis is possible to create from Figure 45 for the west heat exchanger. West heat exchanger optimal performance will be in range between 850 – 1100 KW, for this performance range it is possible to calculate the operating days during the year and the total produced heat. It will be 346 – 325 operating days and the yearly the yearly annual of removed heat: 25,4 – 30,9 TJ/year. The heat which could be delivered to the customers will be much lower.

operating days performance (kW)	21	22	24	26	28	30	32	35	38	42	50	58	62	66	70	77	83	87	94	95	93	97	98	100	102	108	114	120	122	124
150	0.27	0.29	0.31	0.34	0.36	0.39	0.41	0.45	0.49	0.54	0.65	0.75	0.80	0.86	0.91	1.00	1.08	1.13	1.22	1.23	1.21	1.26	1.27	1.30	1.32	1.40	1.48	1.56	1.58	1.61
200	0.36	0.38	0.41	0.45	0.48	0.52	0.55	0.60	0.66	0.73	0.86	1.00	1.07	1.14	1.21	1.33	1.43	1.50	1.62	1.64	1.61	1.68	1.69	1.73	1.76	1.87	1.97	2.07	2.11	
250	0.45	0.48	0.52	0.56	0.60	0.65	0.69	0.76	0.82	0.91	1.08	1.25	1.34	1.43	1.51	1.66	1.79	1.88	2.03	2.05	2.01	2.10	2.12	2.16	2.20	2.33	2.46	2.59		
300	0.54	0.57	0.62	0.67	0.73	0.78	0.83	0.91	0.98	1.09	1.30	1.50	1.61	1.71	1.81	2.00	2.15	2.26	2.44	2.46	2.41	2.51	2.54	2.59	2.64	2.80	2.95			
350	0.64	0.67	0.73	0.79	0.85	0.91	0.97	1.06	1.15	1.27	1.51	1.75	1.87	2.00	2.12	2.33	2.51	2.63	2.84	2.87	2.81	2.93	2.96	3.02	3.08	3.27				
400	0.73	0.76	0.83	0.90	0.97	1.04	1.11	1.21	1.31	1.45	1.73	2.00	2.14	2.28	2.42	2.66	2.87	3.01	3.25	3.28	3.21	3.35	3.39	3.46	3.53					
450	0.82	0.86	0.93	1.01	1.09	1.17	1.24	1.36	1.48	1.63	1.94	2.26	2.41	2.57	2.72	2.99	3.23	3.38	3.65	3.69	3.62	3.77	3.81	3.89						
500	0.91	0.95	1.04	1.12	1.21	1.30	1.38	1.51	1.64	1.81	2.16	2.51	2.68	2.85	3.02	3.33	3.59	3.76	4.06	4.10	4.02	4.19	4.23							
550	1.00	1.05	1.14	1.24	1.33	1.43	1.52	1.66	1.81	2.00	2.38	2.76	2.95	3.14	3.33	3.66	3.94	4.13	4.47	4.51	4.42	4.61								
600	1.09	1.14	1.24	1.35	1.45	1.56	1.66	1.81	1.97	2.18	2.59	3.01	3.21	3.42	3.63	3.99	4.30	4.51	4.87	4.92	4.82									
650	1.18	1.24	1.35	1.46	1.57	1.68	1.80	1.97	2.13	2.36	2.81	3.26	3.48	3.71	3.93	4.32	4.66	4.89	5.28	5.34										
700	1.27	1.33	1.45	1.57	1.69	1.81	1.94	2.12	2.30	2.54	3.02	3.51	3.75	3.99	4.23	4.66	5.02	5.26	5.69											
750	1.36	1.43	1.56	1.68	1.81	1.94	2.07	2.27	2.46	2.72	3.24	3.76	4.02	4.28	4.54	4.99	5.38	5.64												
800	1.45	1.52	1.66	1.80	1.94	2.07	2.21	2.42	2.63	2.90	3.46	4.01	4.29	4.56	4.84	5.32	5.74													
850	1.54	1.62	1.76	1.91	2.06	2.20	2.35	2.57	2.79	3.08	3.67	4.26	4.55	4.85	5.14	5.65														
900	1.63	1.71	1.87	2.02	2.18	2.33	2.49	2.72	2.95	3.27	3.89	4.51	4.82	5.13	5.44															
950	1.72	1.81	1.97	2.13	2.30	2.46	2.63	2.87	3.12	3.45	4.10	4.76	5.09	5.42																
1000	1.81	1.90	2.07	2.25	2.42	2.59	2.76	3.02	3.28	3.63	4.32	5.01	5.36																	
1050	1.91	2.00	2.18	2.36	2.54	2.72	2.90	3.18	3.45	3.81	4.54	5.26																		
1100	2.00	2.09	2.28	2.47	2.66	2.85	3.04	3.33	3.61	3.99	4.75																			
1150	2.09	2.19	2.38	2.58	2.78	2.98	3.18	3.48	3.78	4.17																				
1200	2.18	2.28	2.49	2.70	2.90	3.11	3.32	3.63	3.94																					
1250	2.27	2.38	2.59	2.81	3.02	3.24	3.46	3.78																						
1300	2.36	2.47	2.70	2.92	3.14	3.37	3.59																							
1350	2.45	2.57	2.80	3.03	3.27	3.50																								
1400	2.54	2.66	2.90	3.14	3.39																									
1450	2.63	2.76	3.01	3.26																										
1500	2.72	2.85	3.11																											
1550	2.81	2.95																												
1600	2.90																													

Figure 44 – Calculation of the optimal east heat exchanger performance and operating days



operating days performance (kW)	32	35	36	39	43	45	47	53	58	62	70	76	83	84	86	93	97	100	103	104	106	108	110	113	115	116	117	118
300	0.83	0.91	0.93	1.01	1.11	1.17	1.22	1.37	1.50	1.61	1.81	1.97	2.15	2.18	2.23	2.41	2.51	2.59	2.67	2.70	2.75	2.80	2.85	2.93	2.98	3.01	3.03	3.06
350	0.97	1.06	1.09	1.18	1.30	1.36	1.42	1.60	1.75	1.87	2.12	2.30	2.51	2.54	2.60	2.81	2.93	3.02	3.11	3.14	3.21	3.27	3.33	3.42	3.48	3.51	3.54	
400	1.11	1.21	1.24	1.35	1.49	1.56	1.62	1.83	2.00	2.14	2.42	2.63	2.87	2.90	2.97	3.21	3.35	3.46	3.56	3.59	3.66	3.73	3.80	3.91	3.97	4.01		
450	1.24	1.36	1.40	1.52	1.67	1.75	1.83	2.06	2.26	2.41	2.72	2.95	3.23	3.27	3.34	3.62	3.77	3.89	4.00	4.04	4.12	4.20	4.28	4.39	4.47			
500	1.38	1.51	1.56	1.68	1.86	1.94	2.03	2.29	2.51	2.68	3.02	3.28	3.59	3.63	3.72	4.02	4.19	4.32	4.45	4.49	4.58	4.67	4.75	4.88				
550	1.52	1.66	1.71	1.85	2.04	2.14	2.23	2.52	2.76	2.95	3.33	3.61	3.94	3.99	4.09	4.42	4.61	4.75	4.89	4.94	5.04	5.13	5.23					
600	1.66	1.81	1.87	2.02	2.23	2.33	2.44	2.75	3.01	3.21	3.63	3.94	4.30	4.35	4.46	4.82	5.03	5.18	5.34	5.39	5.50	5.60						
650	1.80	1.97	2.02	2.19	2.41	2.53	2.64	2.98	3.26	3.48	3.93	4.27	4.66	4.72	4.83	5.22	5.45	5.62	5.78	5.84	5.95							
700	1.94	2.12	2.18	2.36	2.60	2.72	2.84	3.21	3.51	3.75	4.23	4.60	5.02	5.08	5.20	5.62	5.87	6.05	6.23	6.29								
750	2.07	2.27	2.33	2.53	2.79	2.92	3.05	3.43	3.76	4.02	4.54	4.92	5.38	5.44	5.57	6.03	6.29	6.48	6.67									
800	2.21	2.42	2.49	2.70	2.97	3.11	3.25	3.66	4.01	4.29	4.84	5.25	5.74	5.81	5.94	6.43	6.70	6.91										
850	2.35	2.57	2.64	2.86	3.16	3.30	3.45	3.89	4.26	4.55	5.14	5.58	6.10	6.17	6.32	6.83	7.12											
900	2.49	2.72	2.80	3.03	3.34	3.50	3.65	4.12	4.51	4.82	5.44	5.91	6.45	6.53	6.69	7.23												
950	2.63	2.87	2.95	3.20	3.53	3.69	3.86	4.35	4.76	5.09	5.75	6.24	6.81	6.89	7.06													
1000	2.76	3.02	3.11	3.37	3.72	3.89	4.06	4.58	5.01	5.36	6.05	6.57	7.17	7.26														
1050	2.90	3.18	3.27	3.54	3.90	4.08	4.26	4.81	5.26	5.62	6.35	6.89	7.53															
1100	3.04	3.33	3.42	3.71	4.09	4.28	4.47	5.04	5.51	5.89	6.65	7.22																
1150	3.18	3.48	3.58	3.88	4.27	4.47	4.67	5.27	5.76	6.16	6.96																	
1200	3.32	3.63	3.73	4.04	4.46	4.67	4.87	5.50	6.01	6.43																		
1250	3.46	3.78	3.89	4.21	4.64	4.86	5.08	5.72	6.26																			
1300	3.59	3.93	4.04	4.38	4.83	5.05	5.28	5.95																				
1350	3.73	4.08	4.20	4.55	5.02	5.25	5.48																					
1400	3.87	4.23	4.35	4.72	5.20	5.44																						
1450	4.01	4.38	4.51	4.89	5.39																							
1500	4.15	4.54	4.67	5.05																								
1550	4.29	4.69	4.82																									
1600	4.42	4.84																										
1650	4.56																											

Figure 45 – Calculation of the optimal east west exchanger performance and operating days

Table 6 – Heat exchanger performances and operating days summary

Heat exchanger	west	east
Heat exchanger performance (kW)	850 -1100	700 - 850
Number of analysed days	116	124
Number of operating days	346 - 325	335 - 318
Operating days during the year (%)	95 - 89	92 - 87

Table 6 is created basing on data analysis. As a day when the heat exchanger was not operating was marked the day when the average daily temperature was lower than 9,8 °C.

The data analysis has been done only for the most critical months from the heat exchangers' and wastewater treatment processes' point of view (October – March). It is expected that the wastewater temperature during the rest of the year is higher and the heat exchangers could be operating without any problems.

There are not sufficient data for calculating the same information in case of north heat exchanger. But based on available data and a similarity with west heat exchanger is possible to expect that the North heat exchanger performance will be even higher than in case of west heat exchanger circa 1100 - 1300 kW. The average wastewater discharges are displayed in Table 4 as well as the average wastewater temperatures are displayed in Table 5.

Total performance from all three heat exchangers could be circa 3000 kW. Heat exchangers are designed to approximately 330 days in year. The number of operating days could be even higher, if the wastewater temperature and wastewater discharge will be measured above the heat exchanger. Based on known wastewater discharge and temperature above the heat exchanger it could be possible to create an operation software and operate the heat exchangers online. The only condition that should be respected is that the wastewater temperature should not be colder than 10 °C at the wastewater inflow, that means the wastewater after heat exchanger leaving individual heat exchangers and mixing should not decrease under 9,8 °C. The results from the TEMPEST show that wastewater reheating in sewer system is possible. In sewer length 1725m is possible to reheat the wastewater by 0.1 - 0,2 °C before it reaches the WWTP.

7 Summary

The topic of this thesis interconnects more actual topics, such as: greenhouse gas emission reduction, global warming, efficient usage of wastewater. Wastewater can be called as a secondary raw material, savings is another actual topic. Nowadays the heat from wastewater on the territory of Czech Republic is just wasted. Using the heat from wastewater is interesting also from the economical point of view. Reuse of generated heat and cold and increase the use of renewable energy are two of three main strategies in future decarbonisation of European energy system. Nowadays situation with sewer heat exchanger installation is at the beginning, not only in the Czech Republic or in the European Union, but all around the world. It is important to include the heat from wastewater into the green energy sources. What is maybe even more important to bring this energy resource to public awareness. Hopefully this thesis could be a step forward. On the top of this thesis I have participated in competition announced by Ministry of industry and trade in Czech Republic. The competition was about the possibility of the secondary raw material usage.

The whole process of case study Hradec Králové results in the heat exchanger performance calculation and the most suitable heat exchangers placement. Thesis could also serve as a manual how to define the optimal heat exchangers performances and placements.

The whole process could start with the SQUID which serve to identify hot spots in the sewer systems. It is continuing with data from measuring campaign analyzation. Mean hourly flow rate and temperature were calculated for every measuring point in closure profiles of catchments areas in Hradec Králové sewer system. These were further combined into mean value for every day as well as for every month at every measuring point. Based on data analyzation results, the suitable sewer sections for heat exchangers installations, are defined. After definition of suitable sections, the heat exchanger performance needs to be designed. The most important thing is that the wastewater in heat exchangers can not be overcooled, because of the wastewater treatment processes at the WWTP. Therefore the mathematical model TEMPEST was used to describe how the wastewater temperature is developing after it is cooled in the heat exchanger. Based on result from TEMPEST mathematical simulation it is possible to design the heat exchangers performances.

Total performance from all three heat exchangers could be circa 3000 kW. The heat exchangers should operate 330 days in year (based on data analysis). Based on these suggestions the theoretical potential heat per year is 85 TJ/year. It is important to highlight that the real amount of the produced energy and the amount of energy delivered to the customers will be much lower. On the other site, the number of operating days could be even higher. If the wastewater temperature and wastewater discharge will be measured above the heat exchanger, based on known wastewater discharge and temperature above the heat exchanger could be possible create the online software and operate the heat exchangers online. The only condition that should be respected is that the wastewater temperature should not be colder than 10 °C at the wastewater inflow, that means the wastewater after heat exchanger leaving individual heat exchangers and mixing should not decrease under 9,8 °C. For example only one or two of three heat exchangers can be operated and not cooled wastewater from third sewer branch could raise the temperature after mixing.

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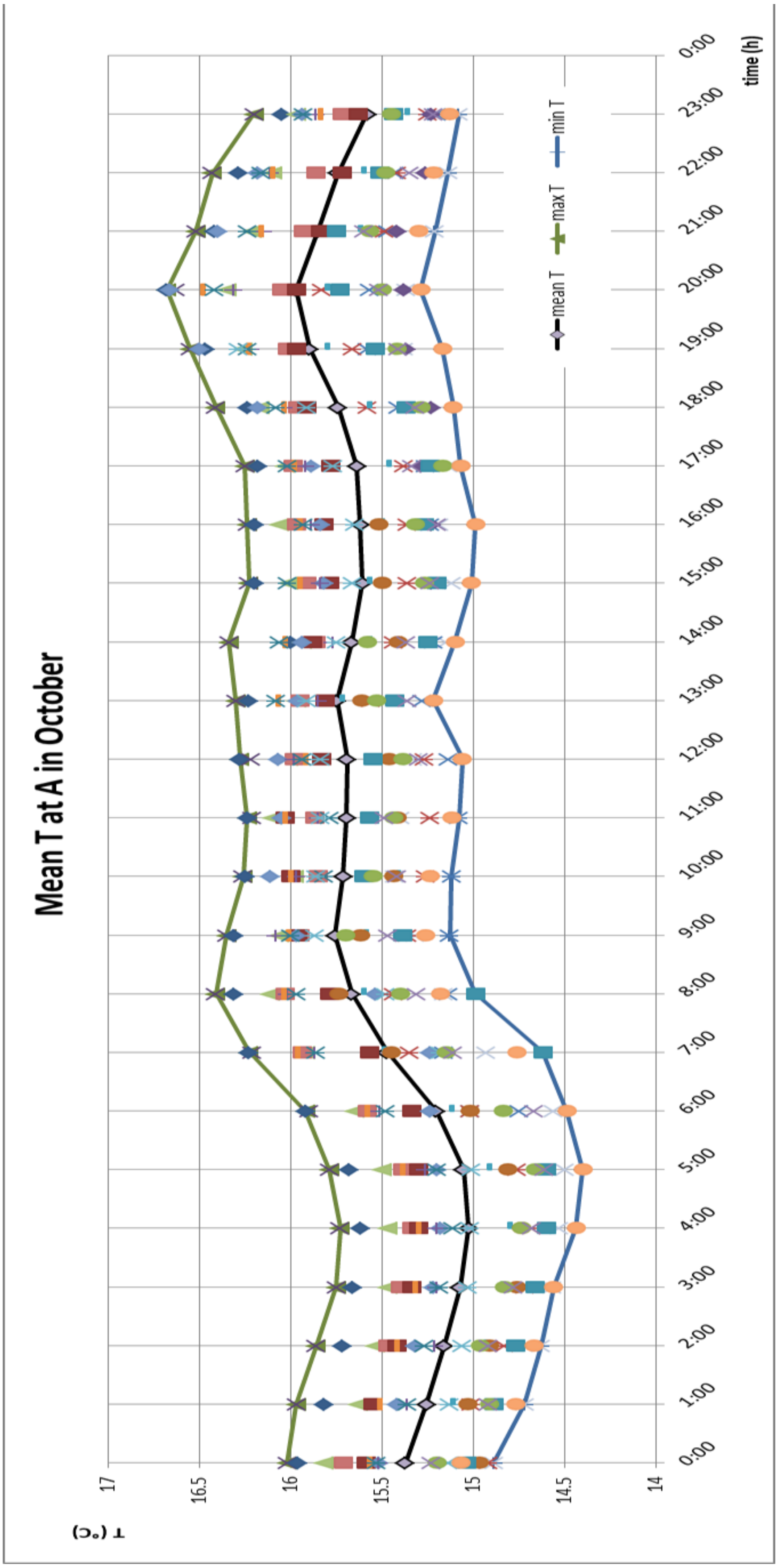
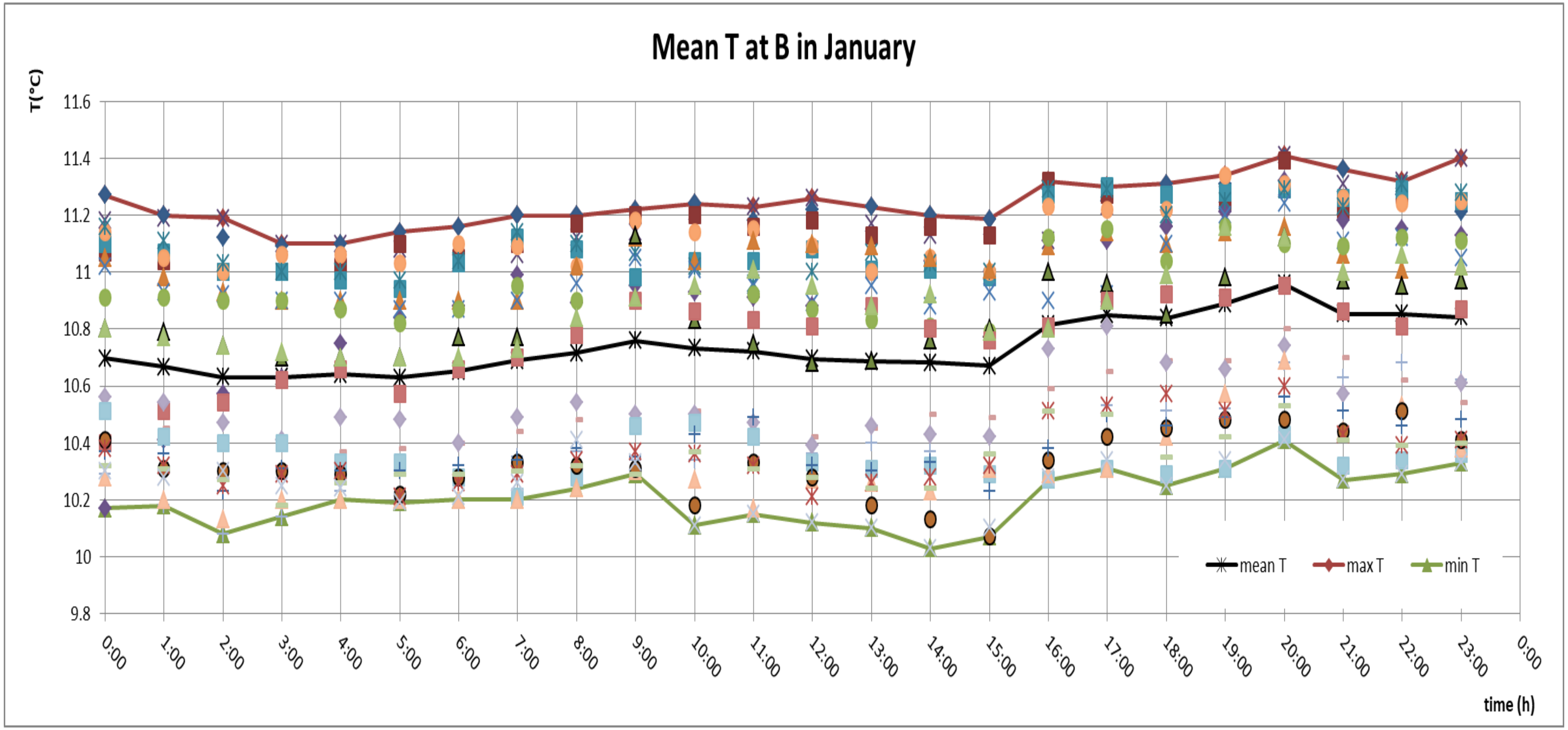
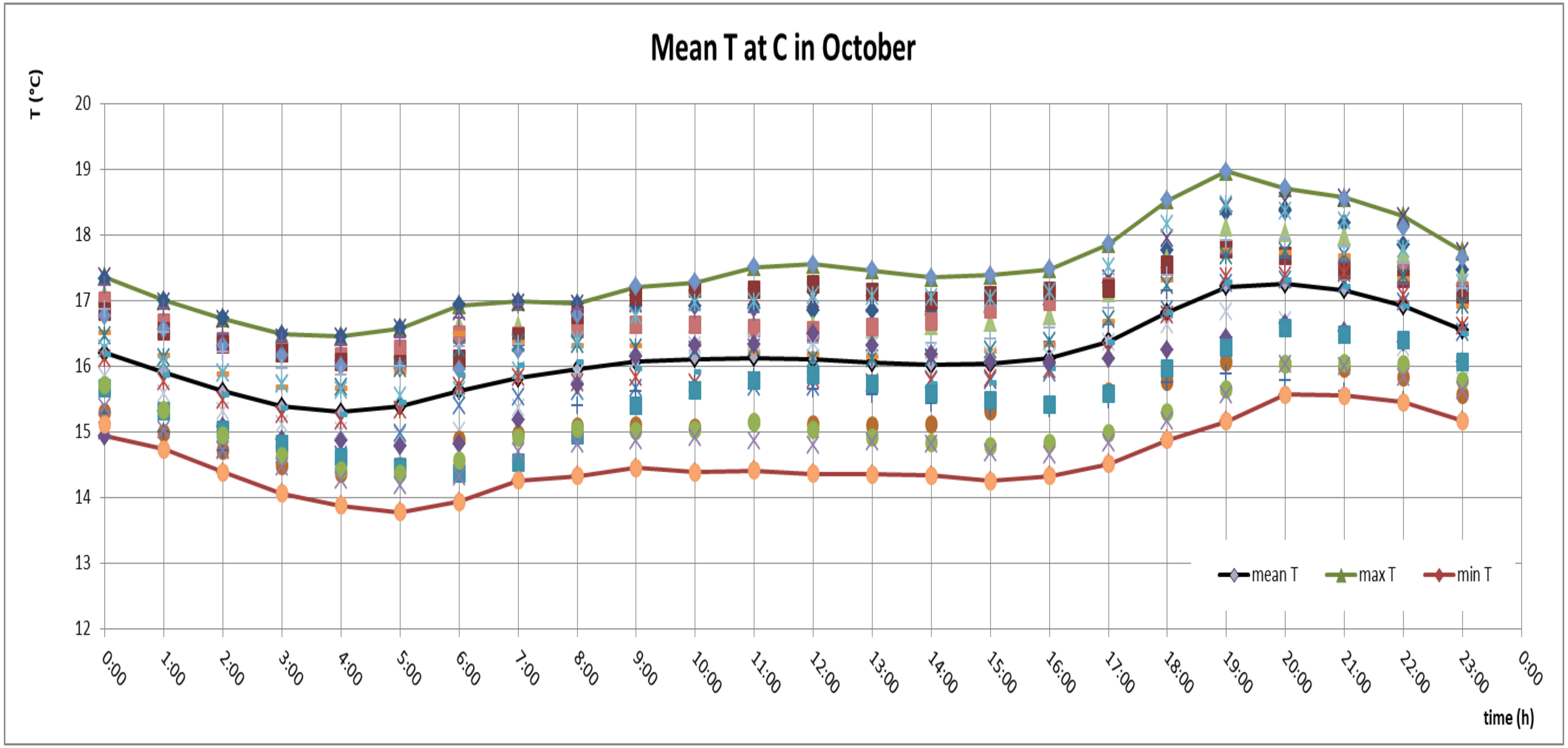
9 Appendix



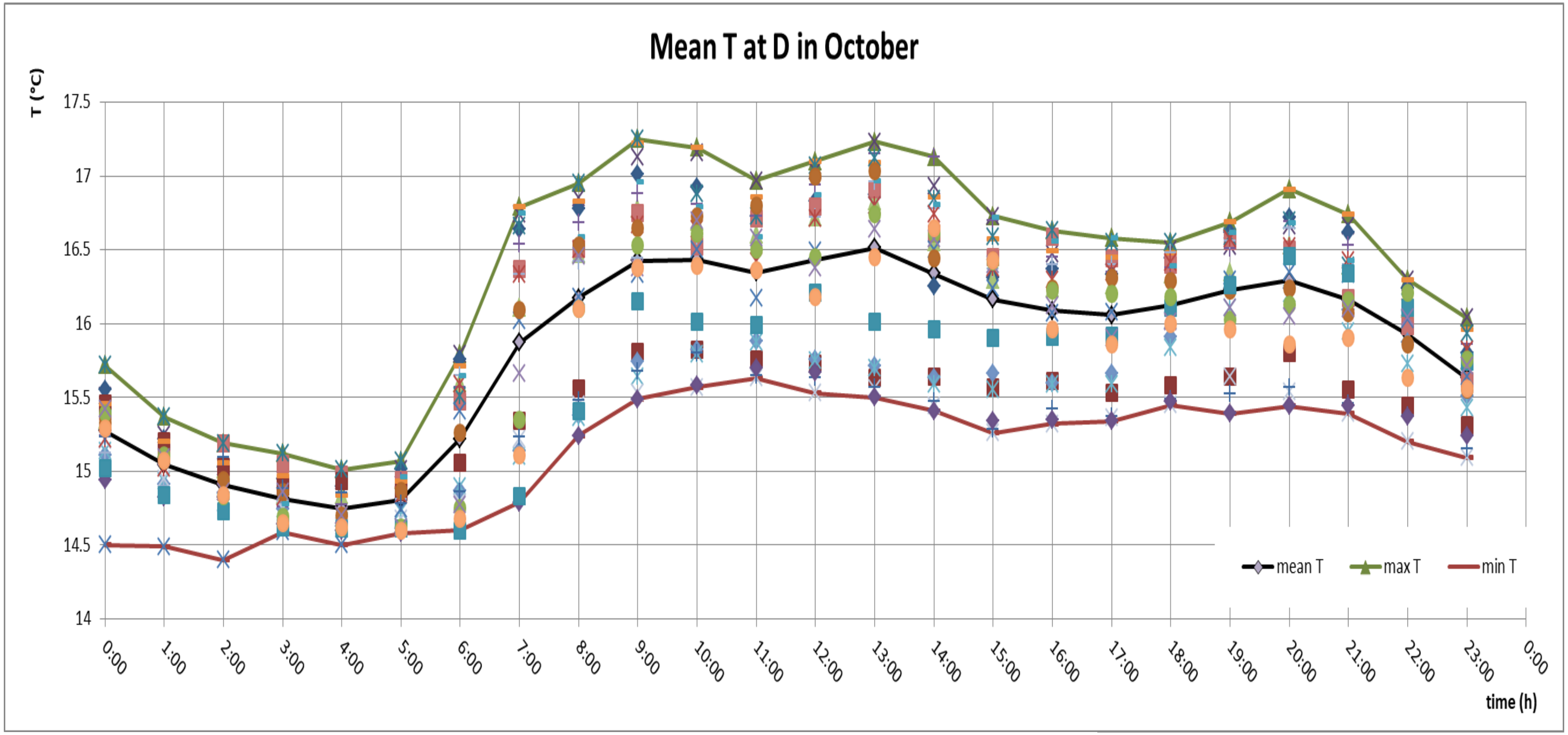
Attachment 1 - Mean hourly temperature T at measuring site A in October



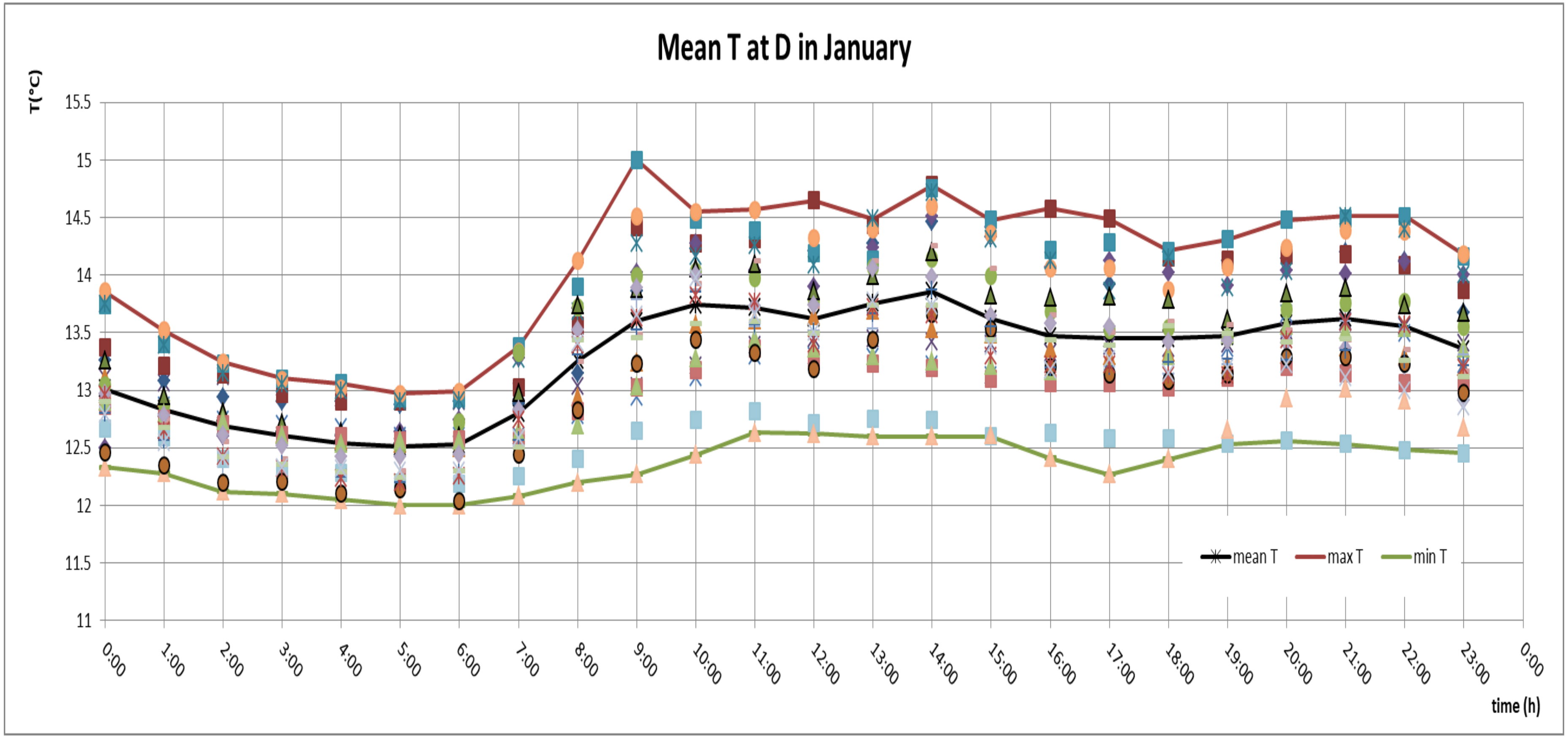
Attachment 2 - Mean hourly temperature T at measuring site B in January



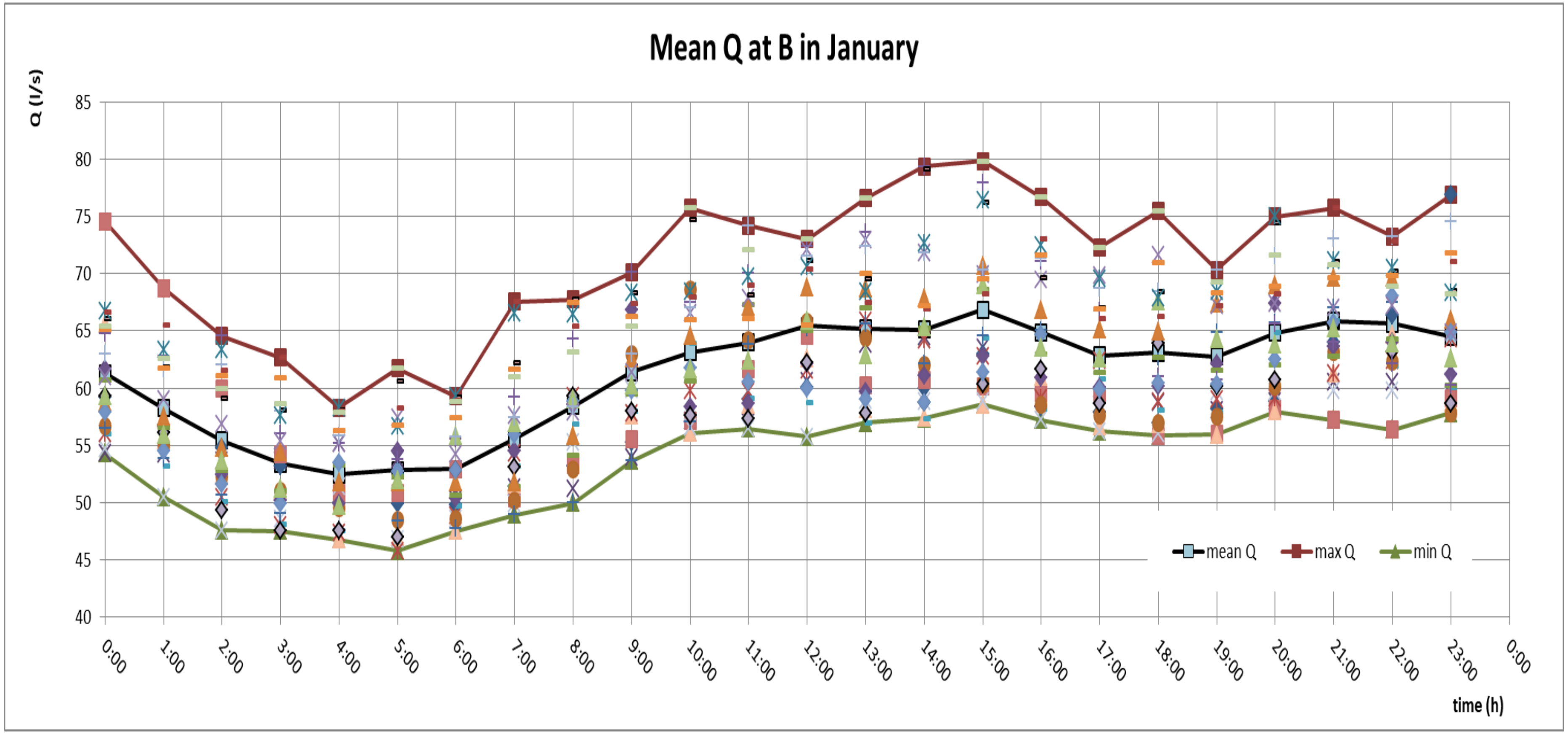
Attachment 3 - Mean hourly temperature T at measuring site C in October



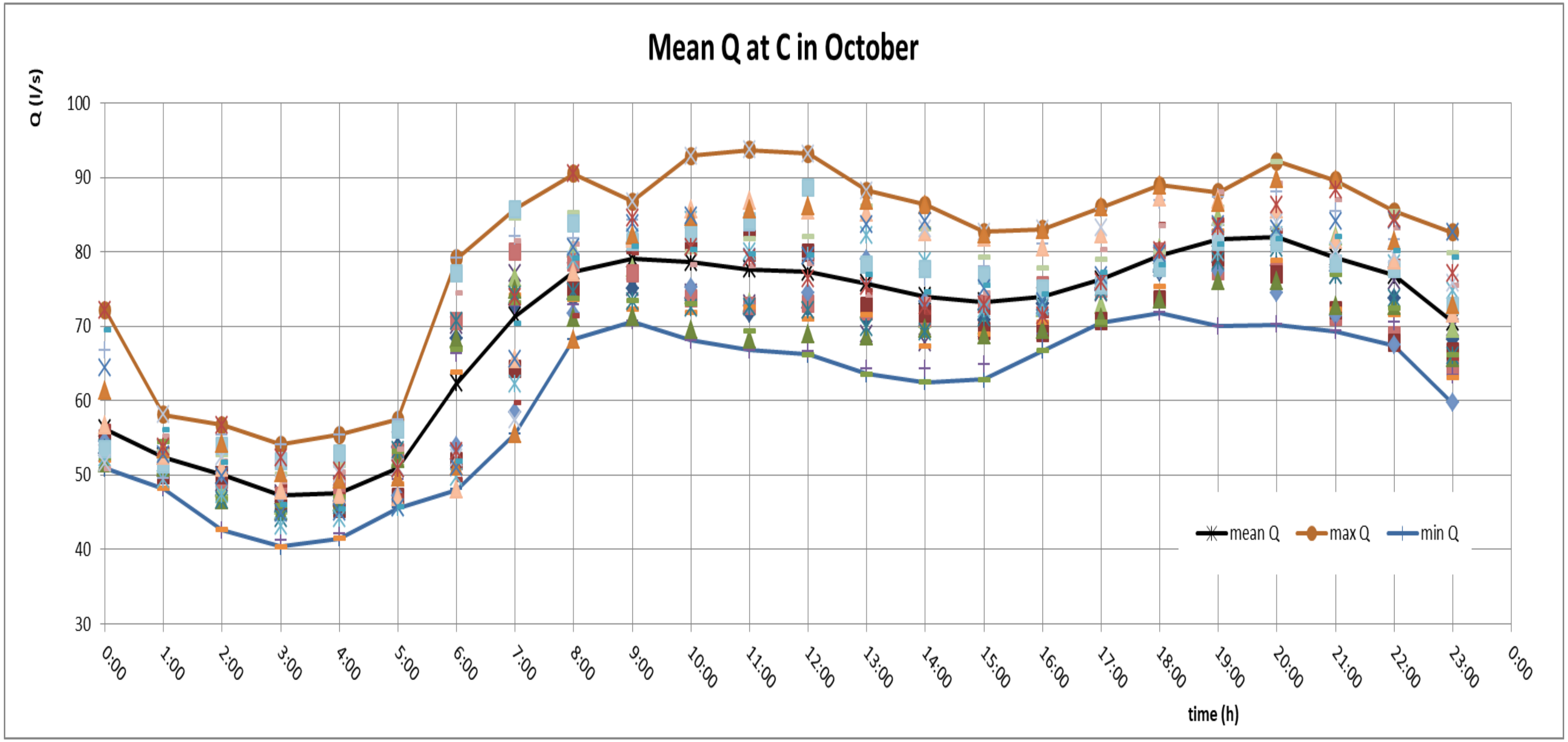
Attachment 4 - Mean hourly temperature T at measuring site D in October



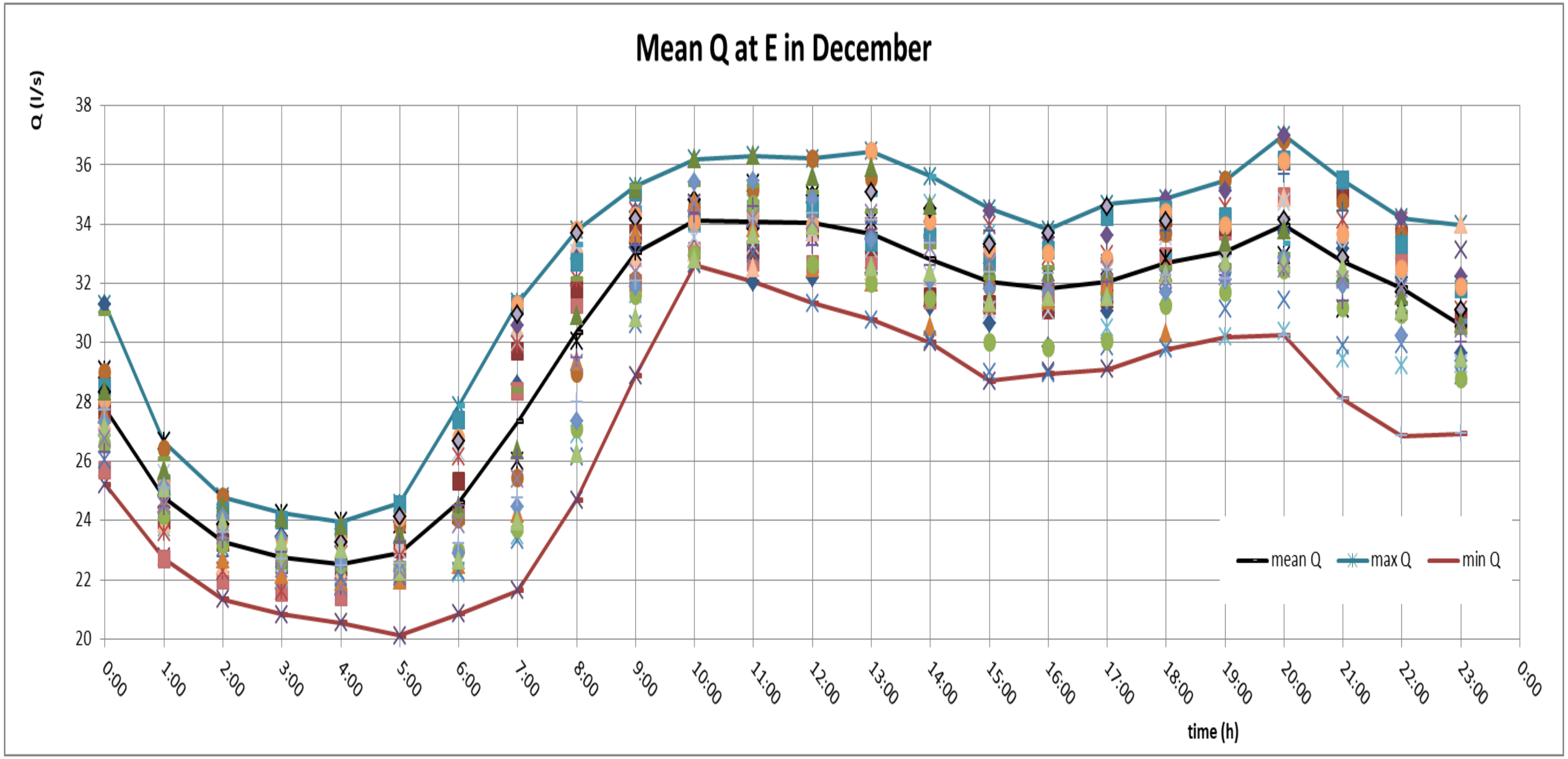
Attachment 5 - Mean hourly discharge Q at measuring site D in January



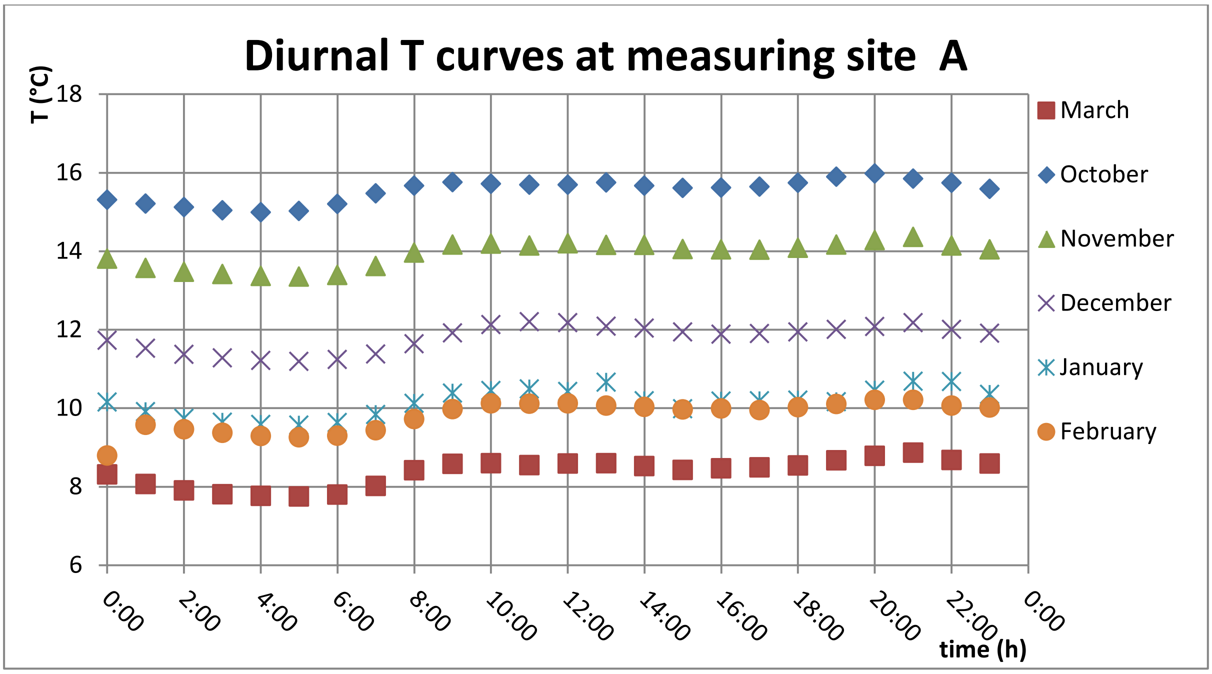
Attachment 6 - Mean hourly discharge Q at measuring site B in January



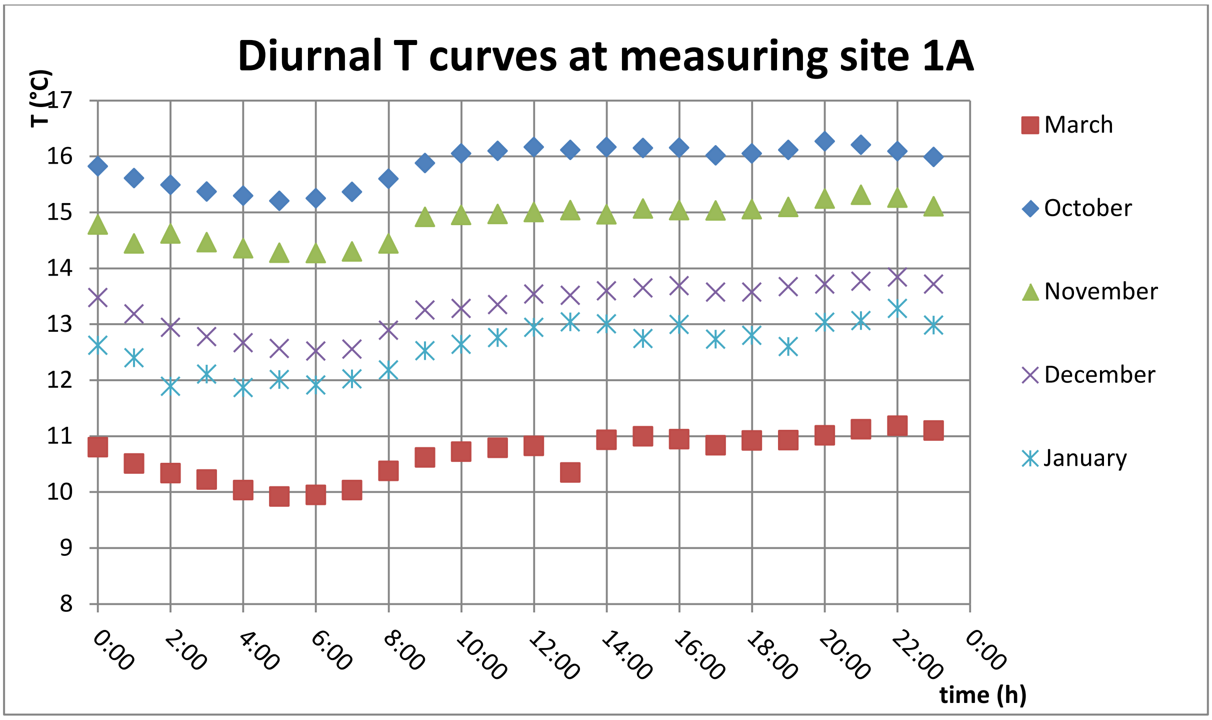
Attachment 7 - Mean hourly discharge Q at measuring site C in October



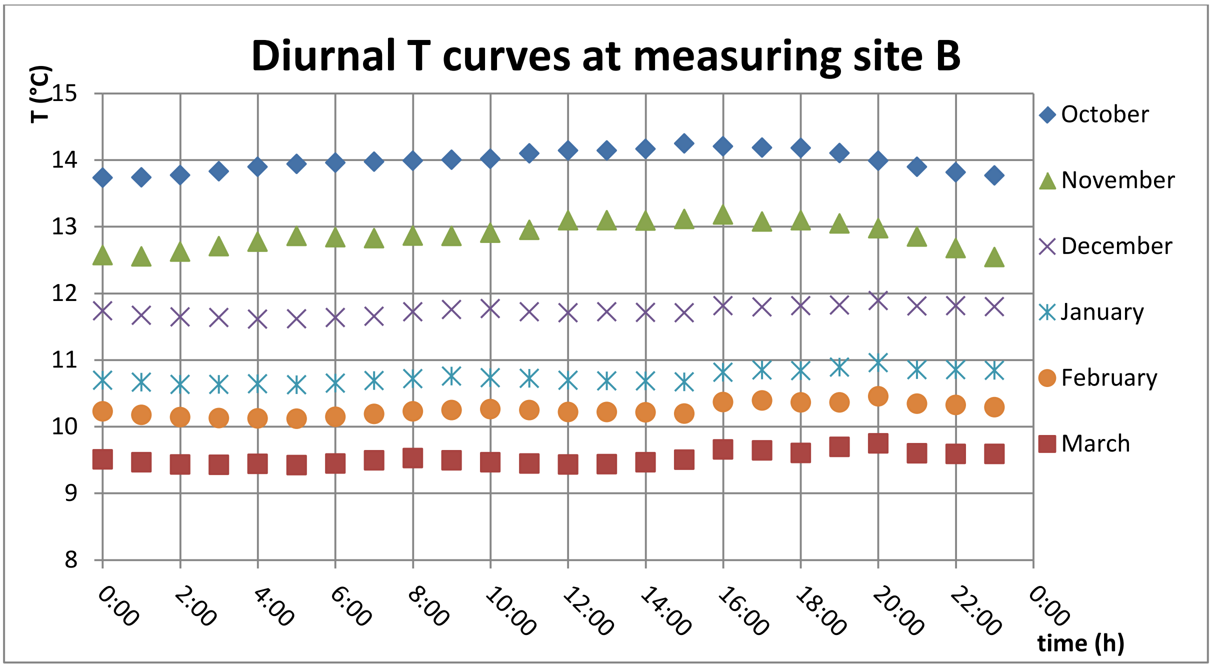
Attachment 8 - Mean hourly discharge Q at measuring site E in December



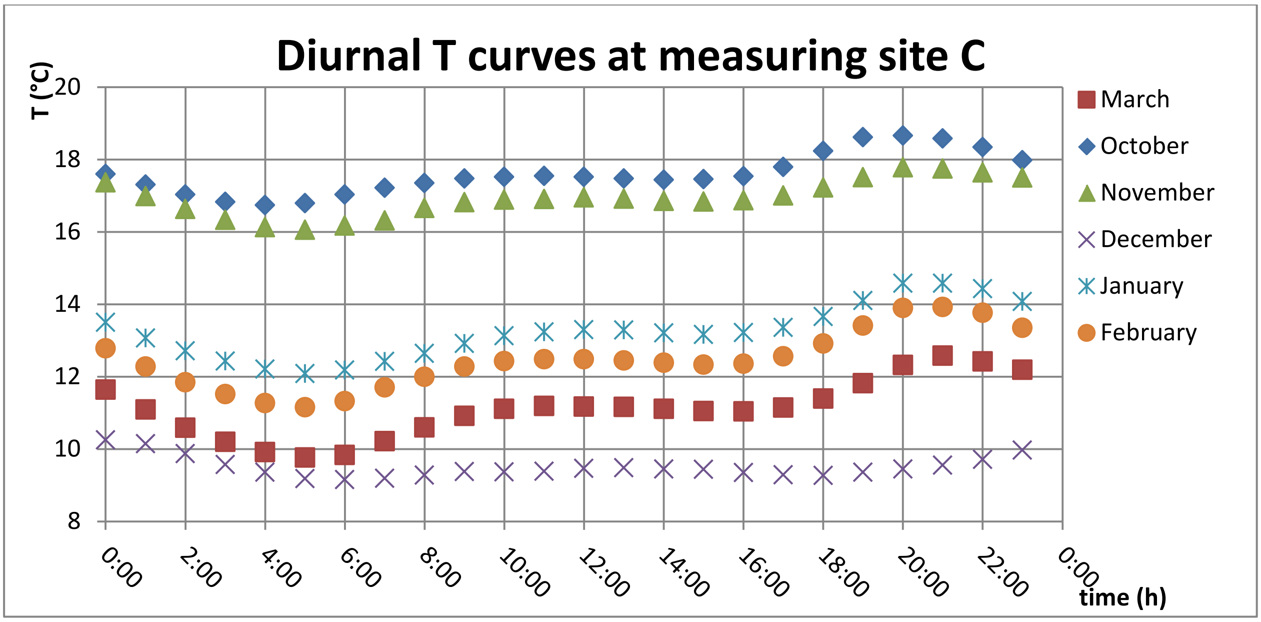
Attachment 9 – Diurnal temperature curves at measuring site A



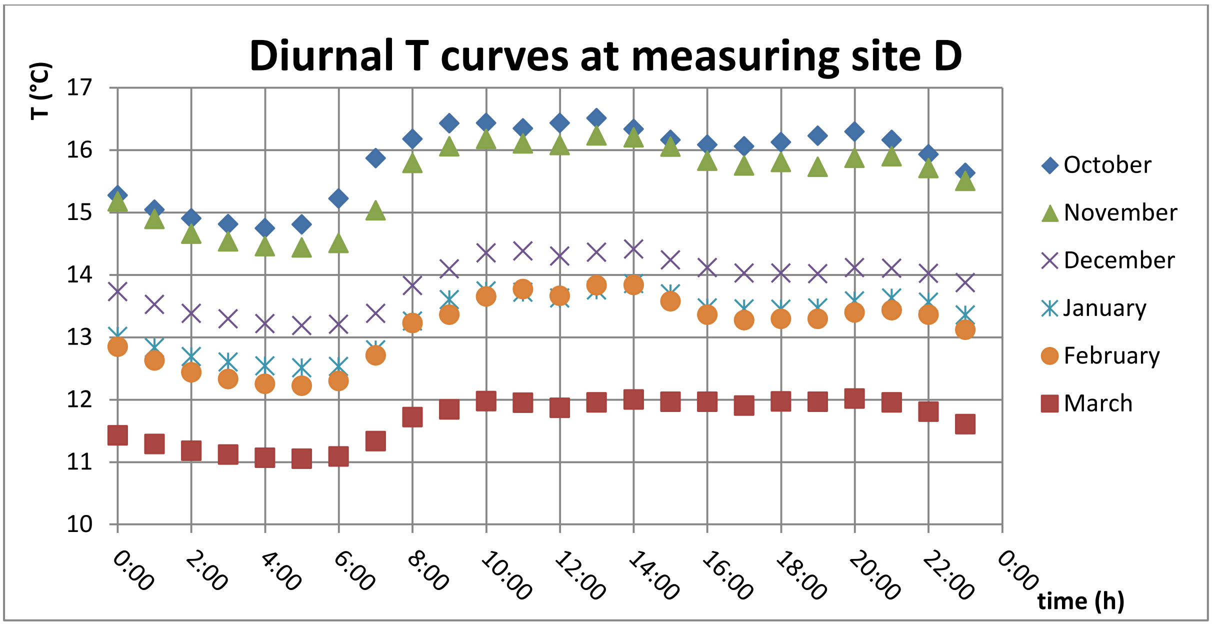
Attachment 10 – Diurnal temperature curves at measuring site 1A



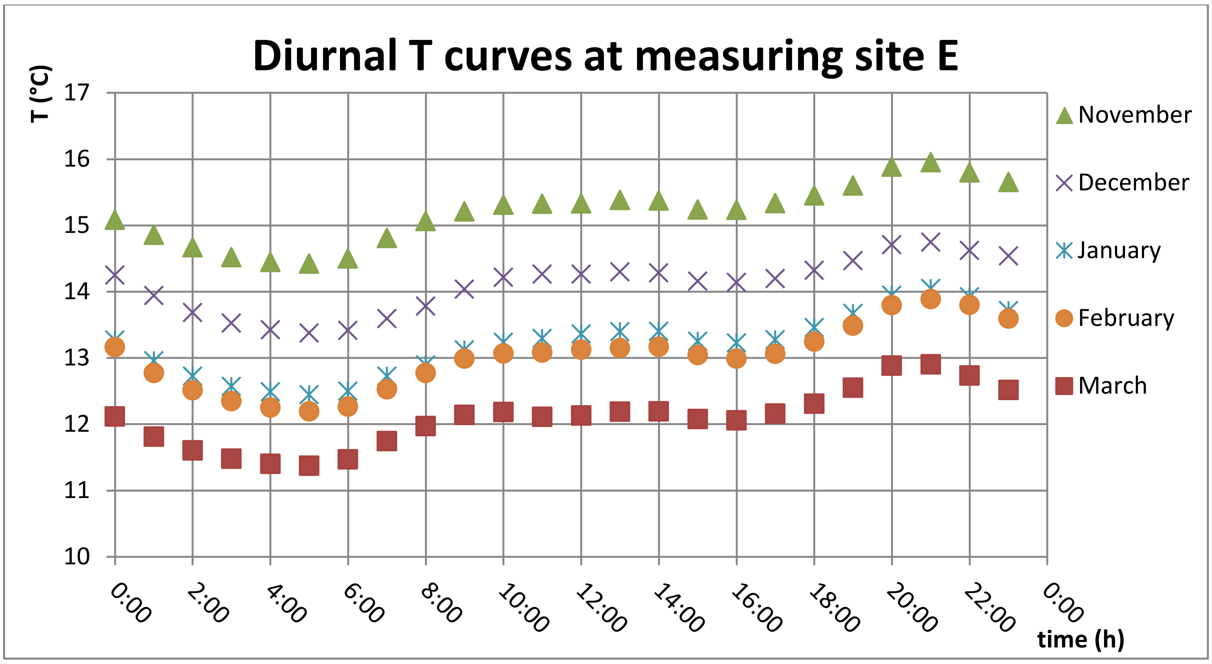
Attachment 11 - Diurnal temperature curves at measuring site B



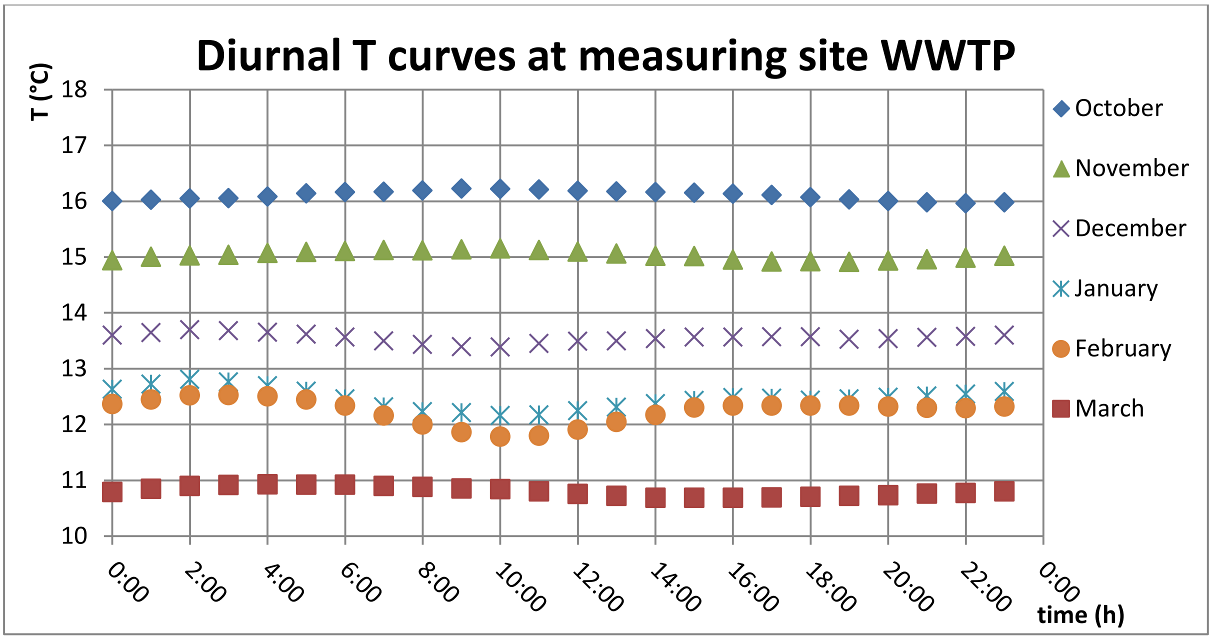
Attachment 12 - Diurnal temperature curves at measuring site C



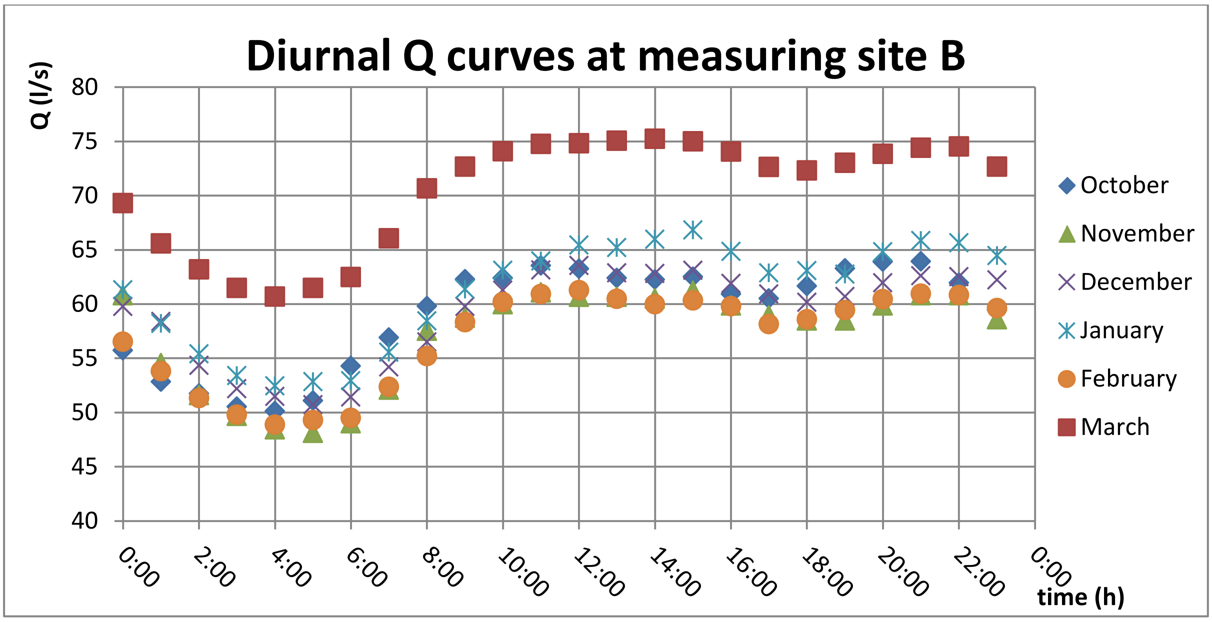
Attachment 13 - Diurnal temperature curves at measuring site D



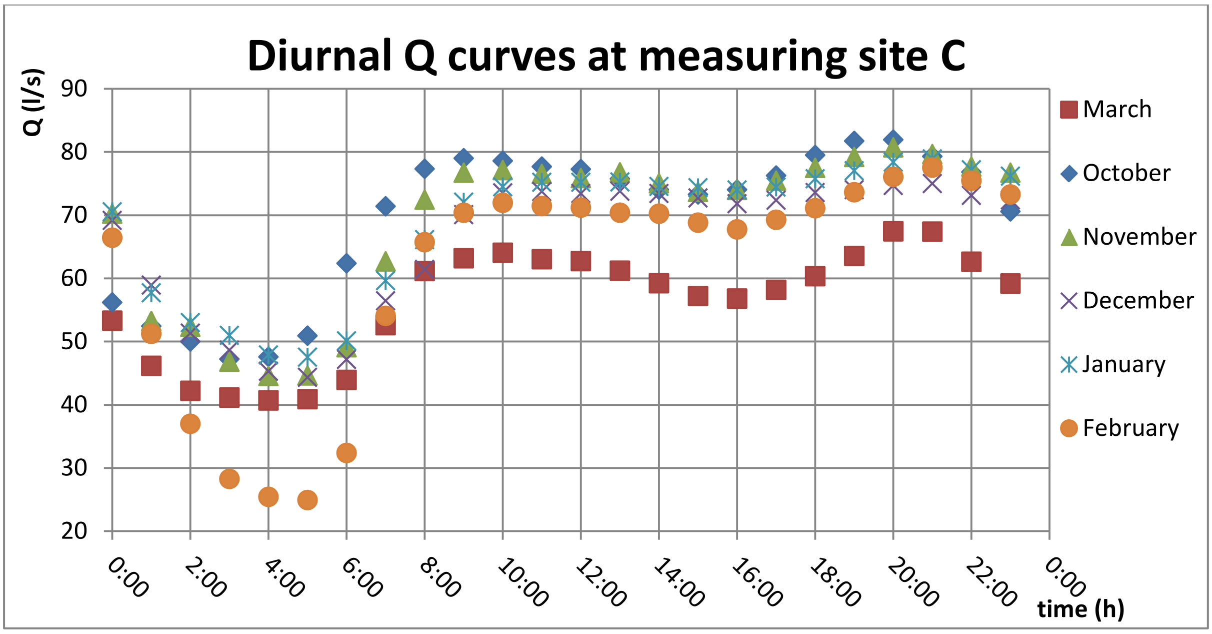
Attachment 14- Diurnal temperature curves at measuring site E



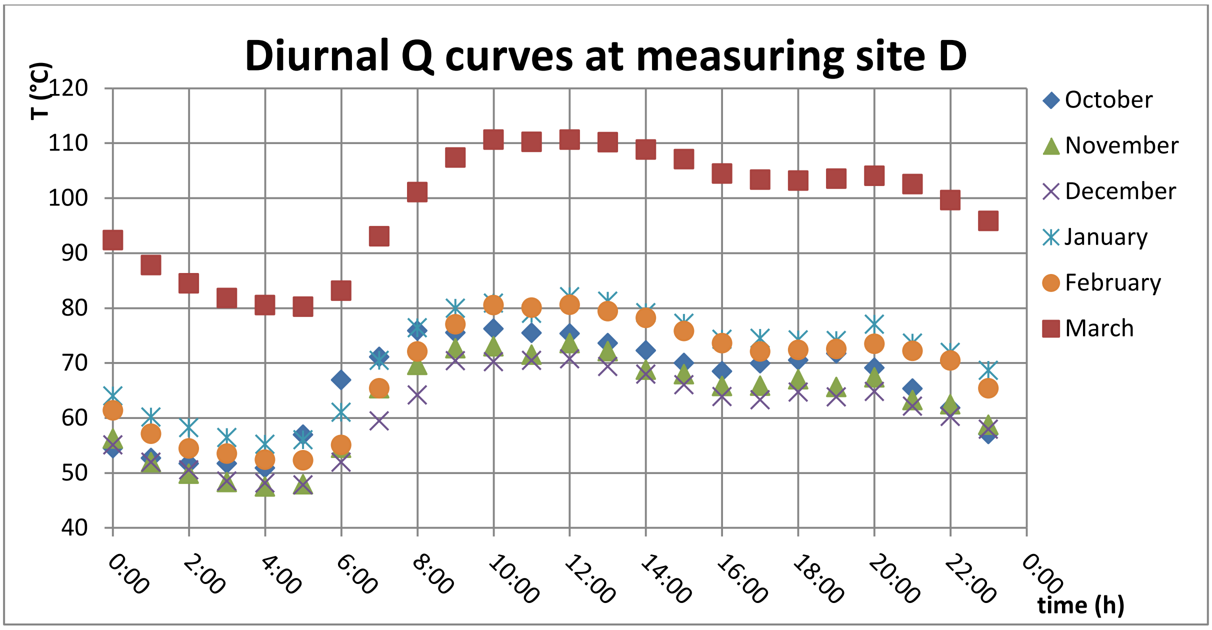
Attachment 15- Diurnal temperature curves at measuring site WWTP



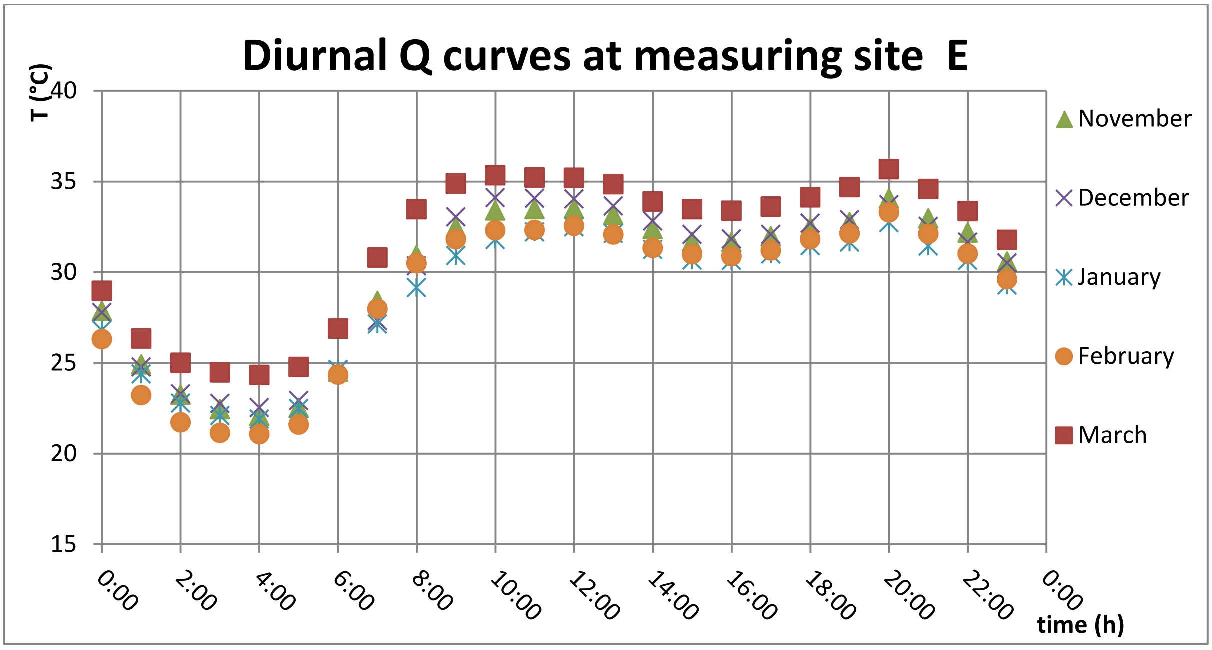
Attachment 16 - Diurnal discharge curves at measuring site B



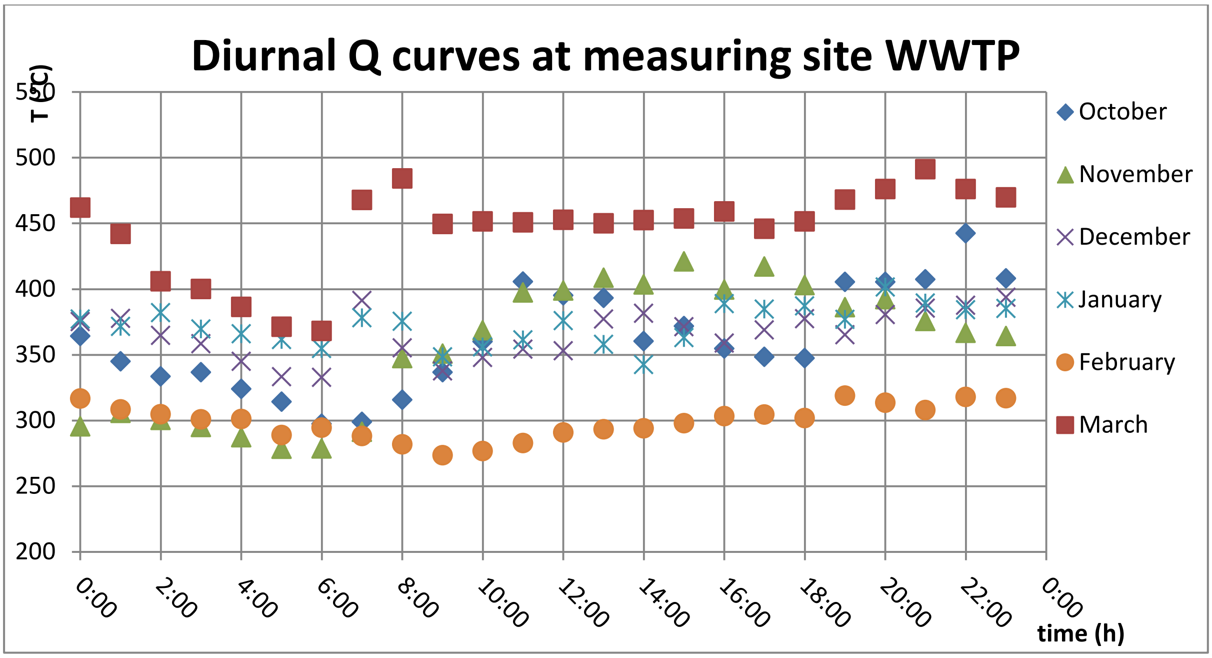
Attachment 17 - Diurnal discharge curves at measuring site C



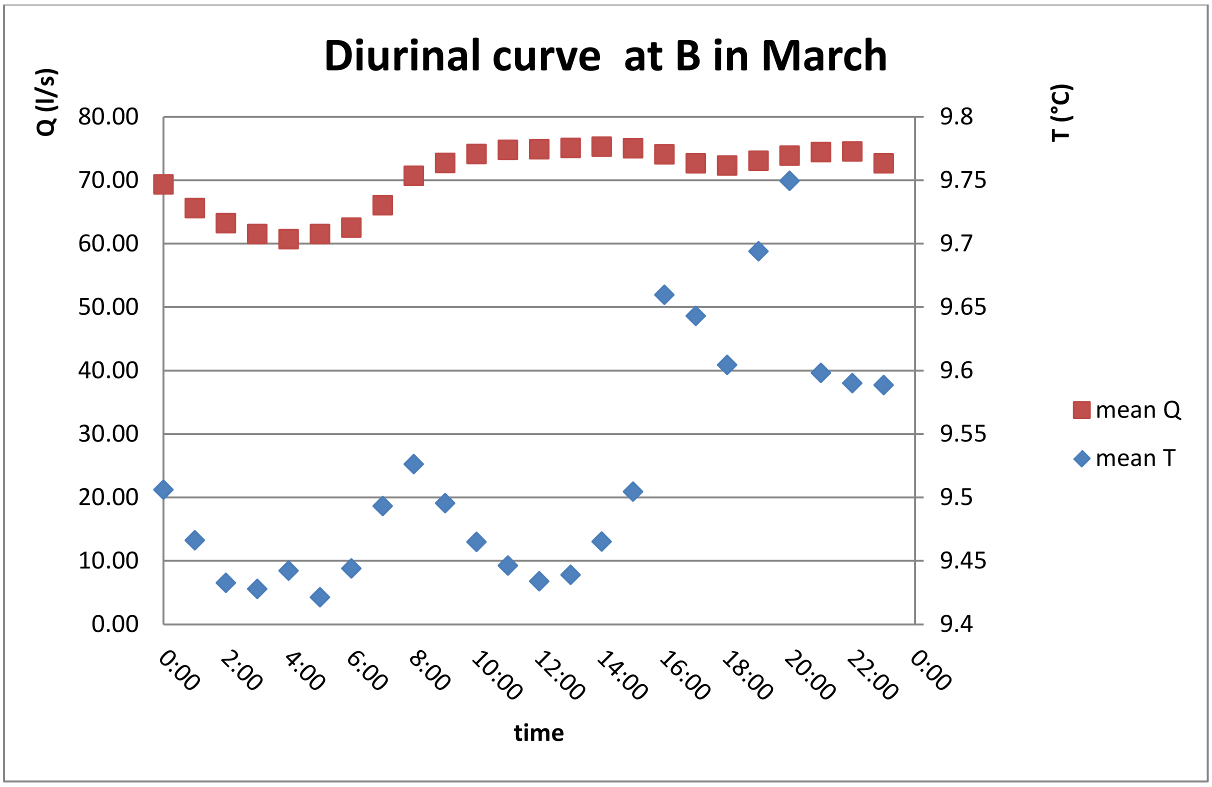
Attachment 18 -Diurnal discharge curves at measuring site D



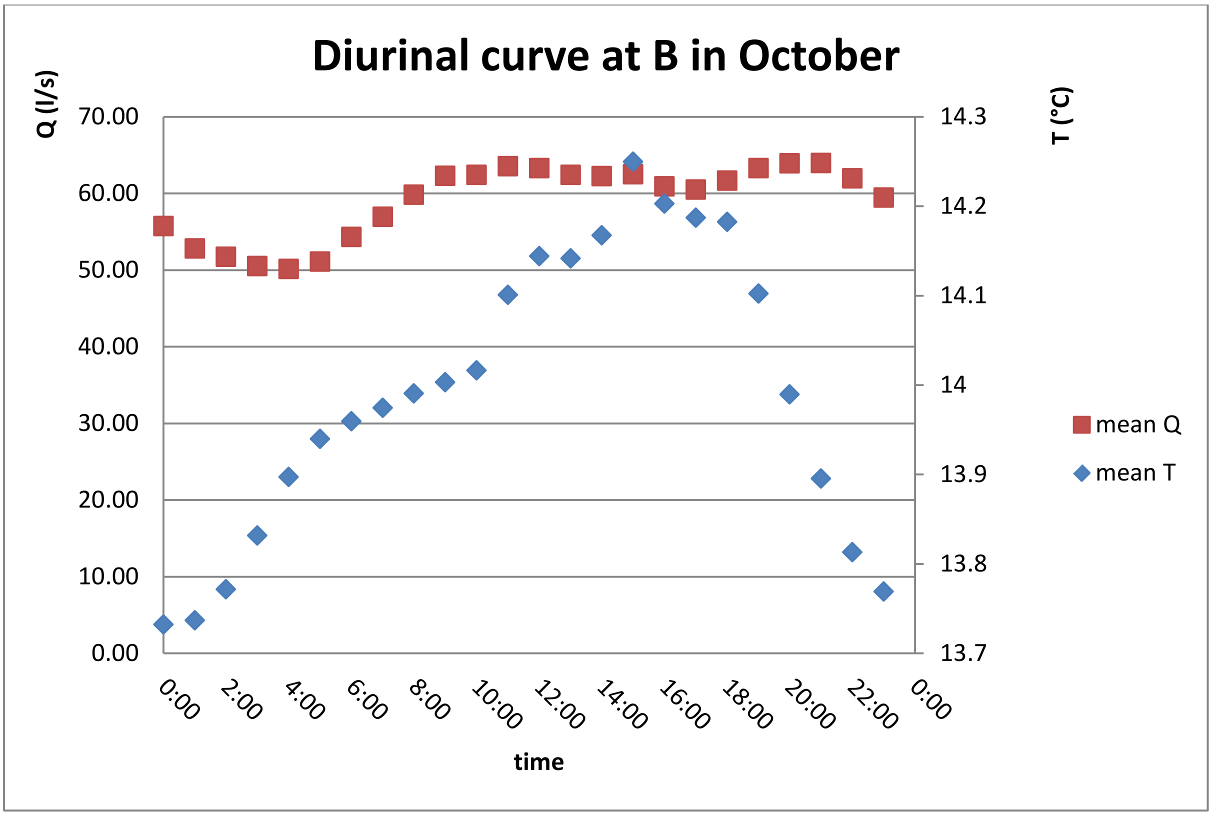
Attachment 19 - Diurnal discharge curves at measuring site E



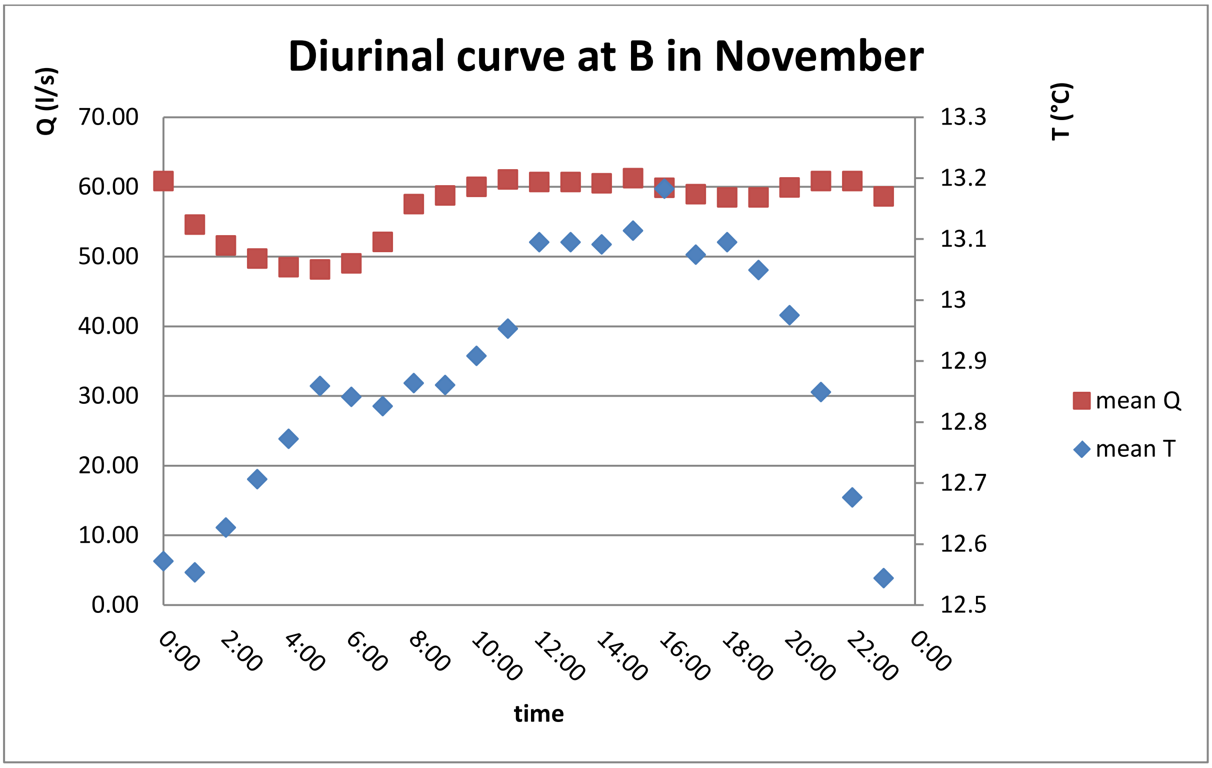
Attachment 20 - Diurnal discharge curves at measuring site WWTP



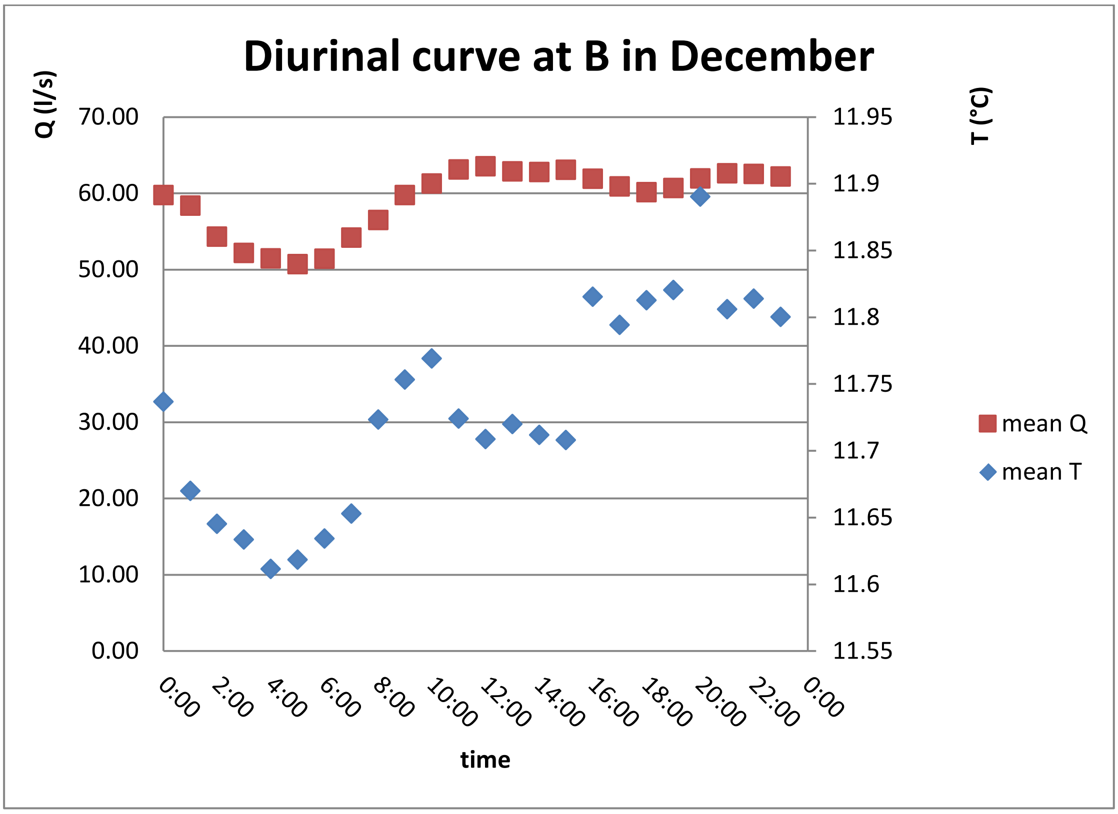
Attachment 21 – Diurnal temperature and discharge curves at measuring site B in March



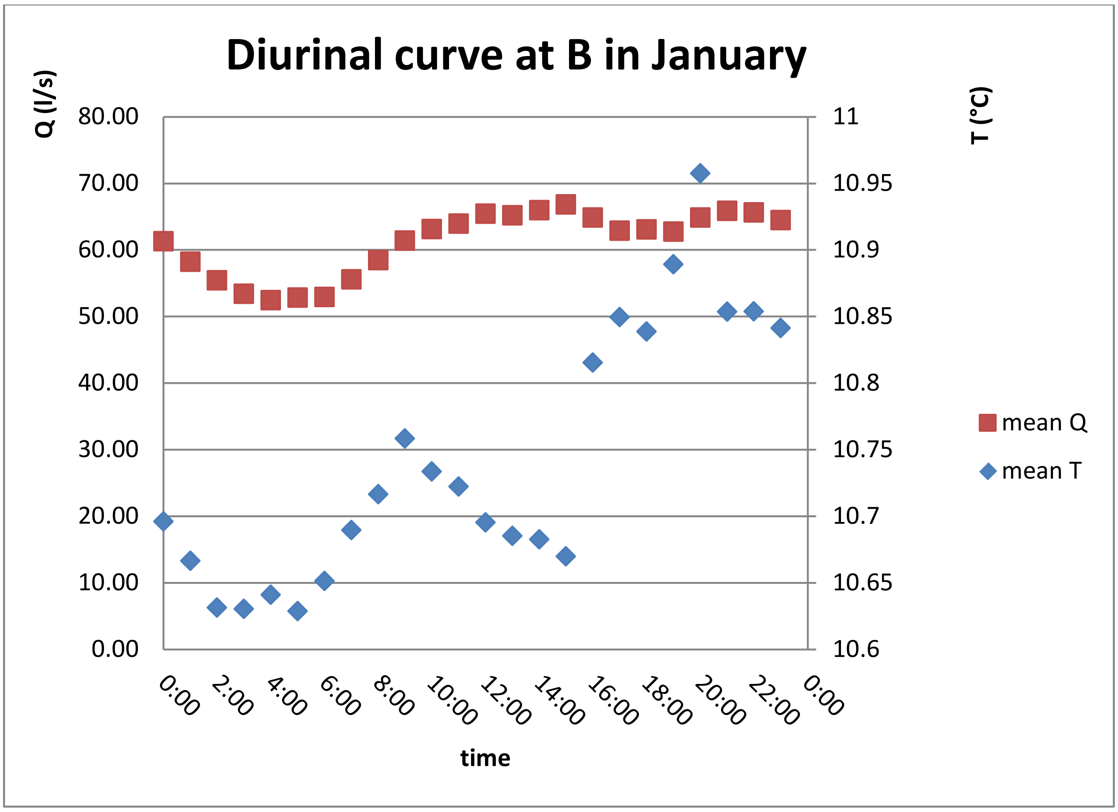
Attachment 22 - Diurnal temperature and discharge curves at measuring site B in October



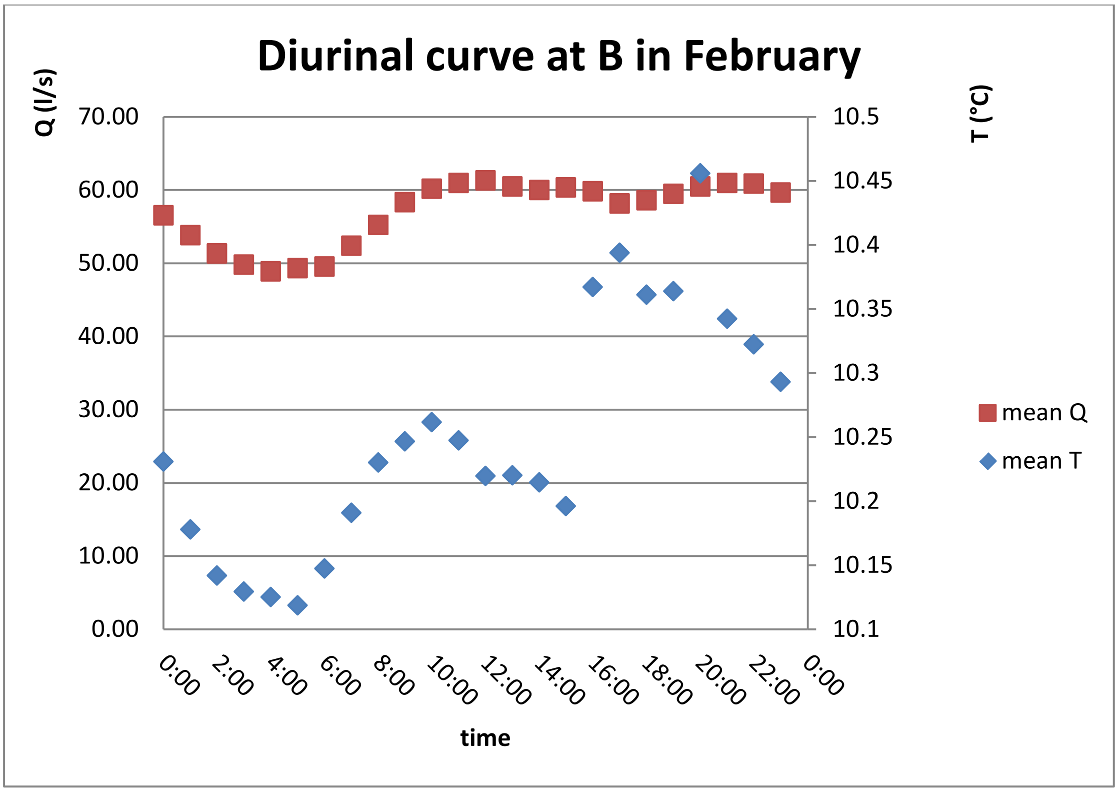
Attachment 23 - Diurnal temperature and discharge curves at measuring site B in November



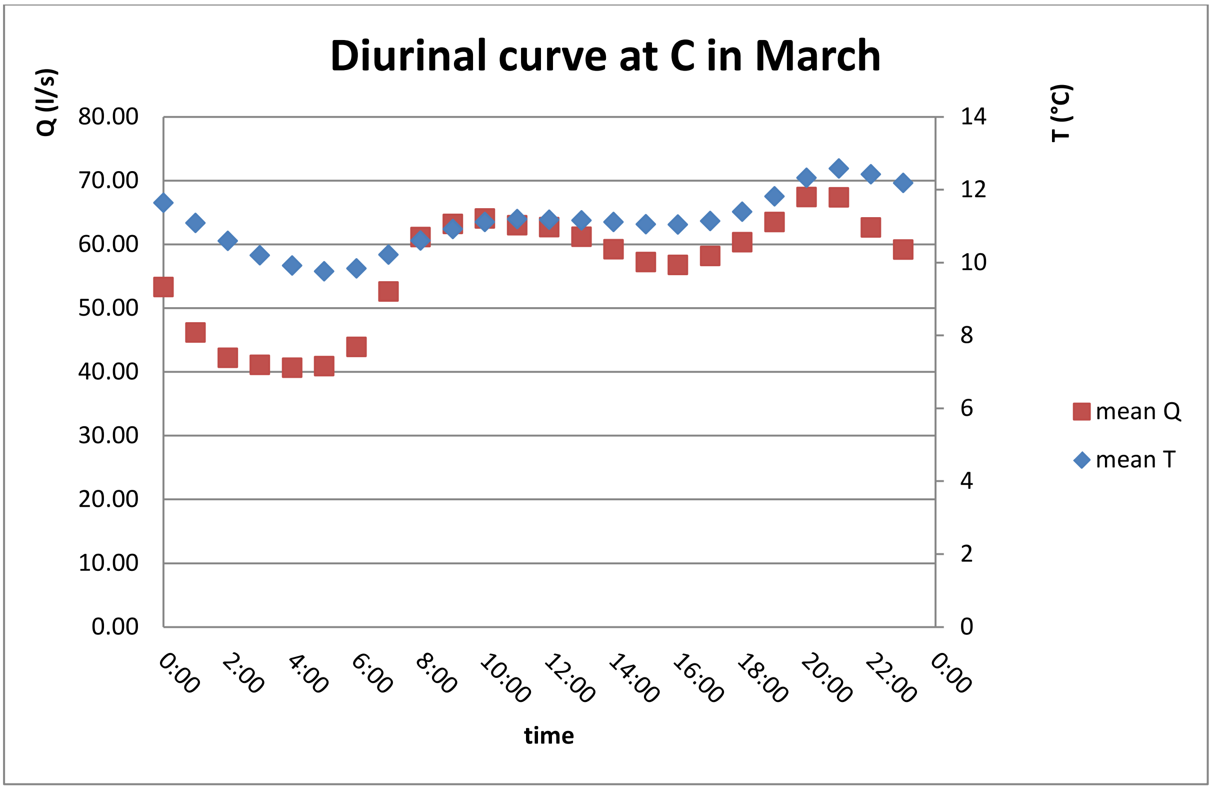
Attachment 24 - Diurnal temperature and discharge curves at measuring site B in December



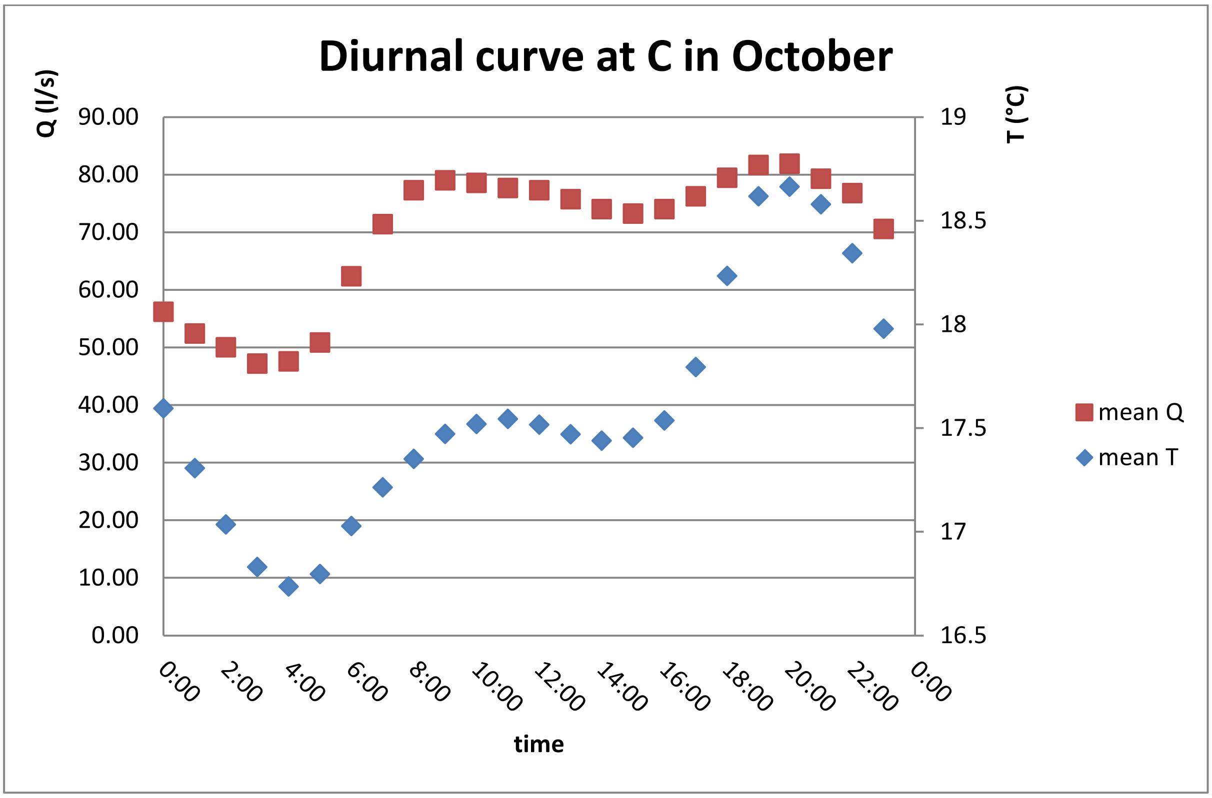
Attachment 25 - Diurnal temperature and discharge curves at measuring site B in January



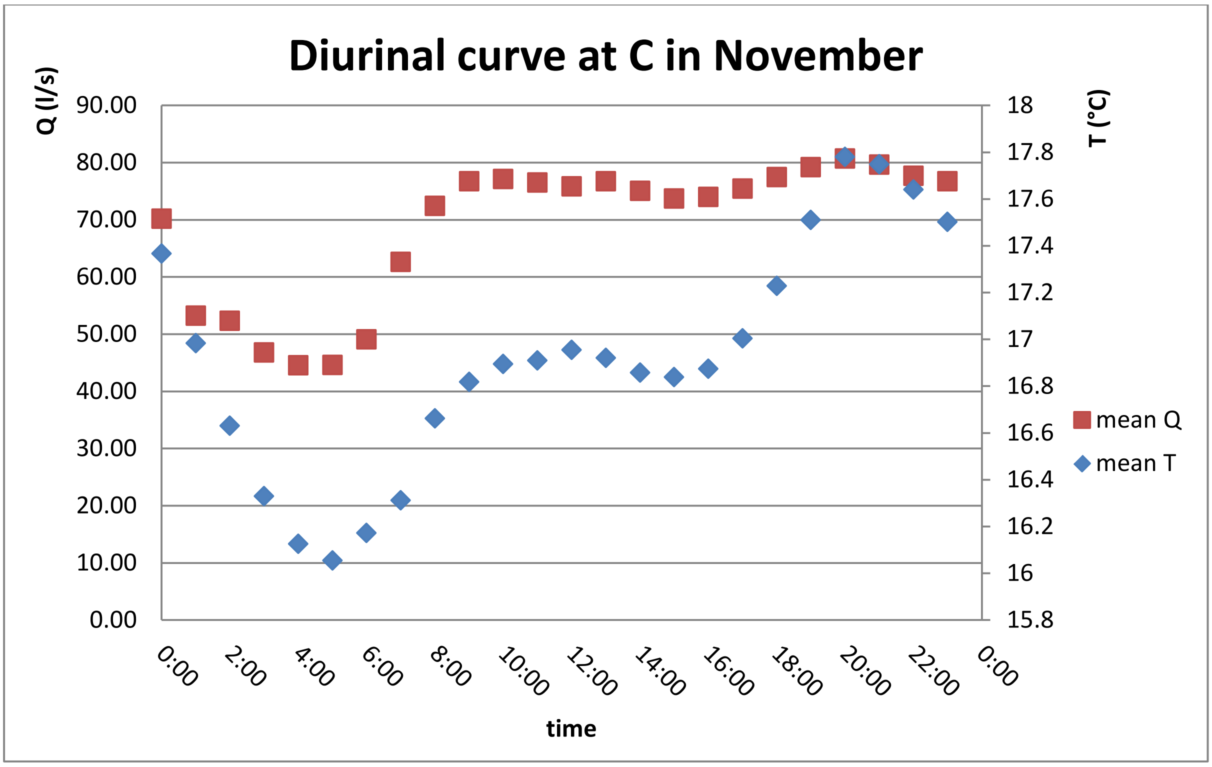
Attachment 26- Diurnal temperature and discharge curves at measuring site B in February



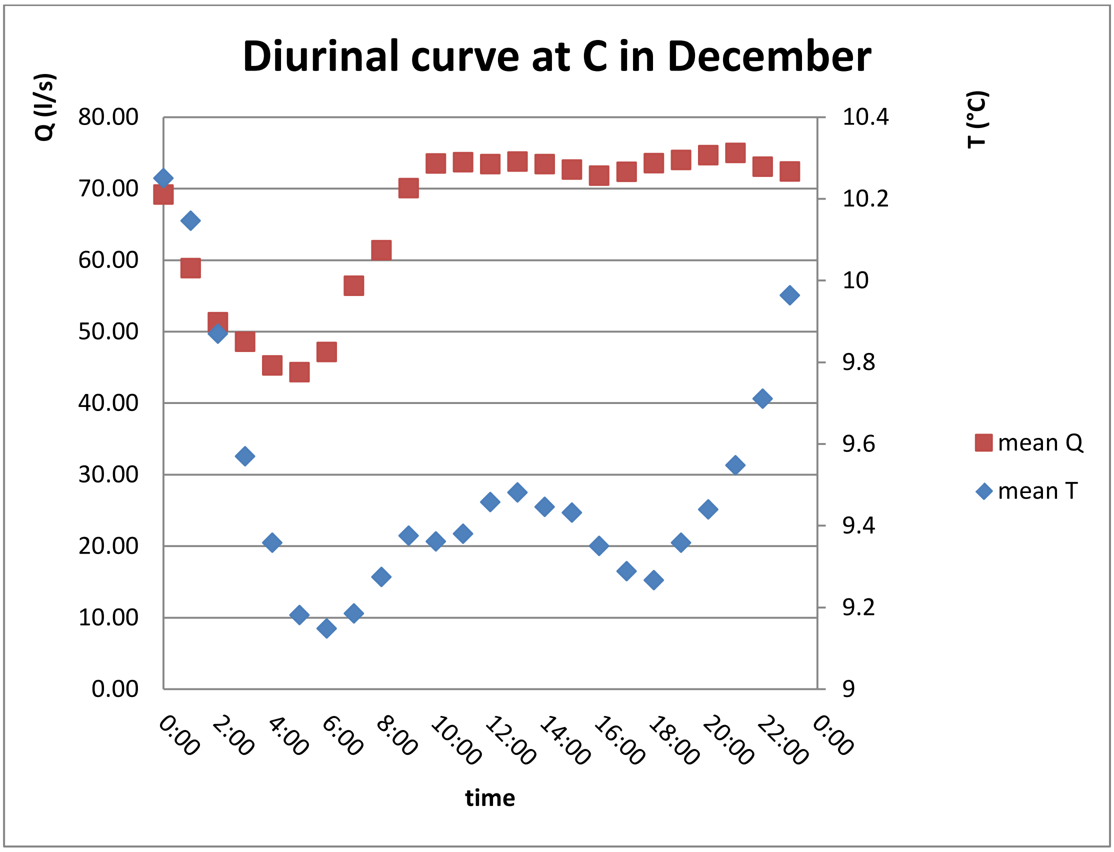
Attachment 27 - Diurnal temperature and discharge curves at measuring site C in March



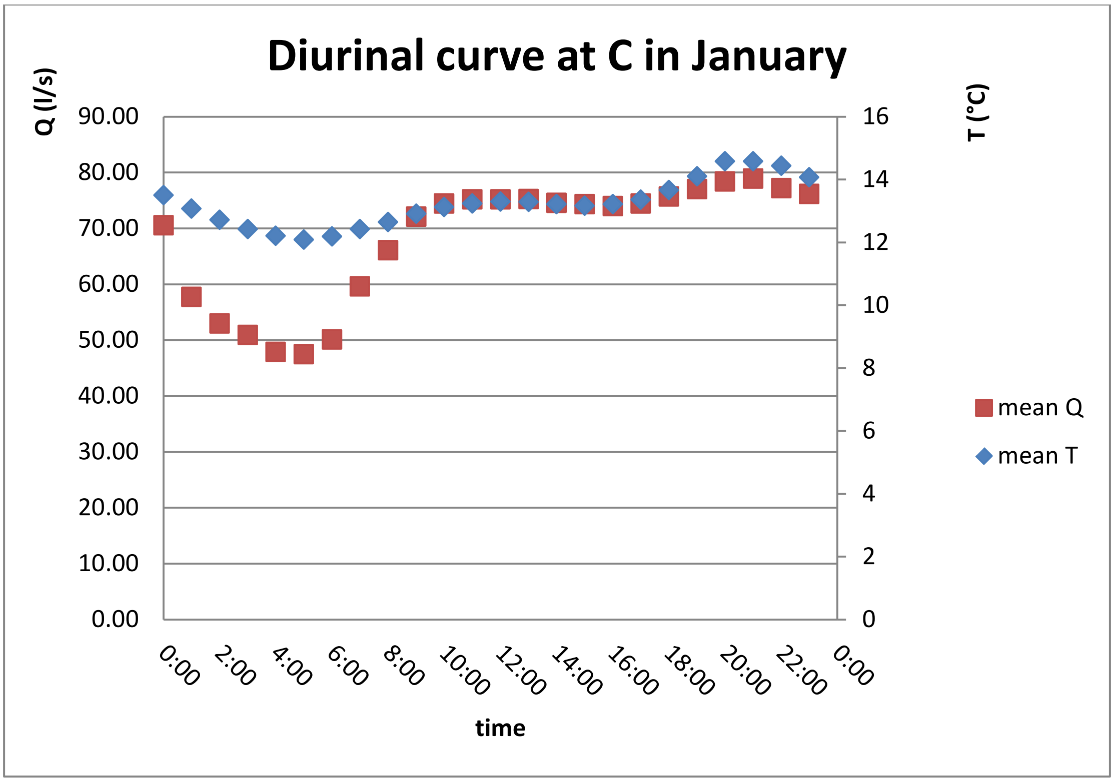
Attachment 28 - Diurnal temperature and discharge curves at measuring site C in October



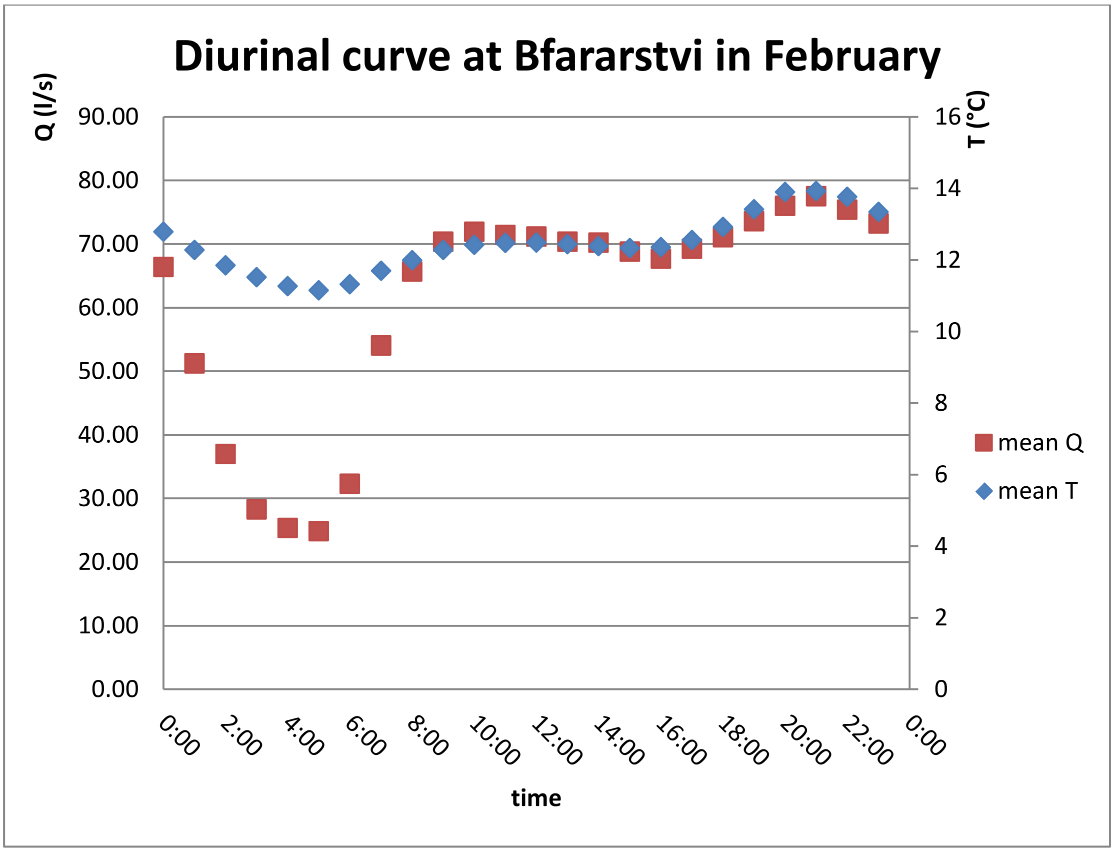
Attachment 29 - Diurnal temperature and discharge curves at measuring site C in November



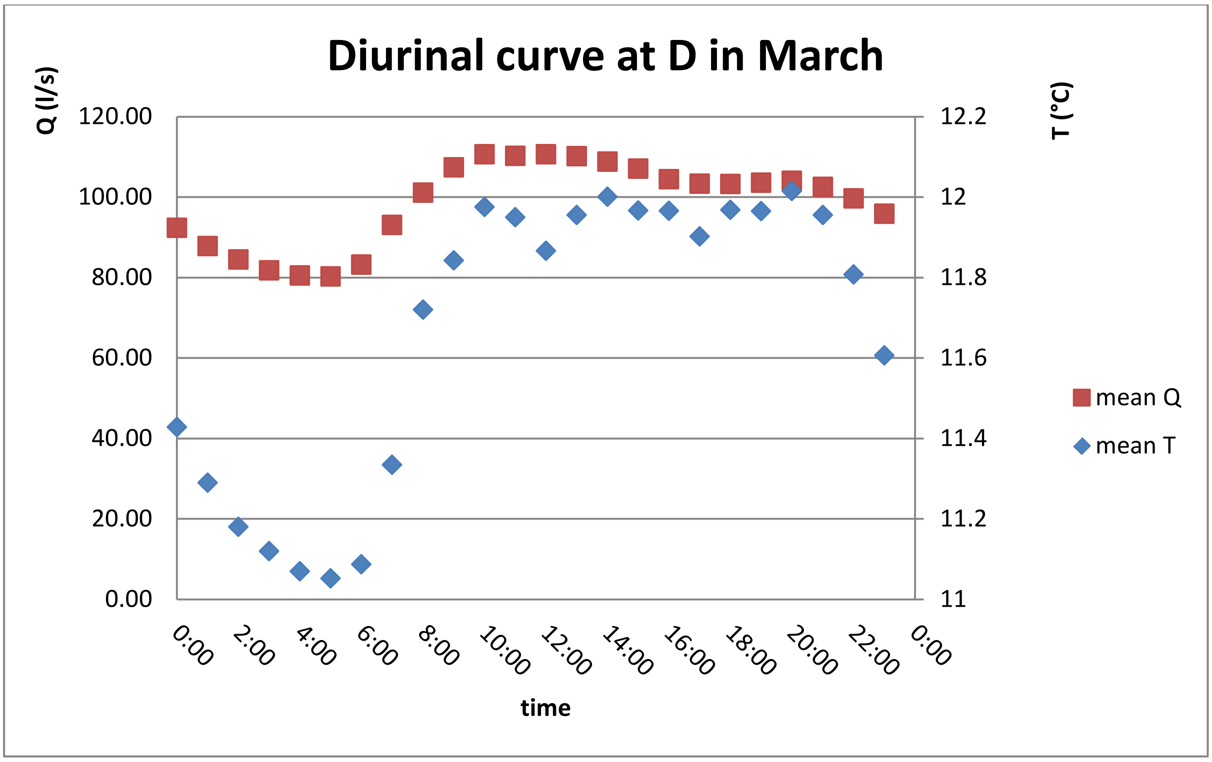
Attachment 30 - Diurnal temperature and discharge curves at measuring site C in December



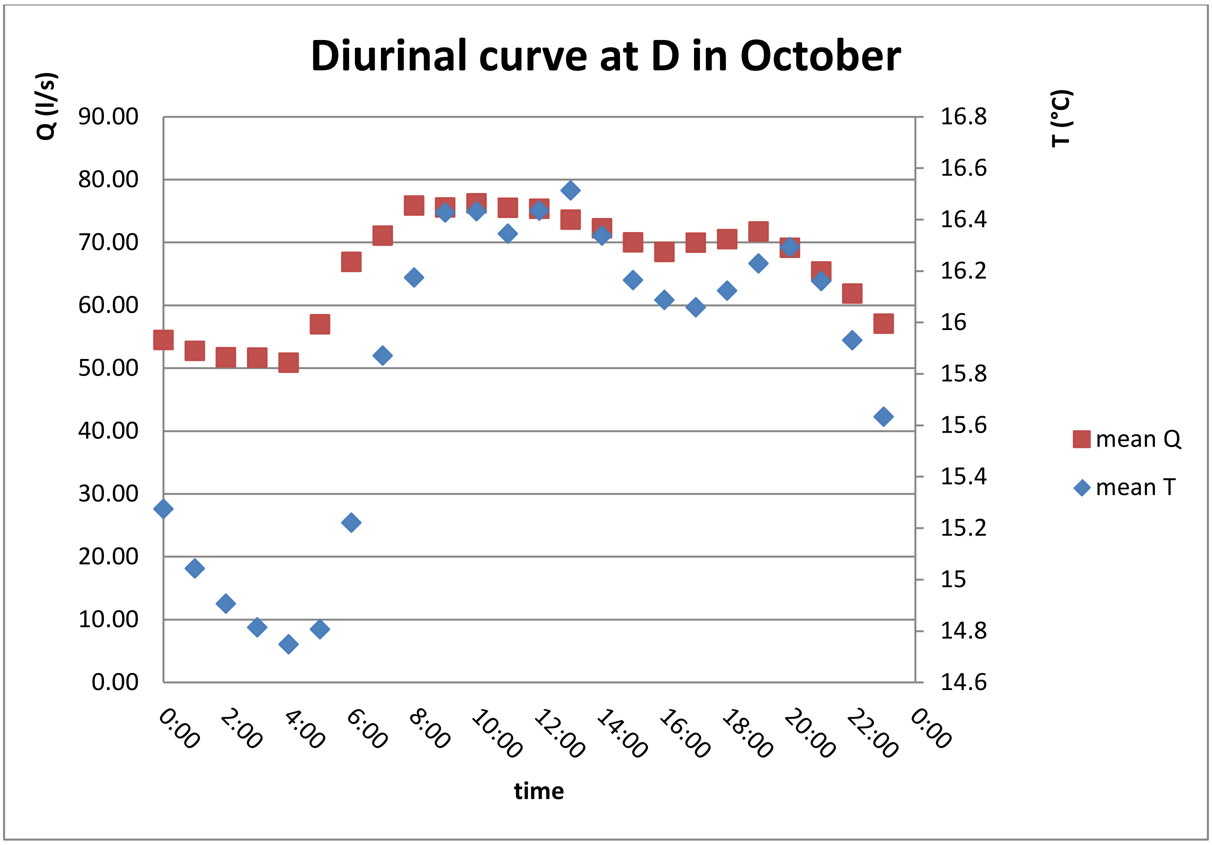
Attachment 31 - Diurnal temperature and discharge curves at measuring site C in January



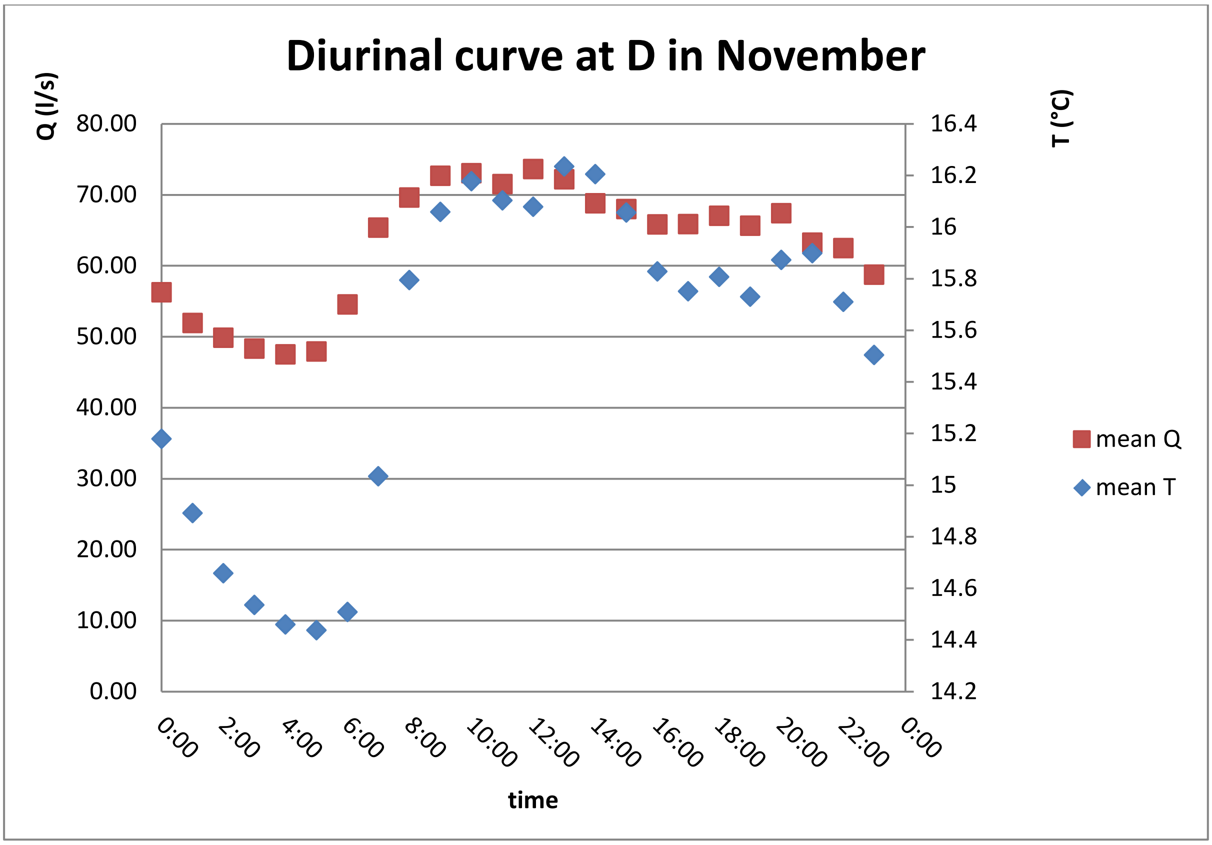
Attachment 32 - Diurnal temperature and discharge curves at measuring site C in February



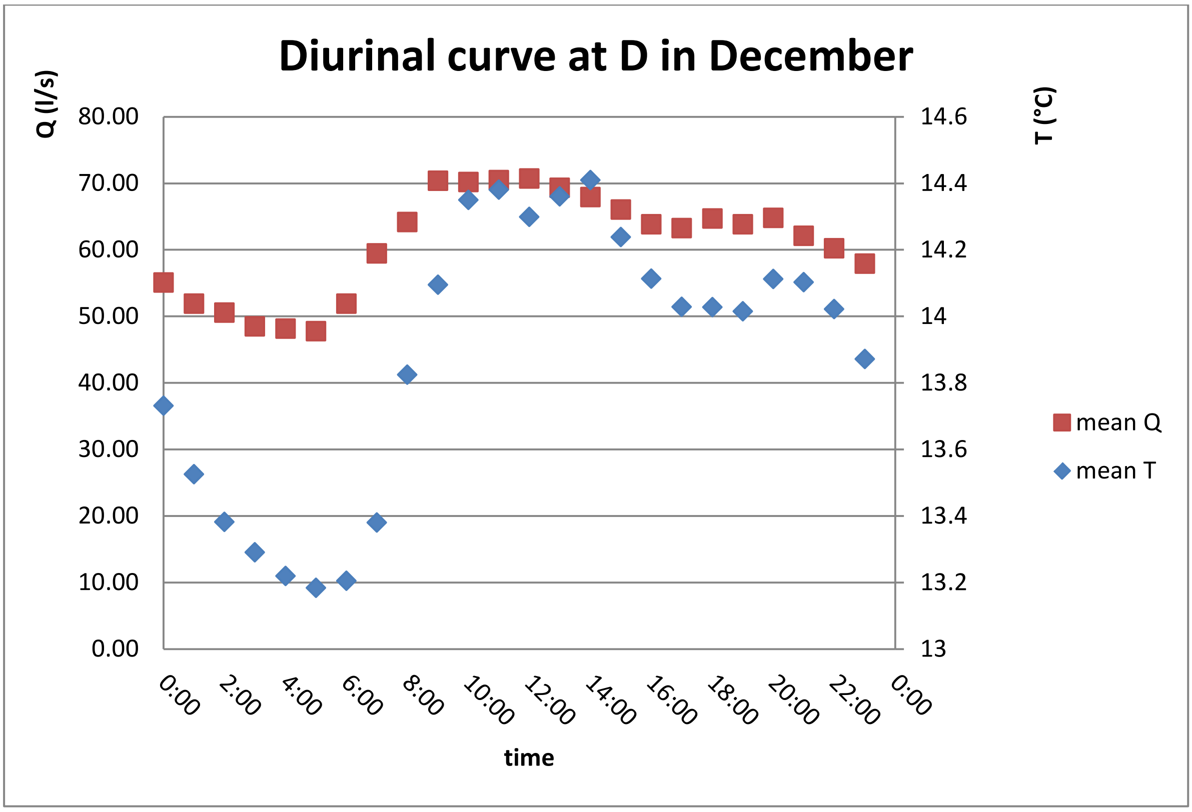
Attachment 33 - Diurnal temperature and discharge curves at measuring site D in March



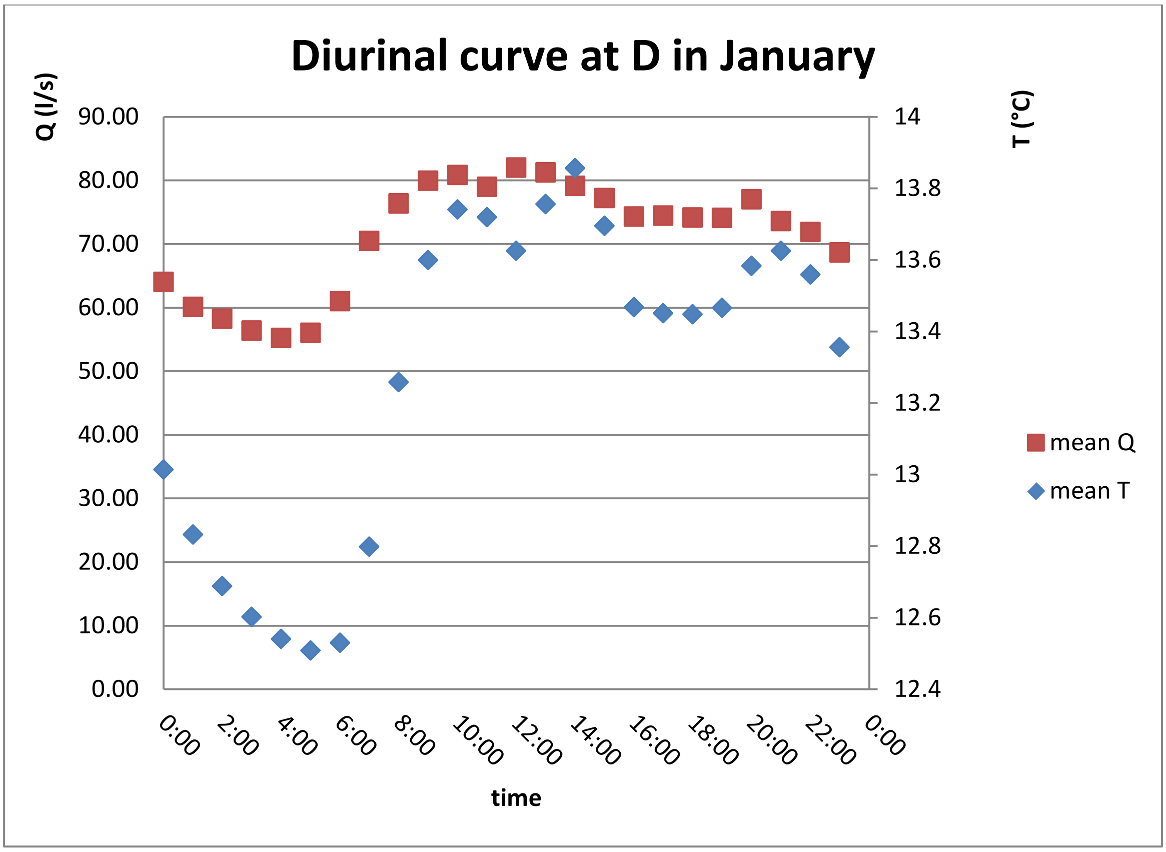
Attachment 34 - Diurnal temperature and discharge curves at measuring site D in October



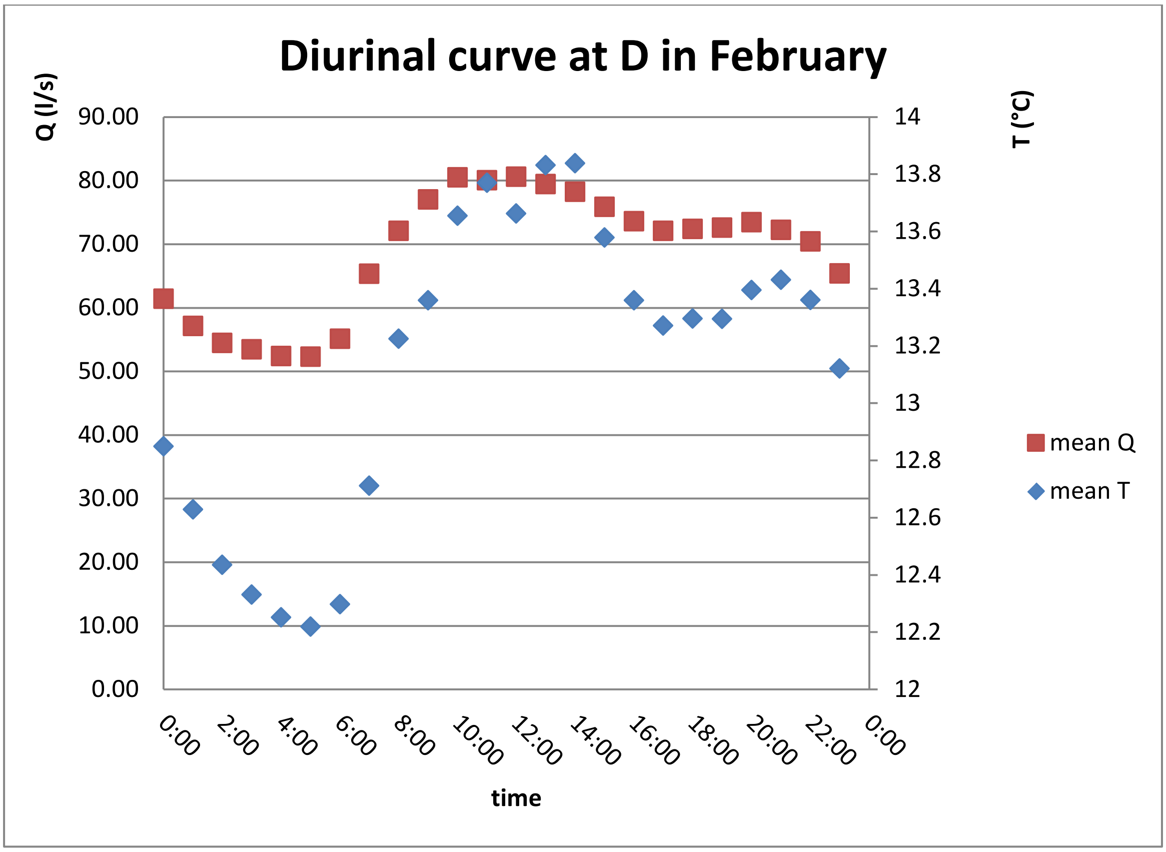
Attachment 35 - Diurnal temperature and discharge curves at measuring site D in November



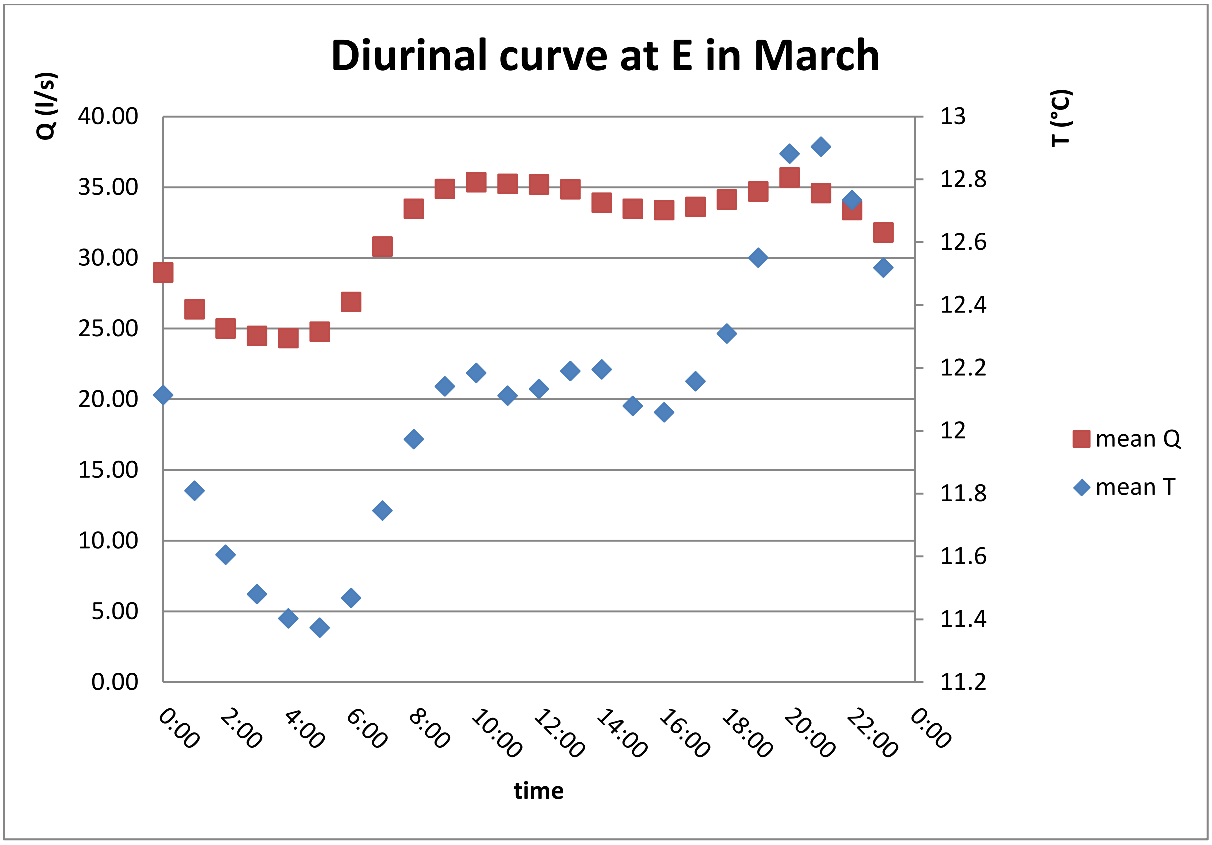
Attachment 36 - Diurnal temperature and discharge curves at measuring site D in December



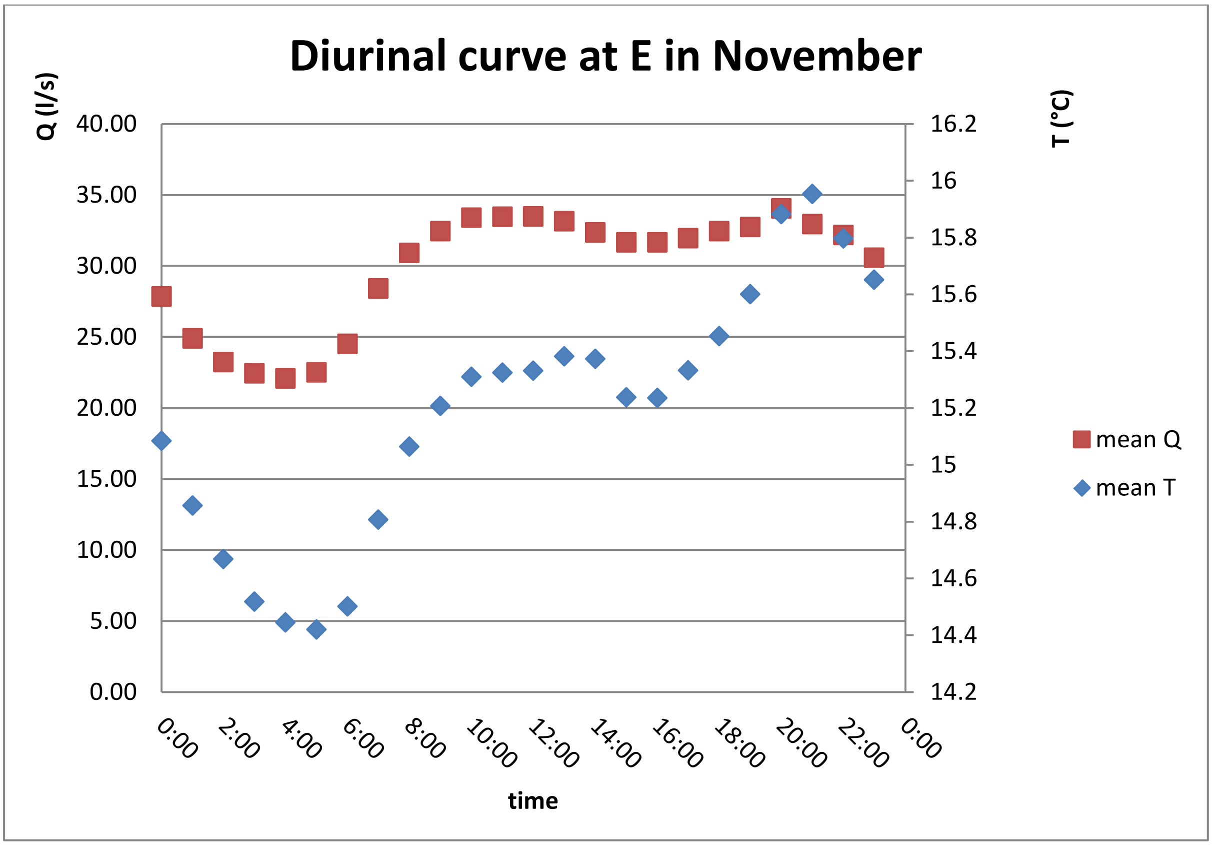
Attachment 37 - Diurnal temperature and discharge curves at measuring site D in January



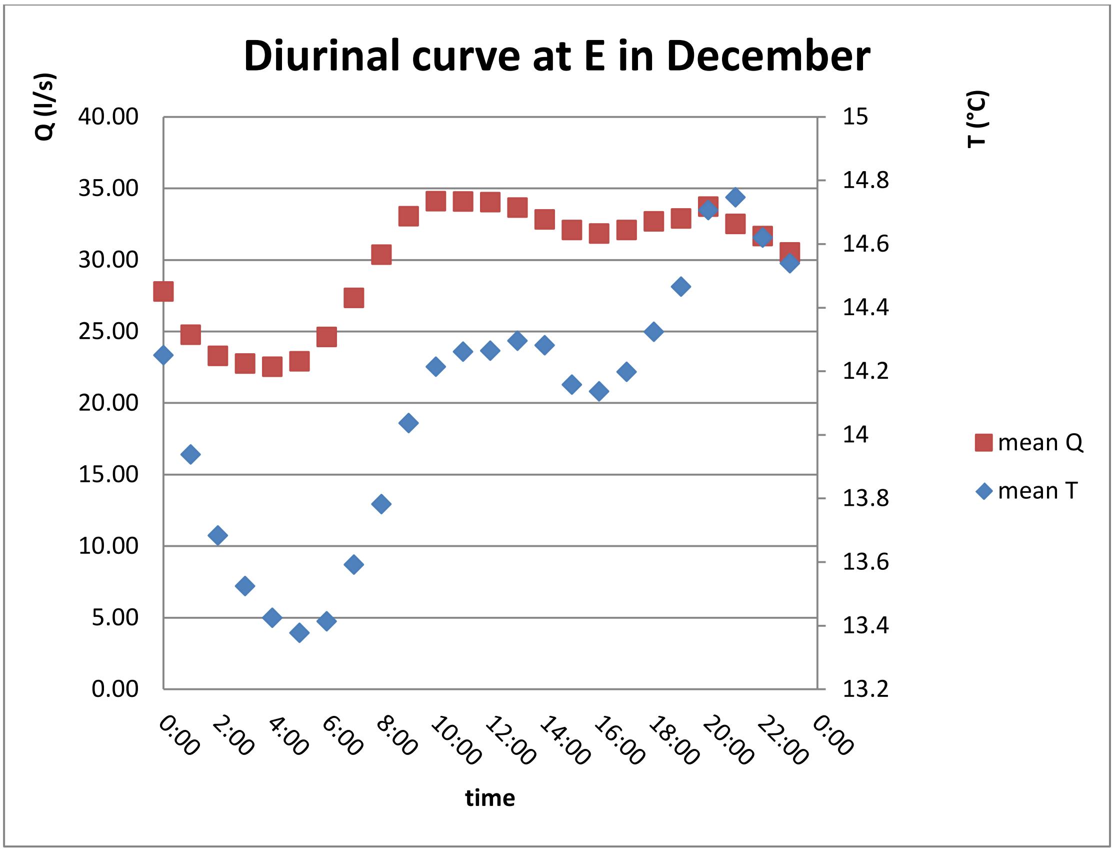
Attachment 38 - Diurnal temperature and discharge curves at measuring site D in February



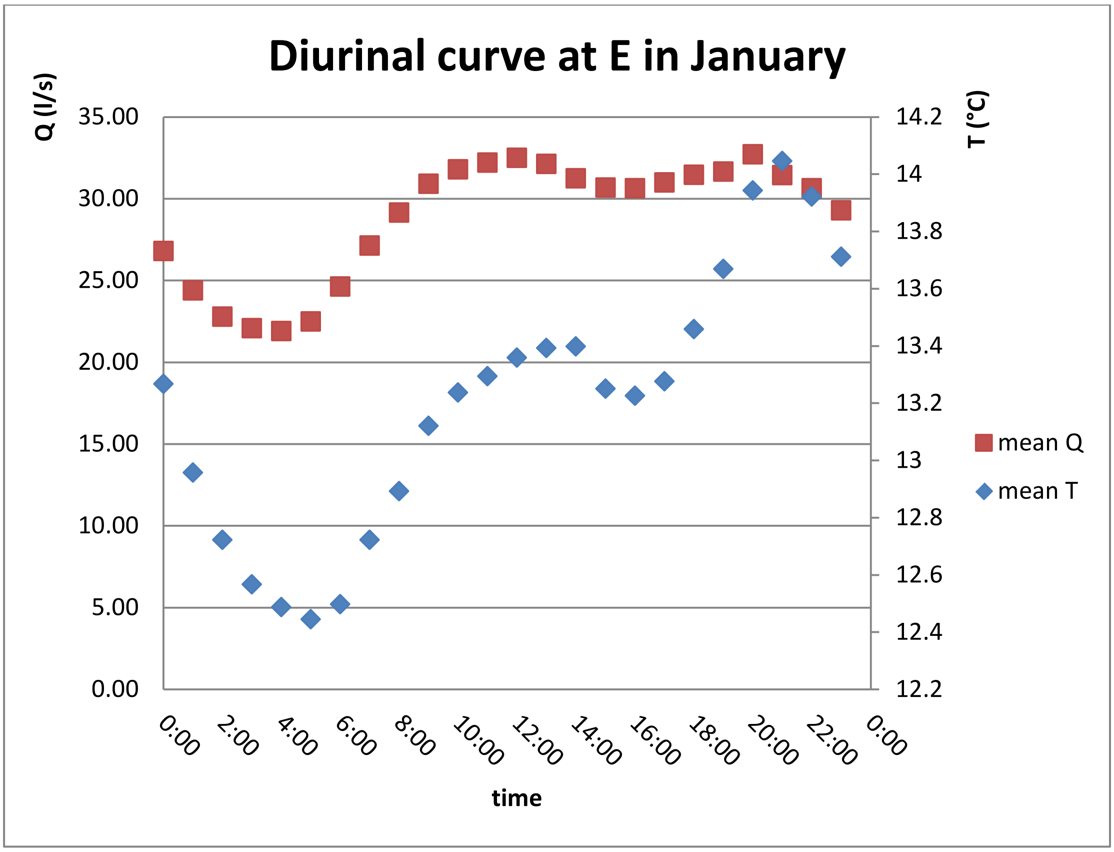
Attachment 39 - Diurnal temperature and discharge curves at measuring site E in March



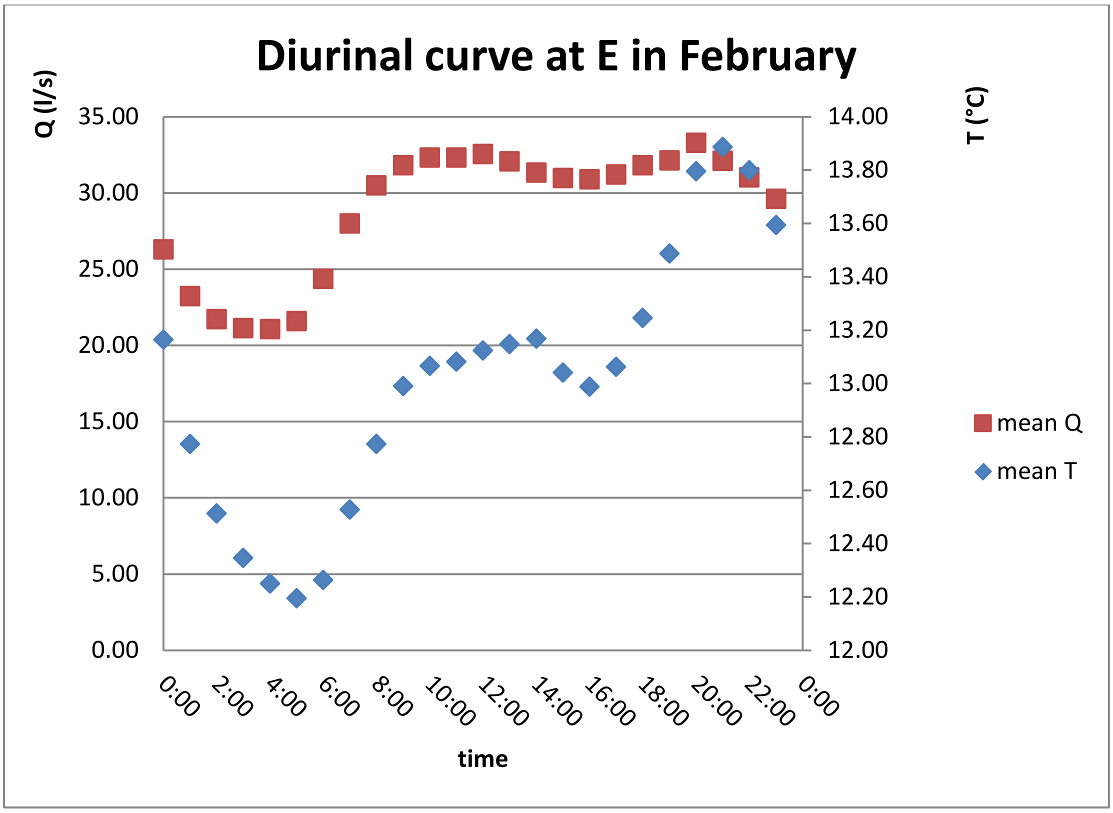
Attachment 40 - Diurnal temperature and discharge curves at measuring site E in November



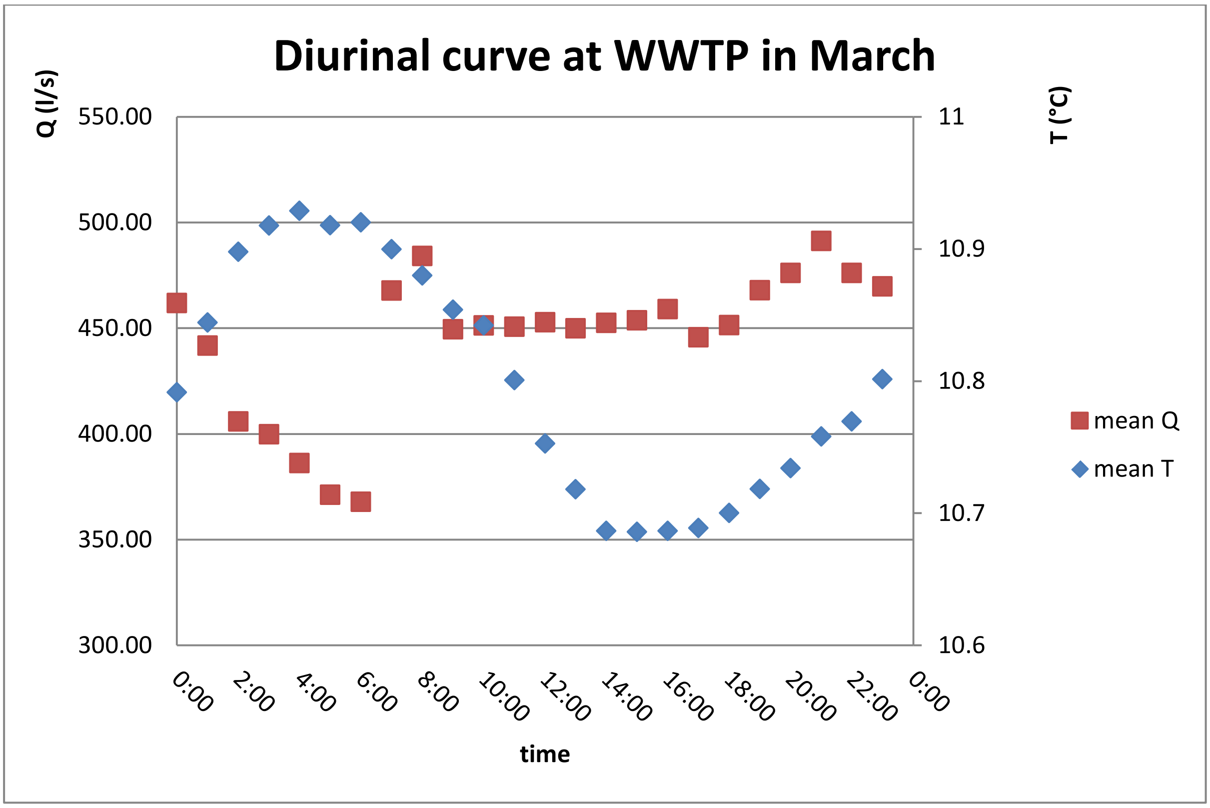
Attachment 41 - Diurnal temperature and discharge curves at measuring site E in December



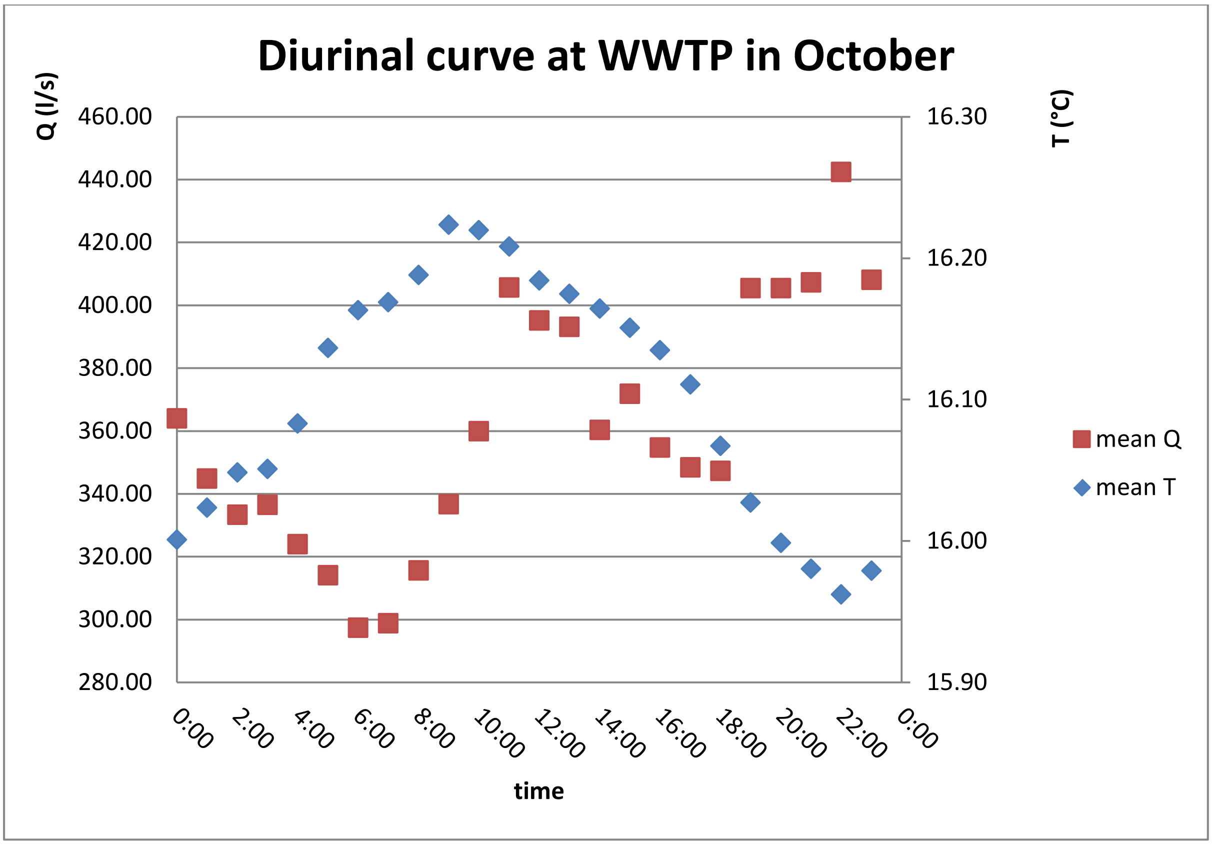
Attachment 42 - Diurnal temperature and discharge curves at measuring site E in January



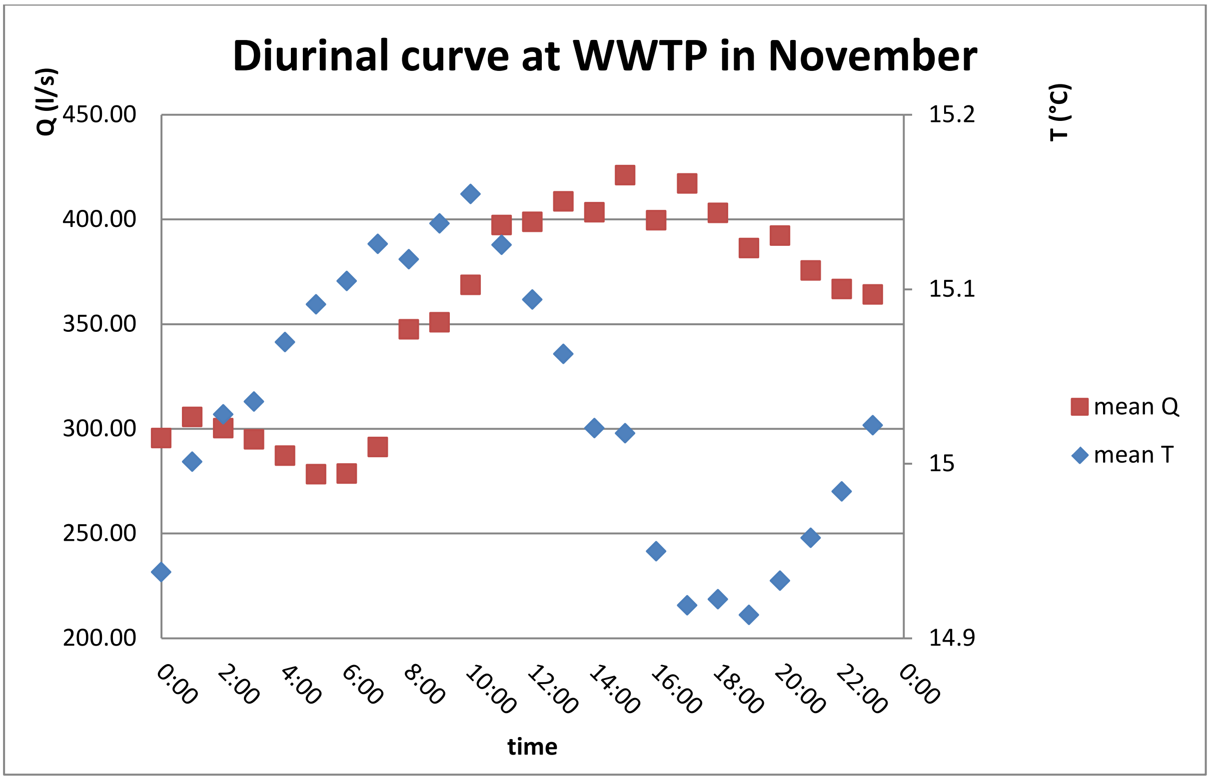
Attachment 43 - Diurnal temperature and discharge curves at measuring site E in February



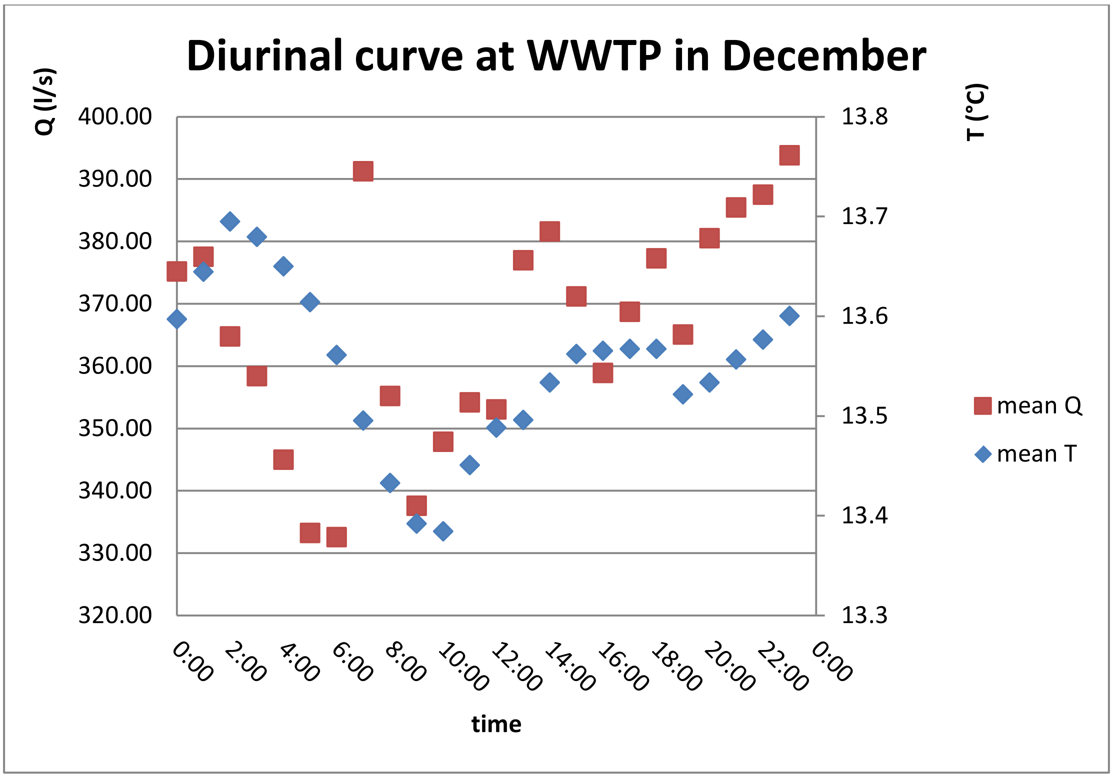
Attachment 44 - Diurnal temperature and discharge curves at measuring site WWTP in March



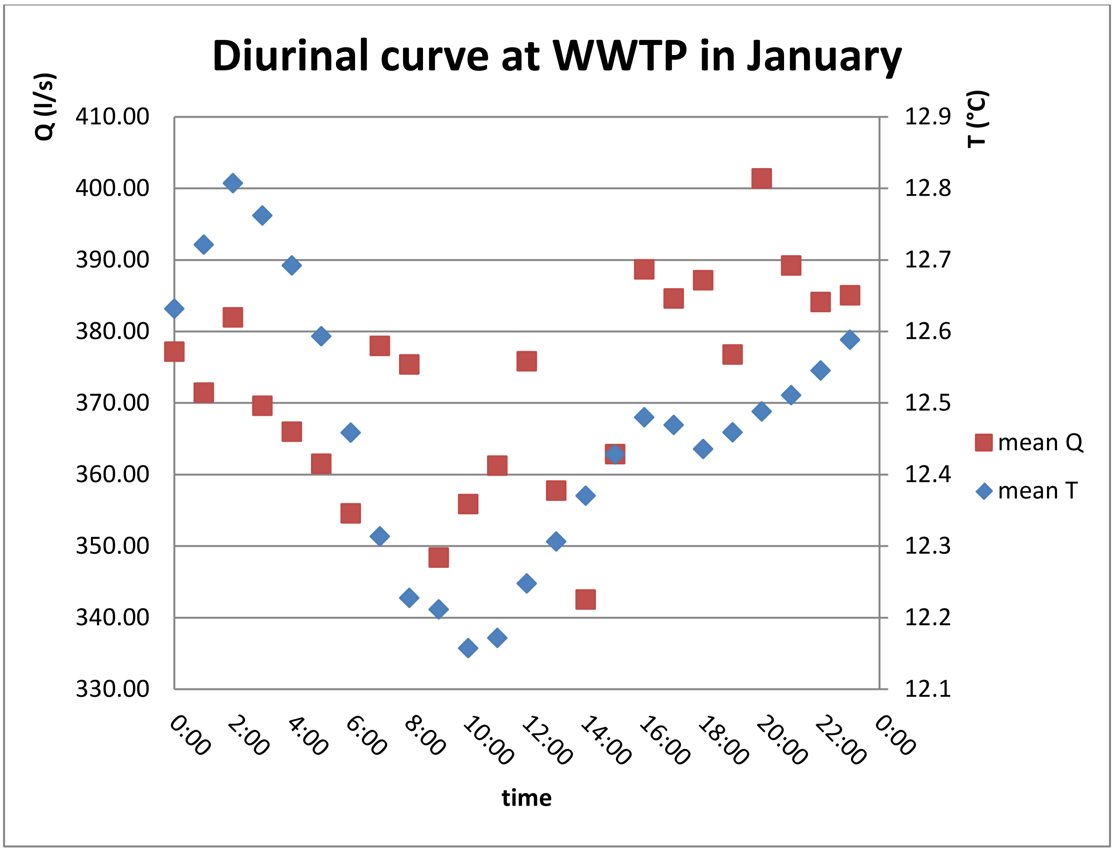
Attachment 45 - Diurnal temperature and discharge curves at measuring site WWTP in October



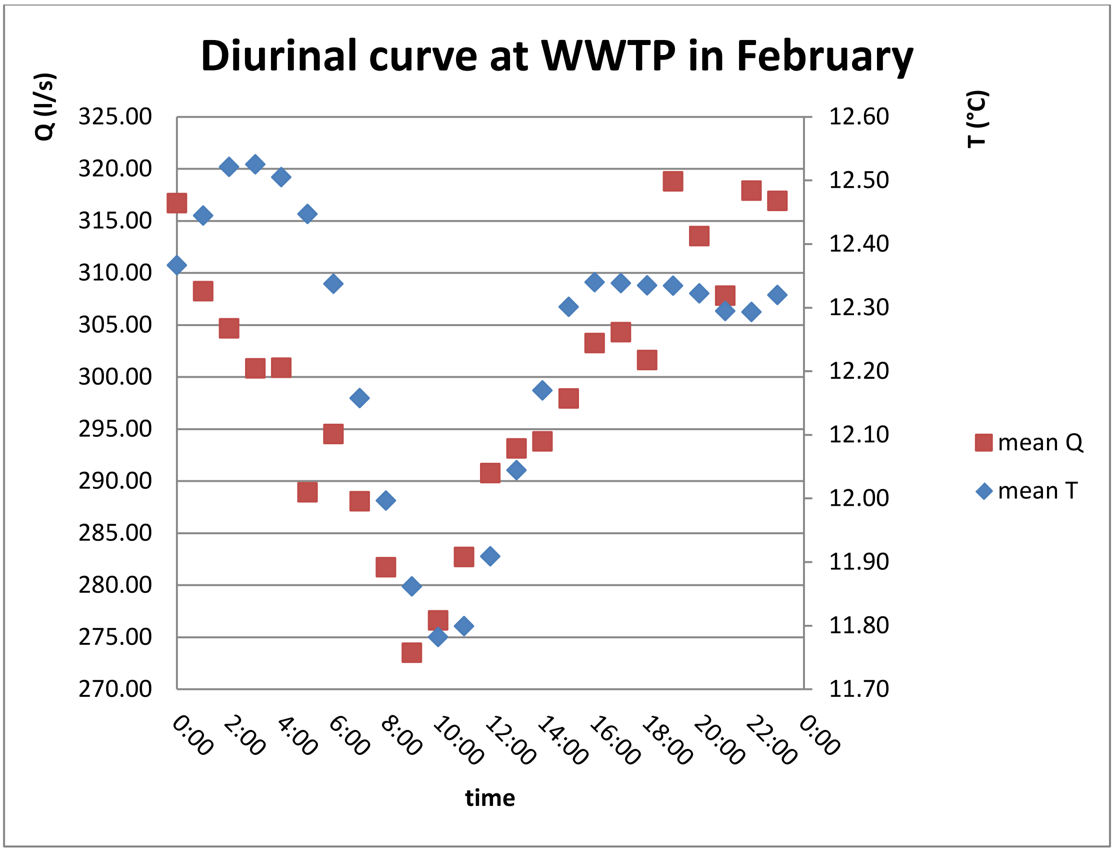
Attachment 46 - Diurnal temperature and discharge curves at measuring site WWTP in November



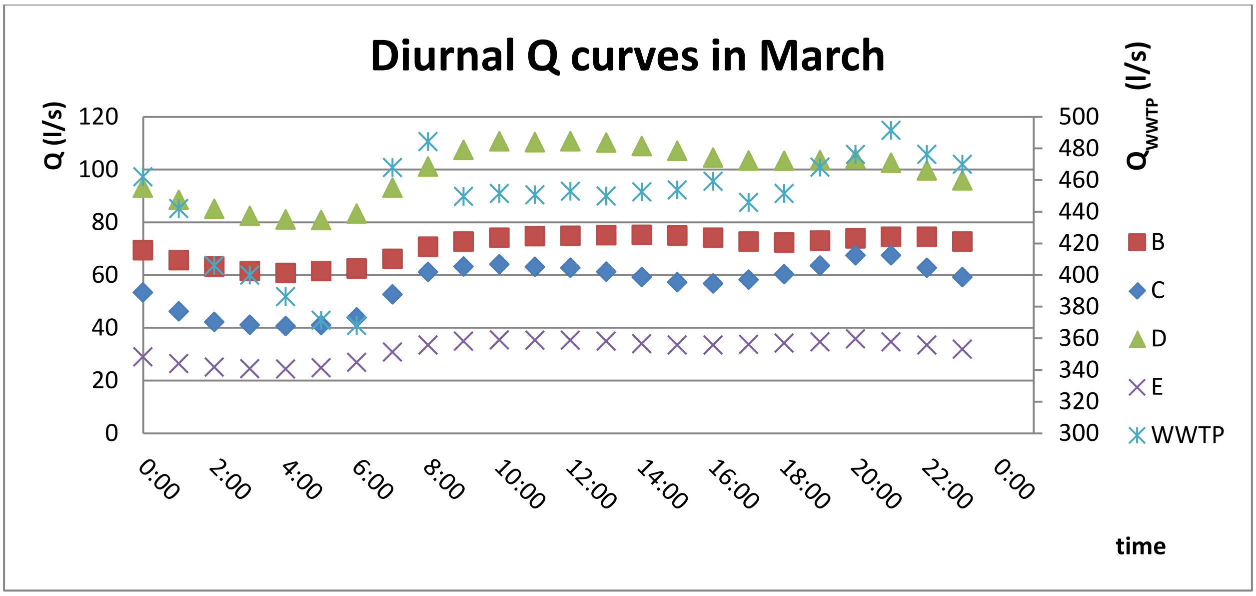
Attachment 47 - Diurnal temperature and discharge curves at measuring site WWTP in December



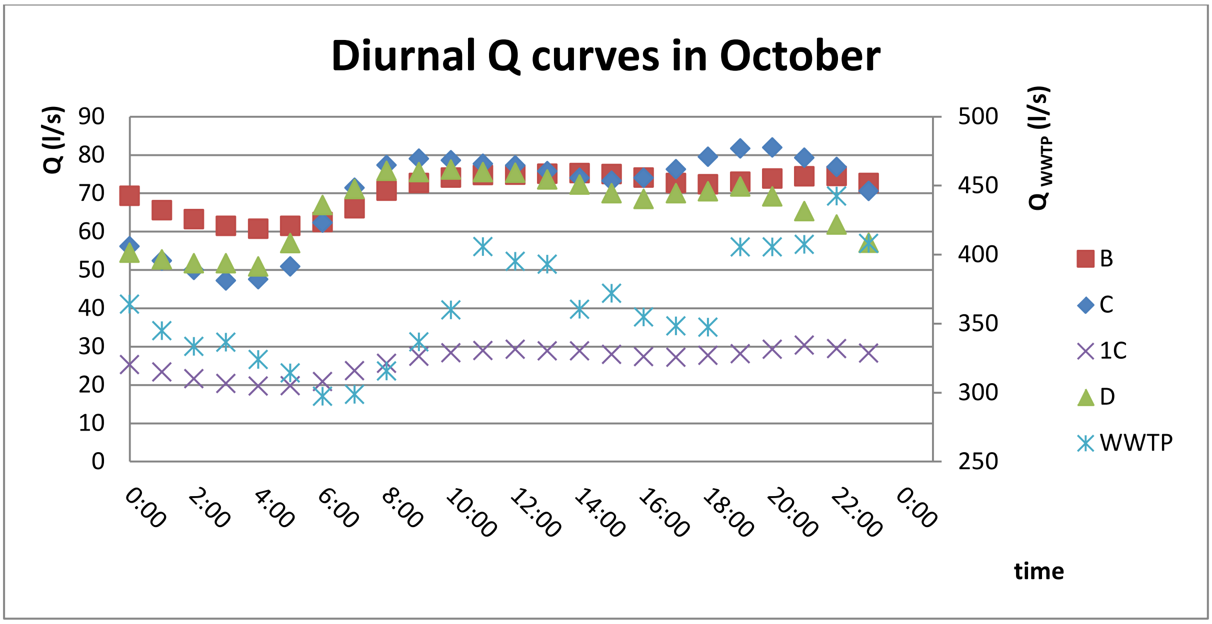
Attachment 48 - Diurnal temperature and discharge curves at measuring site WWTP in January



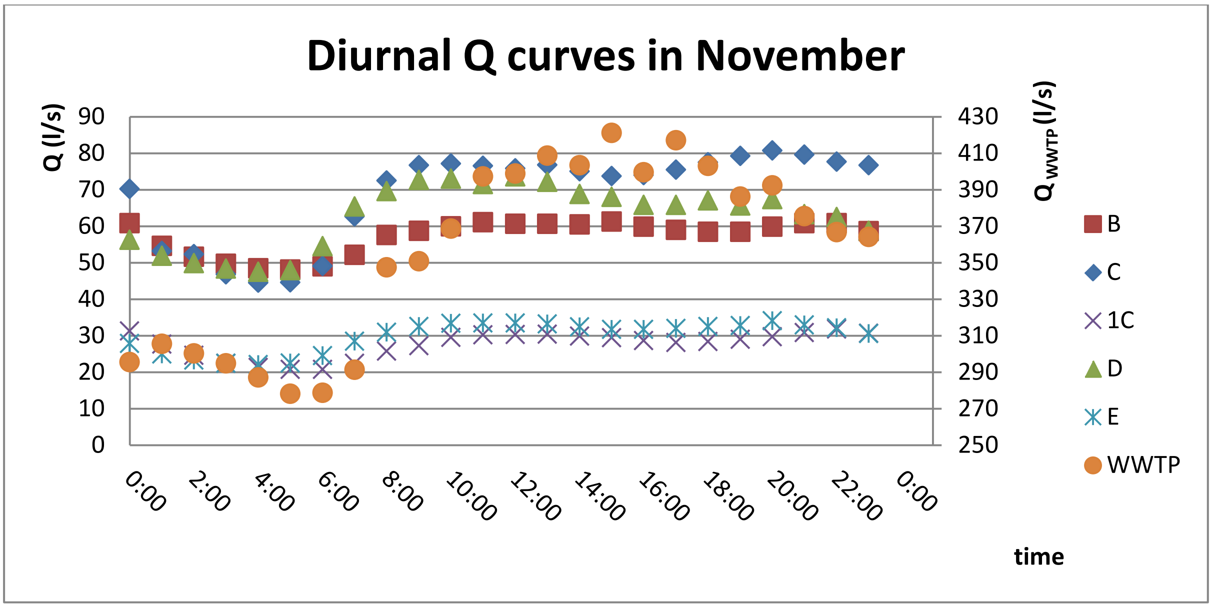
Attachment 49 - Diurnal temperature and discharge curves at measuring site WWTP in February



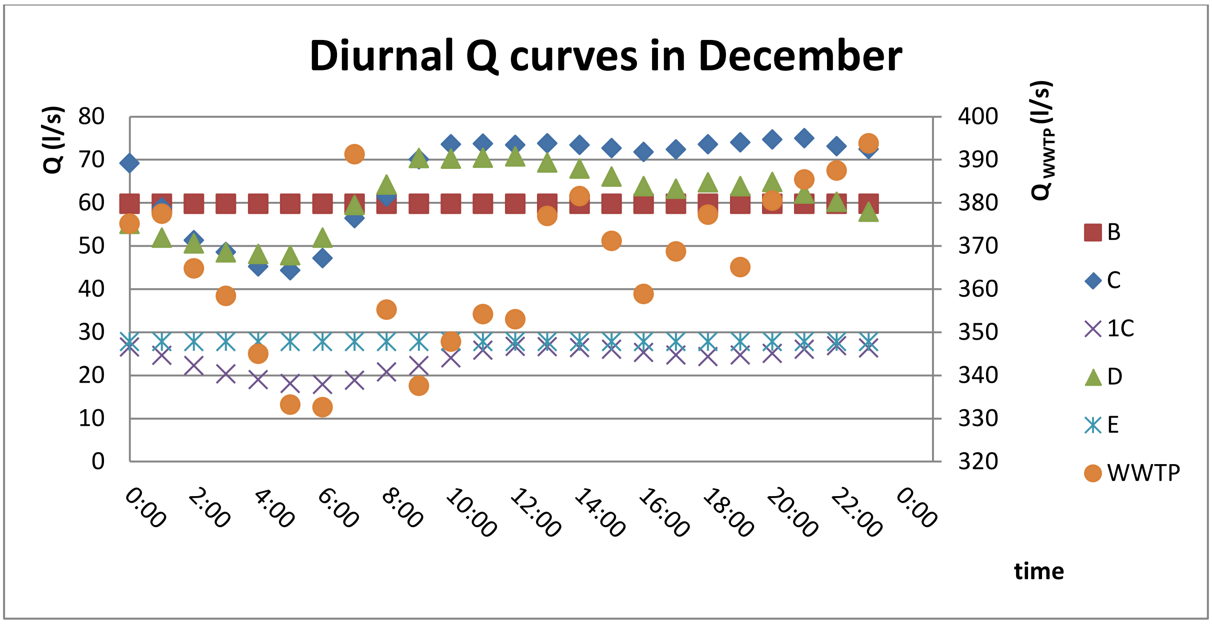
Attachment 50 – Diurnal discharge curves at different measuring sites in March



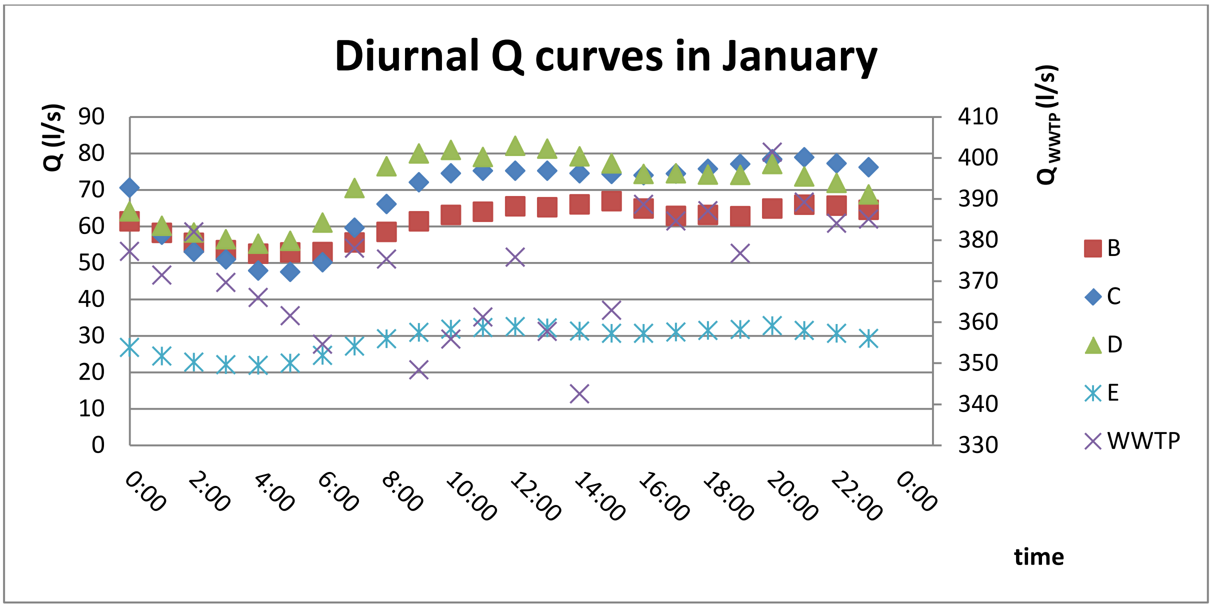
Attachment 51 – Diurnal discharge curves at different measuring sites in October



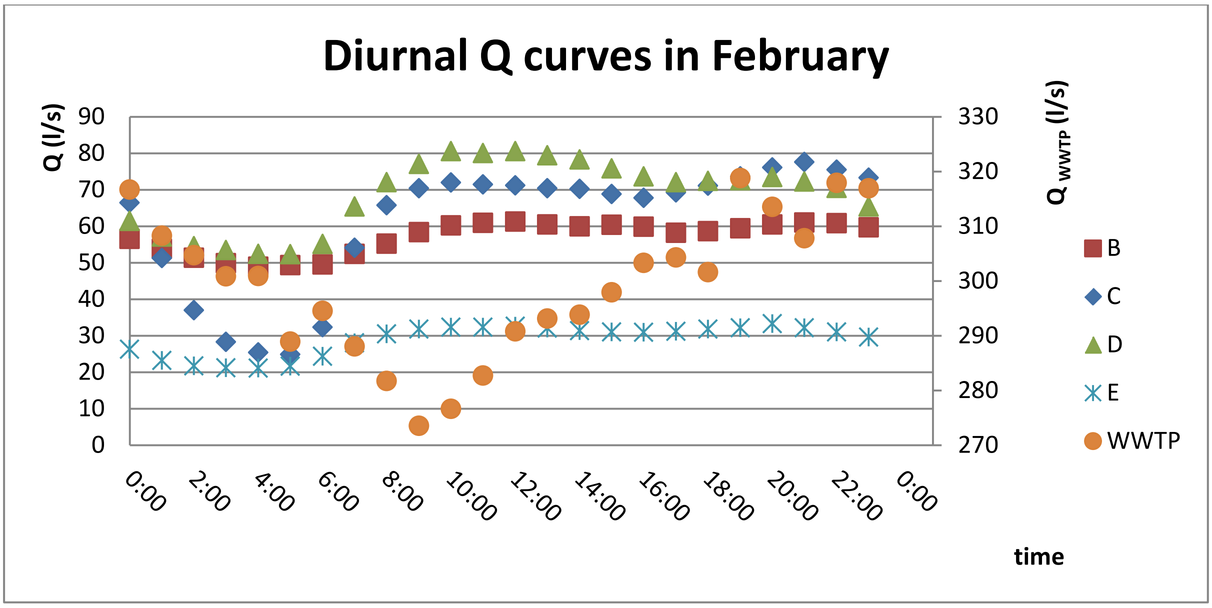
Attachment 52 – Diurnal discharge curves at different measuring sites in November¨



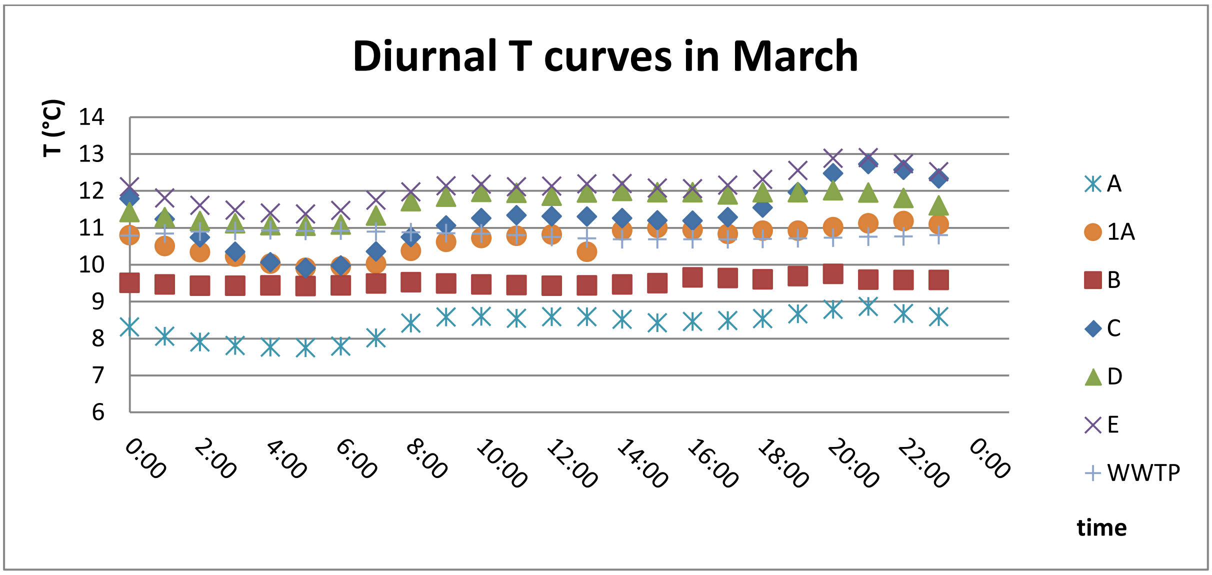
Attachment 53 – Diurnal discharge curves at different measuring sites in December



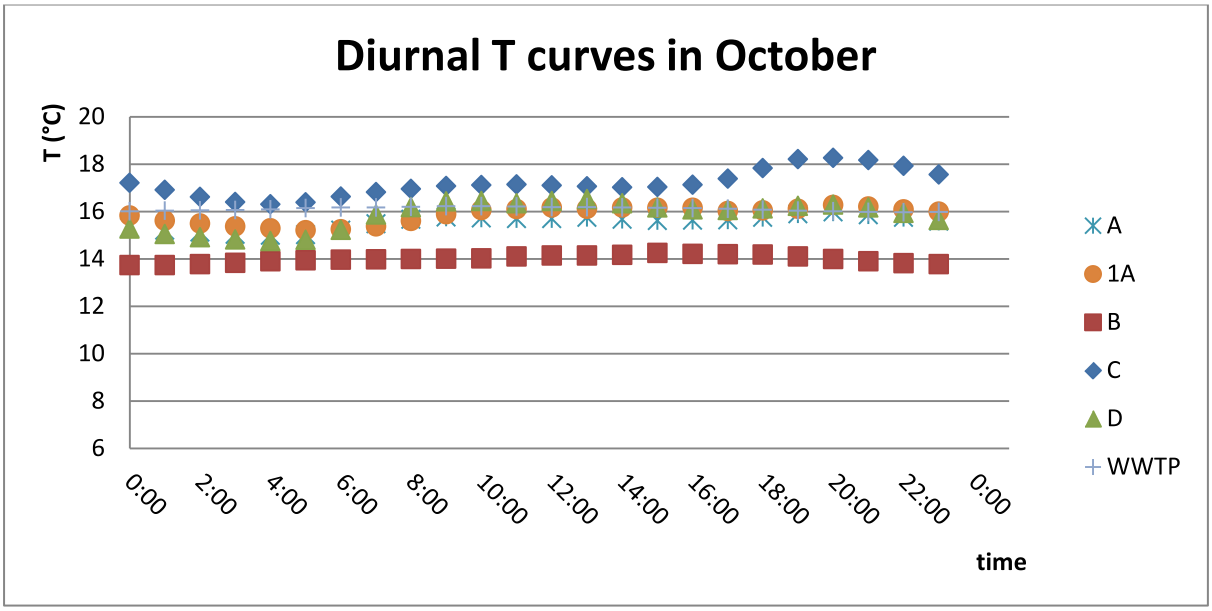
Attachment 54 - Diurnal discharge curves at different measuring sites in January



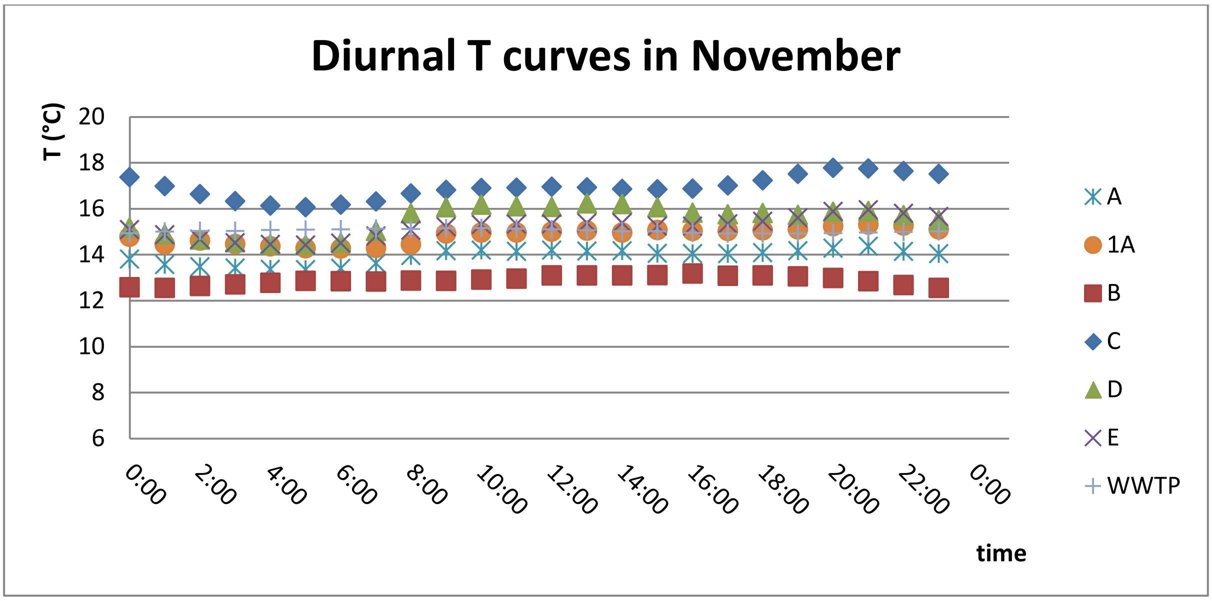
Attachment 55 - Diurnal discharge curves at different measuring sites in February



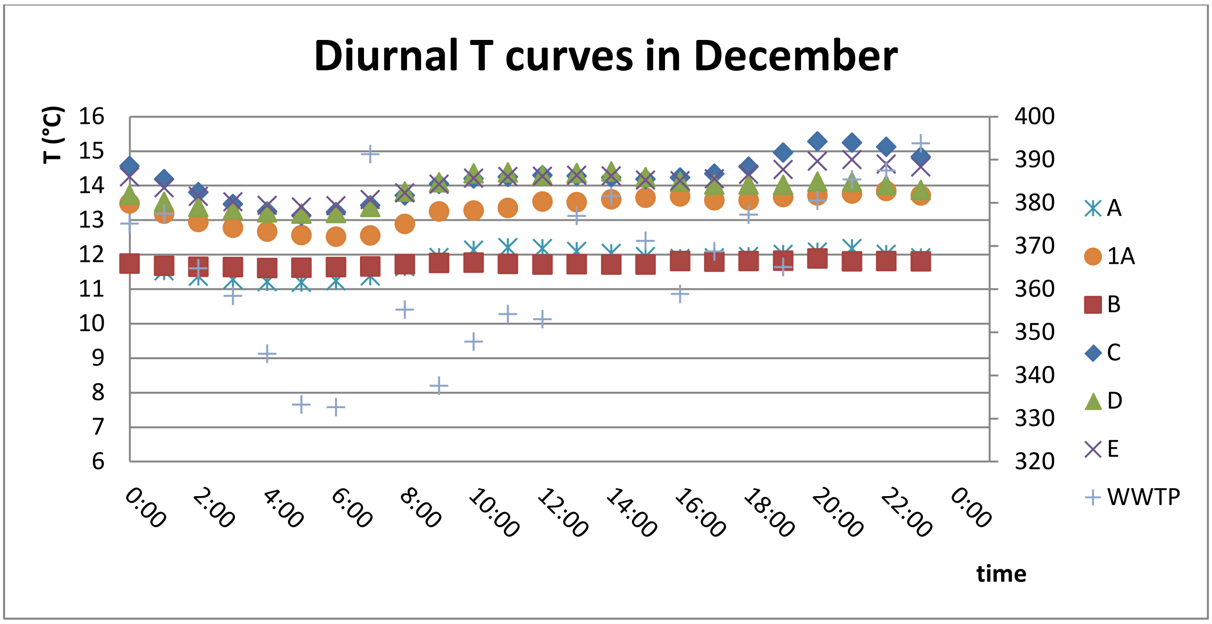
Attachment 56 - Diurnal temperature curves at different measuring sites in March



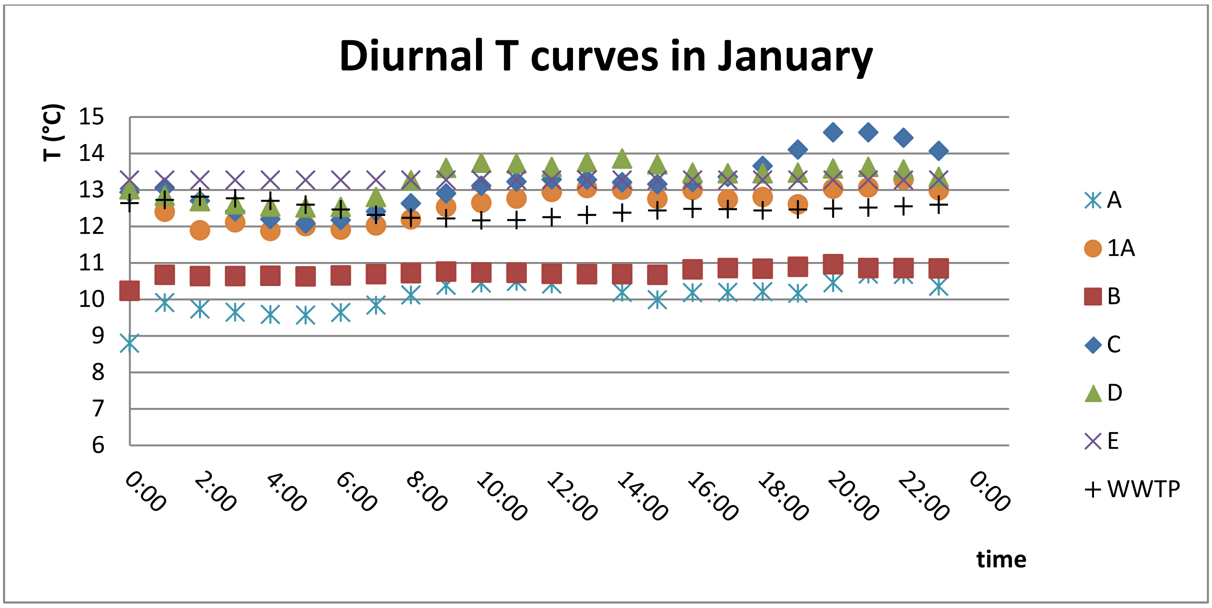
Attachment 57 - Diurnal temperature curves at different measuring sites in October



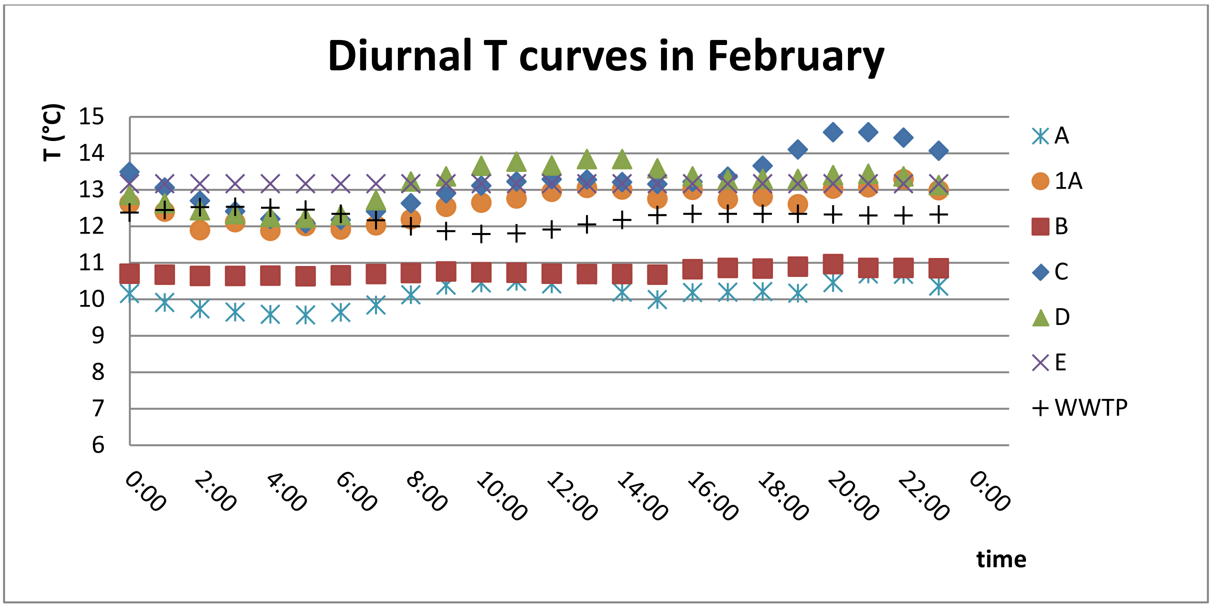
Attachment 58 - Diurnal temperature curves at different measuring sites in November



Attachment 59 - Diurnal temperature curves at different measuring sites in December



Attachment 60 - Diurnal temperature curves at different measuring sites in January



Attachment 61 - Diurnal temperature curves at different measuring sites in February