AALBORG UNIVERSITY
STUDENT REPORT

MSc in Environmental Engineering

Numerical Model of Water Temperature in a Retention Pond and Impact of Discharged Water from the Retention Pond on an adjacent Stream

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June 2020

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MSc in Environmental Engineering, June 2020
Number of pages: 73
Handed in: 10-6-2020
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Preface

This project has been devised at fourth semester of the Master's programme in Water and Environmental Engineering at Aalborg University. The focus has been to develop a numerical model of a water temperature in a water retention pond. The model can be used to avoid of thermal pollution of an adjacent stream to protect organisms living in the stream. To develop such a model, a measured water temperature and water level in the retention pond and in an adjacent stream in Beder-Malling have been used. The data was measured by my supervisor Anja T.H. Thomsen.

The project is devised to obtain knowledge about physical processes affecting water temperature in the pond and in the stream and investigate the impact of discharged water from the pond on trout population living in the stream.

I would like to thank my supervisors Michael R. Rasmussen, Jesper E. Nielsen and Anja T.H. Thomsen for a good guidance and commitment throughout the project and for their patience.

I would like to also thank to Maros Malcicky for a final correction of the text and to my family who always supports me.

Reading Guide

The project includes the main report and appendixes which are referred throughout the report. Electronic appendixes are attached to the project.

The Harvard method for references is used throughout the report. References to sources are indicated in brackets with author's surname followed by year of publication. The sources are listed alphabetically by the last name of the author.

Figures and tables are numbered according to the chapter number, followed by the number of the figure or the table in the chapter.

Klára Kacetlová

Abstract

This project focuses on a numerical model of water temperature in a water retention pond and on impact of discharged water on an adjacent stream. Numerical model of water retention pond is based on energy balance of thermal fluxes which affect water temperature in the pond. The developed model has been used to investigate pond dimensions, especially water surface area. Furthermore, an effect of a runoff water has been modelled. To investigate how organisms live in the stream are affected by discharged water from the pond, the model of the stream water temperature in the discharge point has been developed. Trout population has been chosen to represent a sensitive specious. This model of the stream is based on modelled water temperature in the pond, the volume of the discharge of the pond, a measured water temperature upstream and a flow in the stream before discharge point.

List References

Abbreviation	Definition	Units
α	Albedo	[-]
Δ E	Net heat flux	[J/min/m^2]
ΔT	Change of temperature	[°C]
ϵ_a	emissivity factor of the air	[-]
ρ_a	Air density	[kg/m^3]
ρ_w	Water density density	[kg/m^3]
σ	Stefan-Boltzmann constant	[W/m^2/K^4]
A	Water surface area	[m^2]
A_{imp}	Impervious Area	[red ha]
c_b	Bowen coefficient 1	[mb/°C]
c_L	Stability dependent bulk transfer coeff. for water vapour	[-]
c_p	Heat capacity of water	[J/kg*°C]
c_s	Stability dependent bulk transfer coefficient for heat	[-]
c_w	Heat storage capacity of water body	[J/°C]
e_a	Actual vapour pressure	[mb]
e_d	Mean daily vapour pressure	[kPa]
e_s	Saturation vapour pressure at the water surface	[mb]
e_{sat}	Saturation vapour pressure	[mb]
$f(u)$	Wind speed function	[W/(m^2*mb)]
H	Conduction heat flux	[J/s/m^2]
H_w	Waterl Level	[m]
h	Water level in the stream	[cm]
i	Rain intensity	[μm/s]
K	Equation of batygraphic line for water surface	[m^2]
k	Thermal Conductivity	[W/(m^2*°C)]
LE	Evaporation heat flux	[J/s/m^2]
L_e	Latent heat of evaporation	[J/kg*°C]

Abbreviation	Definition	Units
p	Atmospheric pressure	[hPa]
p_a	Air pressure	[mb]
p_0	Reference air pressure	[mb]
q^*	Saturation specific humidity	[%/100]
q_{air}	Specific air humidity	[%/100]
Q_{in}	Runoff Water Volume/minute	[m^3/min]
Q_{out}	Outflow Water Volume/minute	[m^3/min]
Q_{stream}	Flow in the stream	[l/s]
R	Gas constant dry air	[J/kg*°C]
R_b	Long-wave water back radiation	[J/s/m^2]
RH	Relative humidity	[%]
R_n	Long-wave atmospheric radiation	[J/s/m^2]
$R_{n_{absorbed}}$	Absorbed long-wave atmospheric radiation	[J/s/m^2]
R_s	Absorbed short-wave atmospheric radiation	[J/s/m^2]
R_{si}	Short-wave atmospheric radiation	[J/s/m^2]
R_v	Gas constant water vapor	[J/kg*°C]
S	Bottom Heat Flux	[J/s/m^2]
T	Water temperature	[°C]
T_a	Air temperature	[°C]
T_d	Dew point temperatures	[°C]
T_s	Surface temperature	[°C]
u	Wind speed	[m/s]
V	Volume	[m^3]
WRP	Water Retention Pond	[-]
Z	Elevation above the mean sea level	[m]

Contents

1 Introduction to Thermal Pollution

Thermal pollution is known as variation of water temperature directly caused by people or caused by interference of people into the ecosystem. The most of literature describes thermal pollution from the power plants, where cooling water is discharged usually into a sea, ocean or a big river. This thermal pollution has a great impact on environment and aquatic ecosystem. It is possible to look on thermal pollution from water retention pond in the same way as on the thermal pollution from power plants but in much smaller scale.

Water retention ponds provide additional storage capacity during rainfall. Runoff water from impervious area is collected into the ponds and can be discharged in a controlled way. Since discharged water is controlled to decrease the risk of flooding and polluting of surrounding area and specifically adjacent stream where water is released, there is a trend to decrease a permitted discharge. This attitude can lead into the thermal pollution of the stream as a result of larger temperature variations caused by a larger surface area of the pond which is more affected by weather conditions. Furthermore, with lower discharge the water is retain longer and is affected by weather for longer time.

Water temperature has an impact on living organisms. It can affect metabolic rate and growth rate and development period. The water temperature has a big impact also on oxygen consumption, when aquatic organisms consume more food and they breath more in water with higher temperature. Furthermore, warmer water does not contain as much available oxygen as cold water. It means that temperature has an impact on breathing rate of fishes. The water temperature affects also water viscosity, which makes swimming more energetic demanding. (Santiago, 2017) The water temperature has more significant effect on small fish than on large ones. (Elliott, 1994)

Runoff water retained in ponds contains a lot of different toxins from surfaces such as roofs, roads, parking lots etc. Since higher temperature of water affects also the solubility of toxins, retained water in the pond for too long can result into more harmful water quality especially during a hot weather in the summer.

1.1 Problem Statement

The question of thermal pollution from water retention ponds described above, has been dealt throughout of this project.

The purpose of this master thesis is to develop a model which can predict water temperature in the pond based on dimensions of the pond and meteorological conditions. This model can be used in the design phase of the pond to determine the dimensions of the pond, water retention time in the pond or to see how water temperature reacts on the extreme weather events. Since different types of trouts are living or migrating through streams in Denmark, the model of the pond can be used also to determine the temperature of an adjacent stream in a discharge point and figure out how these sensitive specious are affected by a different temperature in the discharge point.

The aforementioned description leads to the following problem statement which has been attempted to solve throughout this project:

"To develop a model of water temperature in a pond based on its dimensions and meteorological data, which can be used in a designing phase, does not affect sensitive specious living in an adjacent stream."

The problem statement has been attempted to answer by working with the following problems:

- What heat fluxes affect the water temperature and how to calculate them?
- How geometry of the pond affects the water temperature in the pond?
- How big impact has runoff water on the water temperature in the pond?
- How to model a water temperature in the stream?

1.2 Solving Strategy

The problem statement has been processed based on studying of energy balance of the water retention pond and understanding processes affected the water temperature. The potential thermal pollution of the adjacent stream has been analysed by setting up the following models:

- Conceptual of the pond model.
- Model of a water temperature in the pond.
  - Mass Balance
  - Energy Balance
- Model of a water temperature in the stream temperature.

To set up these models, several input parameters has to be described in advance of the model description.

Water temperature is affected by several processes, mainly meteorological and geographical conditions. These processes can be described mathematically to predict how water temperature varies during summer and winter or during night and day.

When creating a numerical model is necessary to make some simplification because is often counterproductive creating a model describing in the real world. A simple model with less parameters can be more accurate than a model describing all processes with a lot of unknown parameters. The uncertainty of parameters can lead into less accurate model. Hence energy balance of water in WRP will be described by a simple conceptual model which is illustrated below in figure 1.1.

There are several different energy fluxes. These are described in chapter 3. Water temperature, respectively energy balance is affected by a lot of processes and parameters. Is necessary to obtain meteorological data as wind speed, air temperature, relative humidity, dew point and solar radiation. Since the meteorological station close to Aalborg University measures all parameters each minute, data from this station are used to create a numerical model.

Model of the WRP will be calibrated based on measurements from Beder pond. The model should have been validating based on meteorological data from the Aalborg University station and measurements of water level and water temperature in the pond next to Aalborg University. Unfortunately, the meteorological data is not available from December to May, when almost all measurements of water temperature and water level were collected. Because of this, the model will be validated based on the measurements from the pond Hovedgroften in Beder-Malling.

Temperature of an ambient stream will be simply described by a mixing equation to determine a water temperature in the point of discharge. The result from the pond model will be used as an input into the mixing equation, the water temperature and discharge from the pond. The conceptual model of a stream adjacent to WRP is illustrated in figure 1.2. The resultant temperature in the stream will be compared to measured downstream temperature.

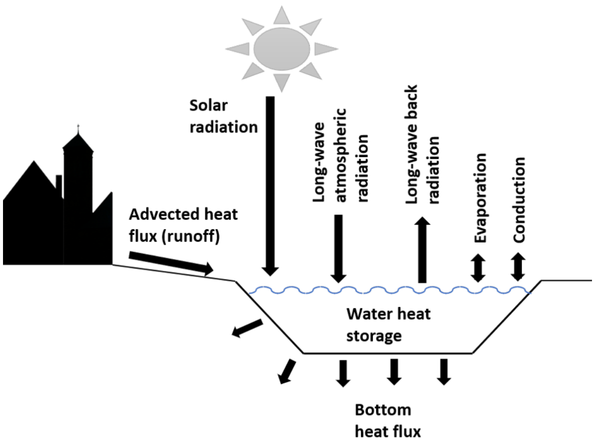

Figure 1.1: The conceptual model of the water retention pond.

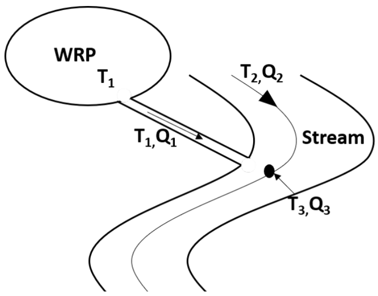

Figure 1.2: The conceptual model of the stream.

Both described models above are summarized into one, shown in figure 1.3 to illustrate relation between them. From this figure can be seen that output from the model of WRP is an input for the model of the water temperature in the stream.

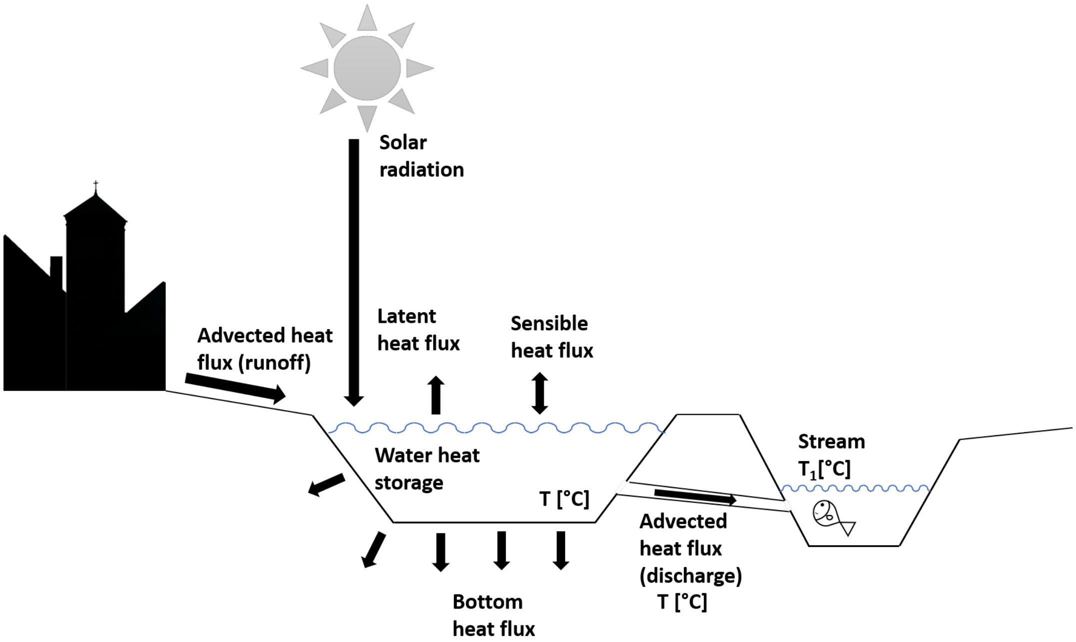

Figure 1.3: The conceptual model of energy balance between water retention pond and adjacent stream.

2 Measured Data Sets for Model

The project location and input parameters used in the models are described in this chapter. The model of water temperature of the water retention pond is based on dimensions of the pond and meteorological data. The measured data as water level and water temperature are used to calibrate the model.

2.1 Ponds Location and Measured Data

Water retention ponds in Beder-Malling should have been used to create a model of water temperature prediction. Beder-Malling is a small town on the south of Aarhus thus it is in the middle of the East coast of Denmark, see left side of the figure 2.1. The location of ponds with available measurements is illustrated on the right side of the figure 2.1.

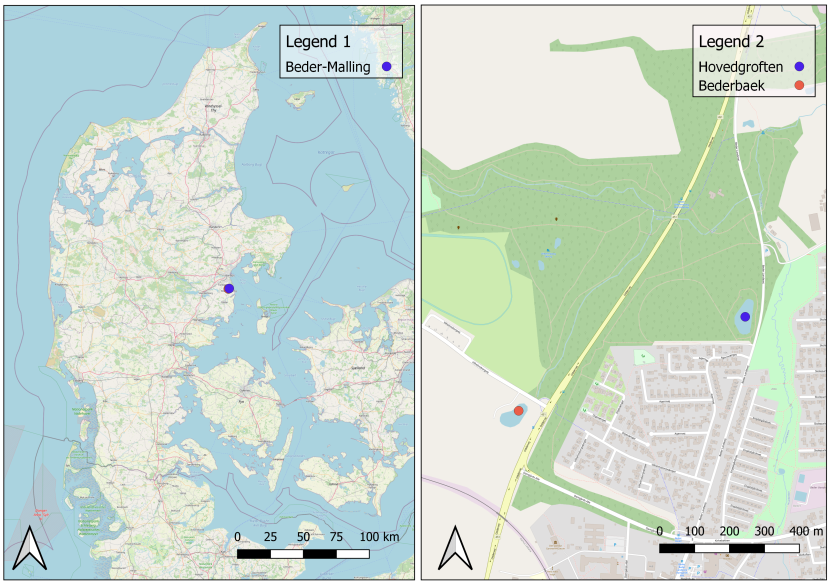

Figure 2.1: Location of the Beder-Malling in Denmark and Location of the ponds in Beder-Malling.

However there are two water retention ponds with adjacent streams with available measurements of water level and water temperature, only one of them will be used to develop the model. Water temperature measurements from the pond Hovedgroften showed some unexplained abnormalities as maximum water temperature in the middle of the night as it is shown in figure 2.2. However the sunset during June in Denmark is around 10 pm, the highest water temperature is expected later afternoon. To reduce the most uncertainties as possible the measurement from Hovedgroften will not be used to develop the water temperature model.

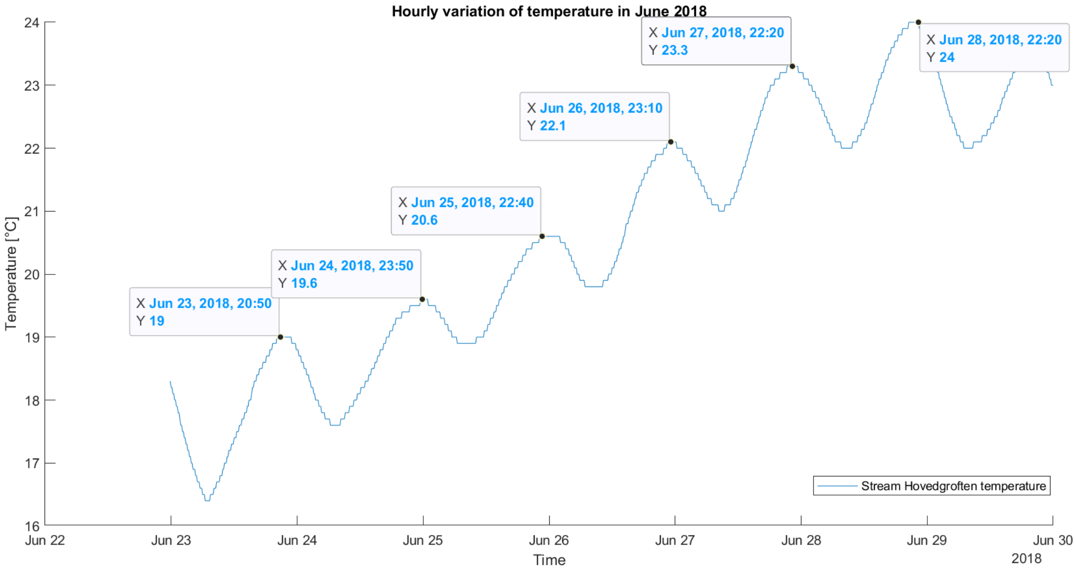

Figure 2.2: Daily peaks of water temperature in Hovedgroften pond in summer 2018.

Figure 2.3 shows daily peaks of water temperature for Bederbaek pond in June 2018. These measurements fulfill expectation about the lower temperature at night except 25^{th} of June. It can be explained by incoming warm front at night.

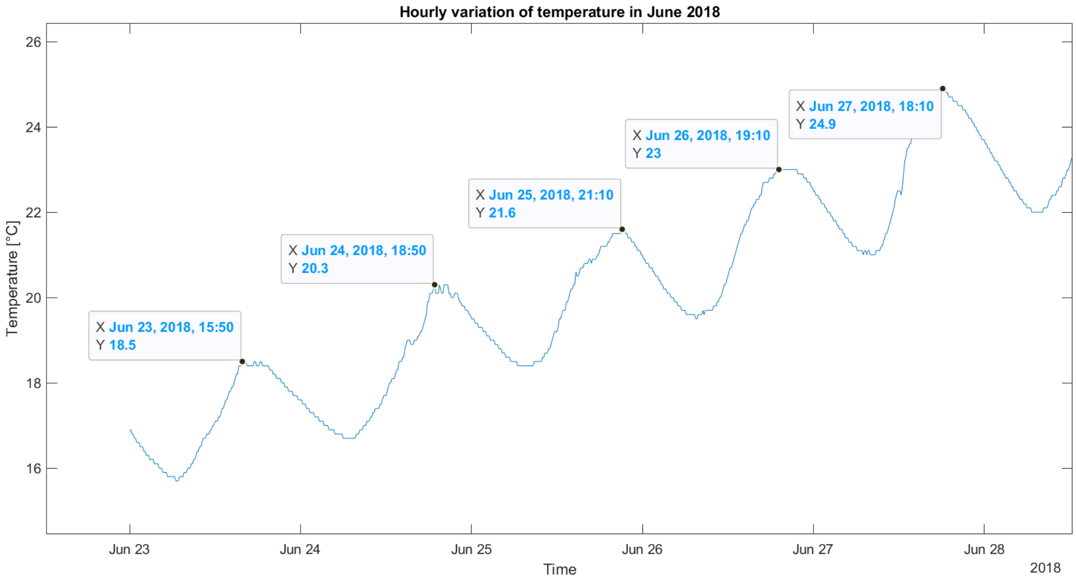

Figure 2.3: Daily peaks of water temperature in Bederbaek pond in the summer 2018.

2.2 Pond characteristics

To determine energy balance in Bederbaek water retention pond is crucial to find out how volume of the pond and water surface area depend on the depth. This dependency is expressed by bathygraphic curves what are shown in figure 2.4.

The batygraphic curves were determined based on the geometry of the pond, which was found out from a layout of the pond, see figure 9.1 in appendix 9.1. This layout was created by Niras A/S and Aarhus Vand A/S and provided by Thomsen, 2020 after personal consultation. The layout gives information about three different water levels and corresponding areas. It is summarized in table 2.1.

Table 2.1: Depth and corresponding depth, water surface area and volume according to layout.

Depth [m]	Area [m^2]	Volume [m^3]	Note
0	1768	0	empty
1.09	3079	3380	permanent water
2.77	4894	5380	max. water level

However the pond has irregular shape, it was assumed that the pond has a circular shape for a simple calculation of water surface area and volume in arbitrary depth.

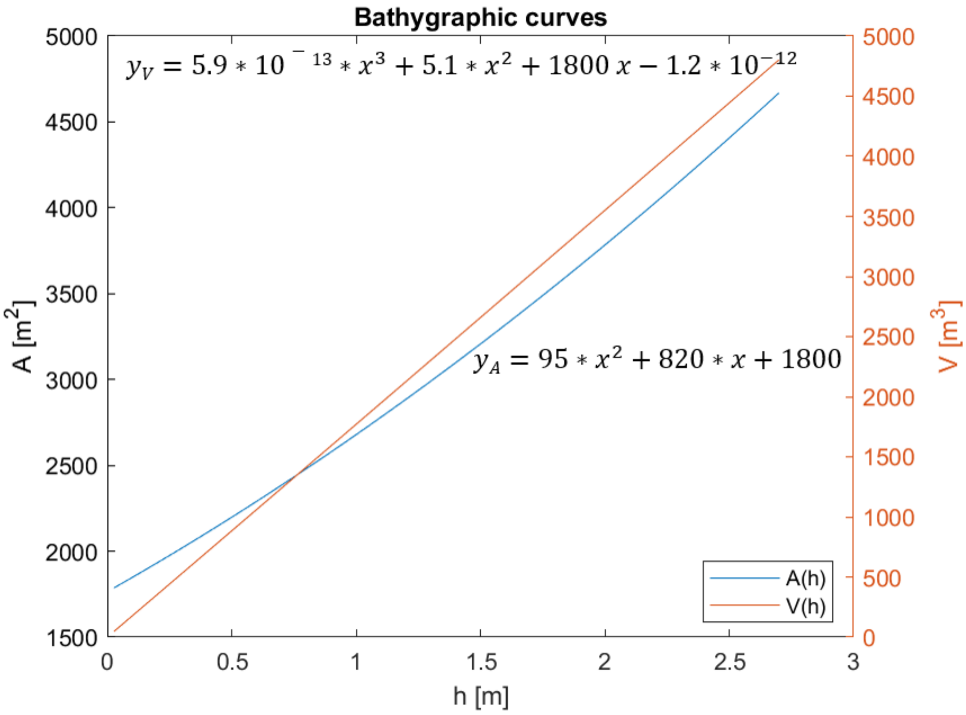

Figure 2.4: Bathygraphic curves for Bederbaek water retention pond

To create a smooth bathygraphic curves maximum water depth was divided into 100 small sections how it is illustrated in figure 2.5 and in table 2.2.The slope of banks was determined based on the depth and on surface area with empty and with full pond. Also width of the bottom was determined based on surface area of empty pond and on assumption of circular shape.

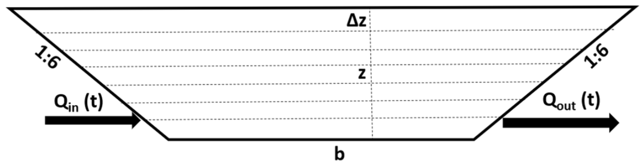

Figure 2.5: Sketch of the pond

Parameter	Value [m]
Δz	0.0277
z	2.77
b	55.44

Table 2.2: Values of the parameters from figure 2.5.

Since logger placed in the pond measures the water level based on the pressure, measured water level is a relative depth. Absolute depth is determined from the permanent water level from the layout and from the typical water level after water is discharged into the stream, The absolute water level achieved after each discharge event is called as permanent water level, see figure 2.6.

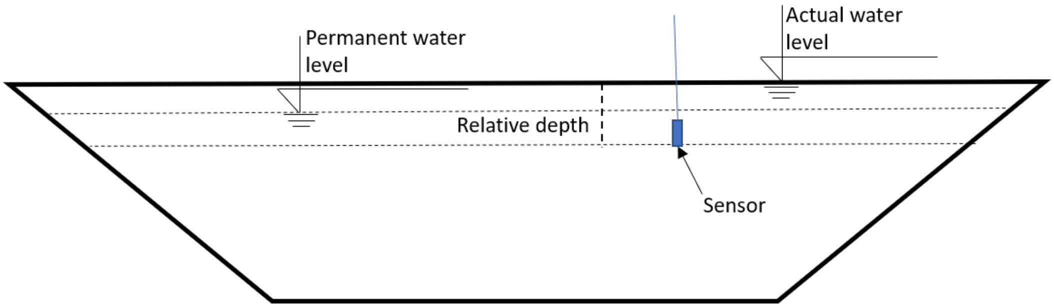

Figure 2.6: Princip of water level measurements.

The permanent water level, respectively minimal depth, was determined on 1.14 meter. However determined water level based on measurements is slightly higher than permanent water level from the layout, the difference 5 cm is not consider as significant and permanent water level from layout will be used further. Fluctuation of the water level due to evaporation is not taking into account.

2.3 Meteorological data

The numerical model of water temperature in the pond requires a lot of measured variables. It is necessary to measure air temperature, humidity, wind speed and solar radiation. However the precipitation is not crucial to make a simple model of the water temperature in the pond, the runoff water is added to determined a water level variation. The first three meteorological data could have been measured from the meteorological station from Aarhus which is 12 km far from Beder-Malling. The measurement of solar radiation is not easily available.

The available data of solar radiation is not measured long enough. Because of these unavailable measurements of solar radiation from meteorological station close to Beder-Malling, all needed data are obtained from meteorological station at Aalborg University. The figure 2.7 shows a distance between Aalborg-Beder and Aarhus-Beder. The Aalborg is approximately 110 km far. However, this distance can cause some inaccuracies, it is assumed that weather conditions on the both place are fairly similar. The precipitation data set was measured close to Beder-Malling.

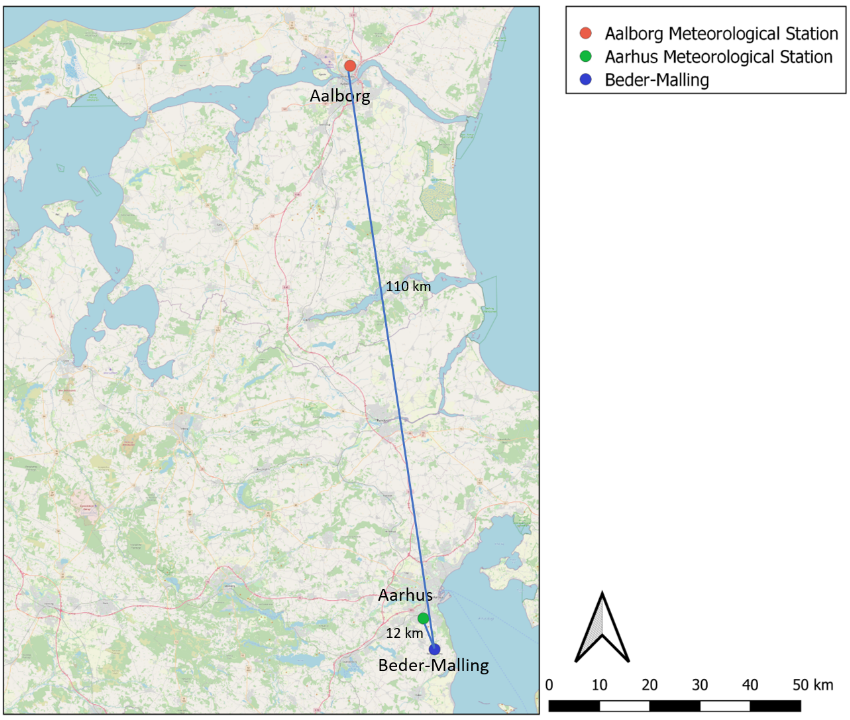

Figure 2.7: The distance between Aalborg, Aarhus and Beder.

The air temperature is measured in °C with time step of 1 minute. Since Stefan-Boltzmann constant is in W/m^2/K^4, which is used further, it is necessary to transfer from °C into Kelvin. Humidity is measured in % with also time step of 1 minute. Wind speed is measured in m/s and solar radiation in W/m^2 which is equal to J/s/m^2. The precipitation is measured by tipping bucket gauge in μm/s with 1 min time step. Tipping bucket gauge registers rain and no-rain. If the rain starts the bucket is gradually filled. In case that the bucket is full, it tips. The number of tips every minute defines the rain intensity.

3 Numerical Model of Water Retention Pond

Focus of this chapter is on explanation of the numerical model of WRP which can predict change of water temperature based on meteorological data and pond geometry. The model explanation is divided into two parts: Mass balance and energy balance. Processes affecting water temperature, assumptions, used equations and parameters are explained throughout this chapter and model calibration and validation are described at the end of the chapter.

3.1 Mass Balance

Mass balance is determined based on inflow and outflow. The sum of the total amount of water flowed in, out and stored water is constant. The figure 3.1 shows the principle of the mass balance.

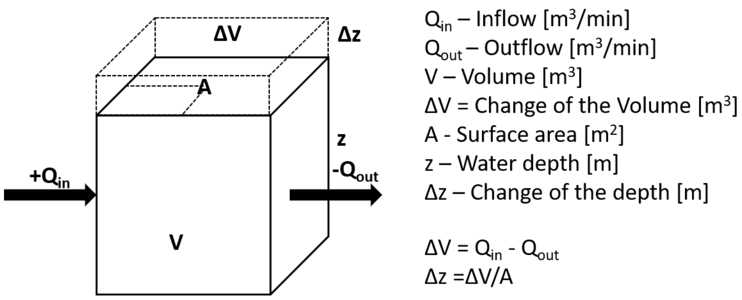

Figure 3.1: The principle sketch of the mass balance.

3.1.1 Inflow and Outflow

Inflow to the pond is not constant and is assumed to be equal to runoff water volume. The initial loss due to evaporation, evapotranspiration and depression was not taking into account, since the difference in water level would be negligible. The water level in the pond was calculated based on the volume of the inflow water, the volume of the outflow water and on the dimensions of the pond. Shown equations in 2.4 for bathygraphic curves were used to determine water surface and volume of the pond. As unknown X, the water level was substitute.

The runoff water volume was calculated from precipitation data measured near the pond and from the area of paved urban catchment according to the equation 3.1. The paved urban catchment is 12.3 red. ha. (AarhusVand, 2016)

$$Q_{in} = \frac{i}{10^6} * A_{imp} * 10^4 * 60 \tag{3.1}$$

Where:

Q_{in}	Runoff Water Volume/minute	[m^3/min]
i	Rain intensity	[μm/s]
A_{imp}	Impervious Area	[red. ha]

The volume of the outflow, Q_{out}, was calculated according to equations provided by Thomsen, 2020. These two equations describe rating curve, which determine the outflow based on the water level, see figure 3.2.

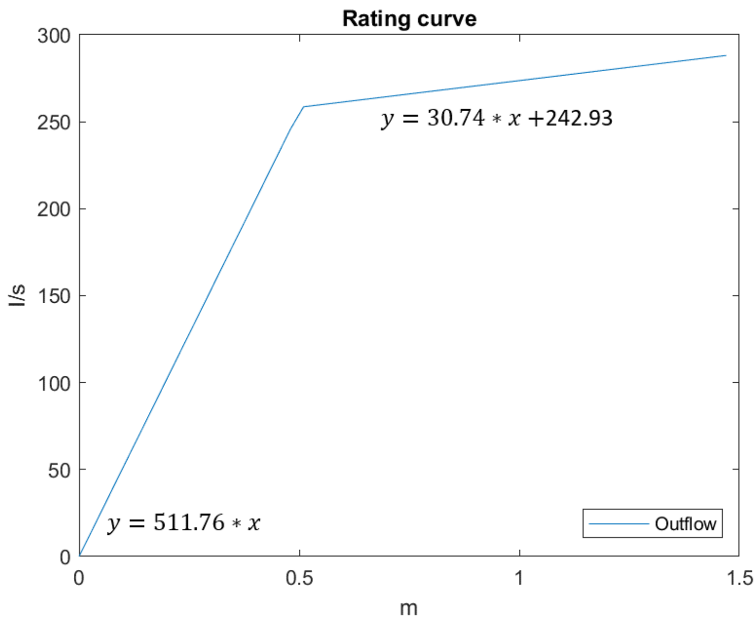

Figure 3.2: The function of the outflow based on the water level.

3.1.2 Water Level

In case that inflow and outflow is determined the water level can be calculate according to 3.2.

$$H_{w(i)} = H_{w(i-1)} + \frac{Qin_i - Qout_i * dt}{K_i} \tag{3.2}$$

Where:

H_w	Waterl Level	[m]
Q_{in}	Runoff Water Volume/minute	[m^3/min]
Q_{out}	Outflow Water Volume/minute	[m^3/min]
dt	Time step	[min]
K	Equation of batygraphic line for water surface	[m^2]

The calculated water level is illustrated in figure 3.3. The maximum water level is 2.77 meters. The modelled water level during the year 2018 and 2019 is 1.63 meters in maximum. It does not fit with measurements, where the maximum water level was 1.99 meters. The difference is probably because of a little knowledge about the shape of the pond. It is assumed that the pond is circular shape to obtain batygraphic lines, however in real situation the pond has a kidney shape. Thus there are two possibilities to focus on:

- Modelled water surface area corresponds to the real water surface area.
- Modelled water level corresponds to measured water level.

Since we are interested how water surface area affects the water temperature, the first option was chosen. The optimal solution would be creating batygraphic lines based on drawing of the pond where it would be possible to measure area and corresponding volume.

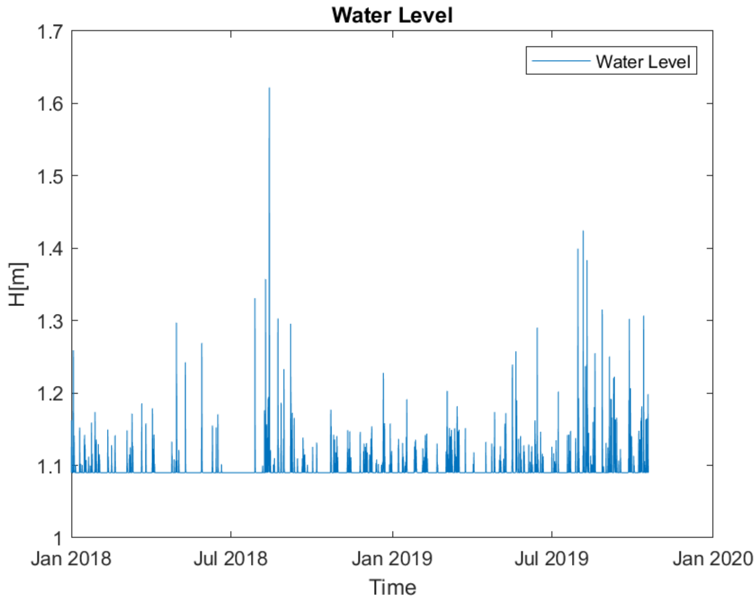

Figure 3.3: The water level during the year 2018 and 2019.

With known water level the water surface area of the pond can be calculated and figure 3.4 shows, how water surface varies corresponding to the mass balance. In the evaporation from water surface is not taking into account, thus even in the dry period the water level does not decrease, how it can be seen during the summer 2018. In the real situation there would be gradual decline of the water level during the dry period.

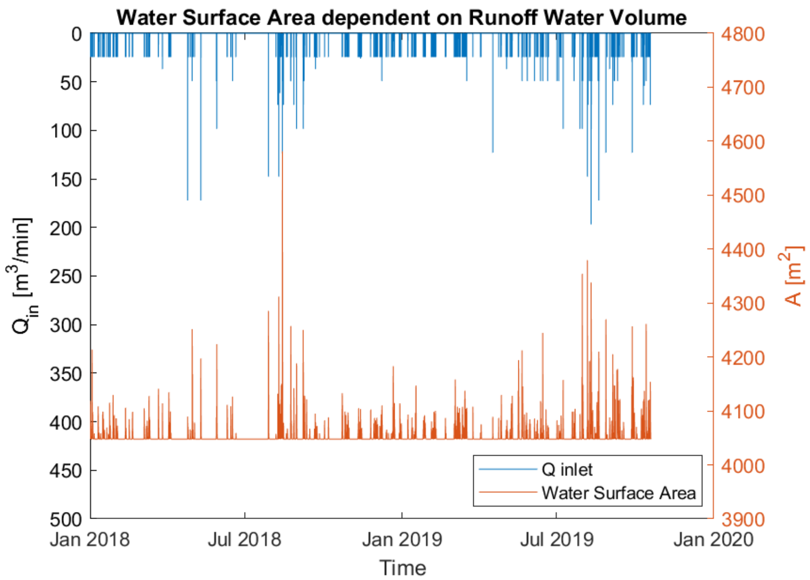

Figure 3.4: Water surface as function of time and depth

3.2 Energy Balance

Water temperature is affected by several heat fluxes, which are illustrated in the conceptual model of WRP in figure 1.1. The net heat flux, based on energy balance, results from the heat exchange at the water-air interface can be written as the following equation 3.3. Energy coming in and out has to be equal to stored energy in the water body.

$$\Delta E = R_s + R_{n_{absorbed}} + R_b + H + LE + S \tag{3.3}$$

Where:

E	Net heat flux	[J/s/m^2]
R_s	Absorbed short-wave atmospheric radiation	[J/s/m^2]
$R_{n_{absorbed}}$	Absorbed long-wave atmospheric radiation	[J/s/m^2]
R_b	Long-wave water back radiation	[J/s/m^2]
H	Conduction/convection heat flux	[J/s/m^2]
LE	Evaporation/condensation heat flux	[J/s/m^2]
S	Bottom heat flux	[J/s/m^2]

The heat exchange between water and atmosphere has the greatest impact on the water temperature (Evans and McGregor, 1998). The intensity of heat exchange depends on meteorological and hydrological conditions.

Figure 3.5 illustrates heat exchange between water and atmosphere. Short-wave and long-wave radiation coming from the atmosphere is always positive. It is illustrated by arrow pointed into the water. On the other hand long-wave back radiation coming from the water is negative and illustrated by arrow pointed from the water to the atmosphere. Condensation and evaporation heat flux is illustrated by double arrow as well as conduction heat flux. These fluxes can be positive or negative depends on the saturation vapor pressure and on actual water pressure for evaporation/condensation and on water and air temperature for conduction.

The bottom heat flux can be negative and positive as well. Usually during the winter the soil around heats the pond up and during summer the soil temperature is lower than water temperature and bottom heat flux is negative.

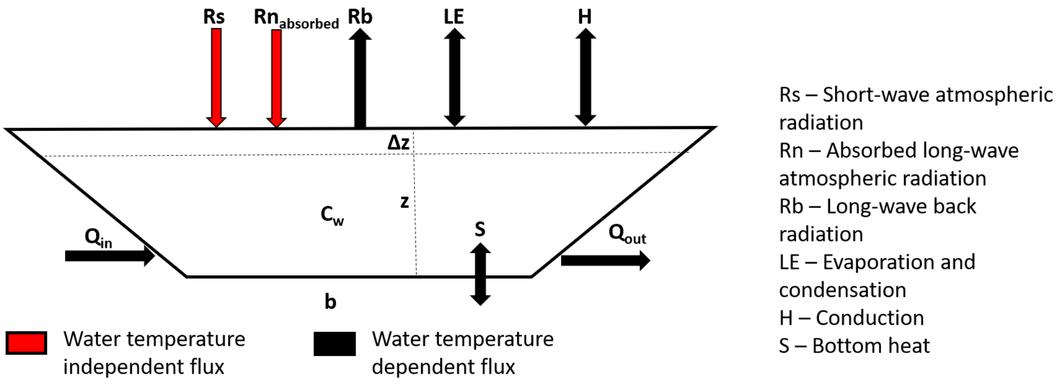

Figure 3.5: A sign convection of heat fluxes on water retention pond and illustrates what flux is dependent on the water.

The inflow and outflow in the figure 3.5 affect just the water surface variation. The effect of the runoff temperature is investigated further.

3.2.1 Assumption and Simplification

Purpose of this section is to consider what fluxes can be neglected and what has to be included in the numerical model.

To calculate the bottom heat flux is necessary to know a soil temperature under the bottom of the lake. Unfortunately this measurement is not available. Since the bottom heat flux is considered as the smallest energy loss or significant only in ice covered lakes (Bengtsson *et al.*, 2012), it is very often omitted.

In many cases also advected heat flux can be omitted, especially in case of lakes with high volume, where advected heat flux as heat coming from the runoff is lower than other fluxes. On the other hand, WRP has to retain the runoff water and thus in the case of the high volume of the runoff water, the effect of the runoff temperature can be significant. However, advected heat flux will be omitted in the model described in the following section 3.2.3, where to model is developed and set, the effect of the runoff water on the water temperature will be investigate and described further in the chapter 4.

The next assumption is about the stratification. Since it is assumed that WRP are usually shallow and fully mixed without stratification, modelled surface temperature can be considered as water temperature in entire pond.

3.2.2 Heat Storage Capacity of the Water

To model water temperature is necessary to calculate how much energy can be stored in water body with specific volume according to equation 3.4. Since water level in the WRP varies due to evaporation, precipitation and runoff from the catchment area, also volume of the WRP differs. Heat storage capacity of water body depends on volume of water. Moreover, because of the slope of the banks, the surface area can differ significantly and heating up or cooling down can be faster.

$$c_{wi} = c_p * V_i * \rho \tag{3.4}$$

Where:

c_w	Heat storage capacity of water body	[J/°C]
$c_p = 4178$	Heat capacity of water	[J/kg*°C]
V	Volume	[m^3]
ρ_w	Water density density	[kg/m^3]

Since heat storage capacity of water body expresses how much energy is necessary to add to heat up the water with specific volume by 1°C, the temperature difference (Δ T) is in direct proportion of the net heat flux in specific time step from specific water surface and in indirect proportion of the heat storage capacity in specific time step. This relation is expressed by equation 3.5.

$$\Delta T_i = \frac{\Delta Ei * Ai * dt}{c_{wi}} \tag{3.5}$$

Where:

A	Water surface area	[m^2]
$dt = 60$	Time step	[s]
c_w	Heat storage capacity of water body	[J/°C]
Δ E	Net heat flux	[J/s/m^2]

Since water temperature is calculated according to equation 3.6, the water temperature for each time step is substituted by the modelled temperature from the previous step.

$$T_i = T_{i-1} + \Delta T i \tag{3.6}$$

Where:

T_i	Water temperature in step 1	[°C]
T_{i-1}	Water temperature in previous step	[°C]
ΔT	Temperature difference	[°C]

3.2.3 Heat Fluxes affecting the Water Temperature

Processes affecting the water temperature can be divided into processes dependent and independent on the water temperature (Edinger *et al.*, 1968).

Since a lot of different equations can be found in the literature to calculate each term from 3.3, it is debatable issue to select the appropriate formula. Despite the fact that calculation of fluxes differs in the literature, generally the net heat flux is calculated primarily based on the water temperature, air temperature and humidity, wind speed, solar radiation and air pressure.(Kalinowska, 2019).

Short-wave Solar Radiation

The short-wave solar radiation is independent on the water surface and can be directly measured by a meteorological station. It varies significantly over a day as well as over a year. According to Kalinowska, 2019 factors affect the short-wave solar radiation are following:

- Sun position - differs based on a date, time of the day and elevation above the sea.
- Reflection and absorption - part of solar radiation is absorbed by the atmospheric gases and dust or reflected by clouds.
- Reflection by surface - Each surface has a different reflection coefficient also called albedo.
- Shading - Vegetation and banks can shade a water surface and decrease the solar radiation.

The heat flux value may vary over the day from 100 J/m^2/s for a very cloudy day to 1000 J/m^2/s for a sunny day. Albedo or reflection coefficient for water depends on the darkness (the darker water, the lower albedo) and clarity as waves, eutrophication, depth, etc. and on the sun position (the higher albedo with the lower sun) (Kalinowska, 2019). Since the albedo have not been measured, the literature value was used. In the literature reflection of the water surface differs from 1-10 %. For the purpose of this study the albedo is assumed as constant with value 0.07. It means that 7 % of short-wave solar radiation is reflected back to the atmosphere. This value was determined based on trial and error calibration of the model to achieve the best fit with measured data. Non-reflected short-wave solar radiation is calculated according to equation 3.7.

$$R_s = (1 - \alpha) * R_{si} \tag{3.7}$$

Where:

R_s	Absorbed short-wave atmospheric radiation	[J/s/m^2]
R_{si}	Short-wave atmospheric radiation	[J/s/m^2]
α	Albedo	[-]

In the figure 3.6 is illustrated measured solar radiation and non-reflected solar radiation. Since solar radiation measurement from the closest meteorological station to the Bederbaek pond is not available, short-wave solar radiation measured by Aalborg University which is approximately 110 km far from Beder-Malling, was applied.

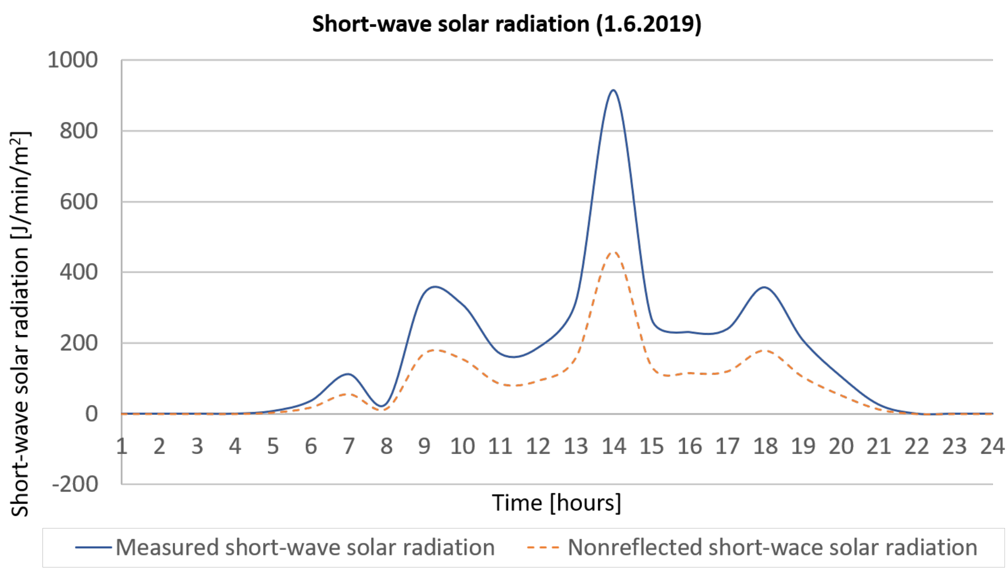

Figure 3.6: Measured short-wave solar radiation and calculated non-reflected short wave solar radiation on the 1st of June 2019.

Water retention pond used in this model is not surrounded by trees or buildings, thus the shading is not taking into the account. In case of shading the shading factor can be added into the equation 3.7 where shading factor can vary from 0 (no shading) to 1 (completely shading). In practical using shading factor is very often omitted since shading varies spatially and seasonally.

In case that solar radiation is not measured is possible to estimate it for the given geographical location and the specific time. The different equations based on solar constant can be found in the literature, for example in Allen *et al.*, 1998.

Long-wave Atmospheric Radiation

Each surface with temperature higher than 0°K emits long-wave radiation. It can range from 30 J/s/m^2 to 450 J/s/m^2 (Kalinowska, 2019). It can be measured by pyrgometer or calculated. Usually measurements of long-wave atmospheric radiation is not available, since pyrgometers are expensive and the meteorological stations usually do not have these devices. However, there is a lot of equations to determine long-wave atmospheric radiation in the literature and generally all of them are based on air temperature, humidity and emissivity of the atmosphere.

The relation of air temperature and emissivity of the atmosphere describes Stefan Boltzmann's law, see equation 3.8. (Boltzmann, 1884), where the long-wave atmospheric radiation is proportional to the power of four of the air temperature.

$$R_n = \sigma * \epsilon_a * T_a^4 \tag{3.8}$$

Where:

R_n	Long-wave atmospheric radiation	[J/s/m^2]
ϵ_a	emissivity factor of the air	[-]
T_a	Air emperature	[°K]
σ	Stefan-Boltzmann constant	[W/m^2/K^4]

Equation 3.8 is valid for clear sky condition. However, in the case of cloudy day, part of the long-wave radiation is reflected, equation for the clear sky is used in this project. Small part of incoming long-wave radiation is also reflected by water surface as well as short-wave solar radiation. According to Kalinowska, 2019 the reflection coefficient for water is 0.03 and absorbed long-wave atmospheric radiation is calculated as following:

$$R_{n_{absorbed}} = R_n * (1 - r) \tag{3.9}$$

Where:

$R_{n_{absorbed}}$	Absorbed long-wave atmospheric radiation	
r	reflection coefficient	[-]

Although equations 3.8 and 3.9 seem simple, the determination of the value of atmospheric emissivity is challenging. Emissivity describes ability of obstacles emit long-wave radiation as thermal radiation. It can range from 0 to 1 where 1 is emissivity of the black body. Emissivity of atmosphere is function of air temperature or actual water pressure or both. (Brutsaert, 1975)

Brutsaert, 1975 suggests to calculate atmospheric emissivity as following:

$$\epsilon = 1.24 * (\frac{e_a}{T_a})^{1/7} \tag{3.10}$$

Where:

e_a	Actual vapour pressure	[mb]
T_a	Air temperature	[°K]

Since relative humidity is defined as the ratio of the actual vapour pressure e_a to the saturation vapour pressure e_{sat} (Lawrence, 2005), actual vapour pressure can be calculated according to the equation 3.11. Saturation vapour pressure can be determined according to Magnus empirical formula shown in 3.12. (Lawrence, 2005)

$$e_a = \frac{RH}{100} * e_{sat} \tag{3.11}$$

Where:

e_{sat}	Saturation vapour pressure	[mb]
RH	Relative humidity	[%]

$$e_{sat} = r_1 * exp\frac{r_2 * T_a}{T_a + r_3} \tag{3.12}$$

Where:

e_{sat}	Saturation vapour pressure	[mb]
T_a	Air temperature	[°C]
r_1,r_2	Empirical coefficients	[-]
r_3	Empirical coefficient	[°C]

Table 3.1 illustrates used values for saturation vapour pressure e_{sat} calculation. (Lenouo *et al.*, 2008), (Bolton, 1980),(Kalinowska, 2019)

Table 3.1: Used values in equation 3.12

Coefficient	Value	Units
r_1	6.112	[-]
r_2	17.67	[-]
r_3	243.5	[°C]

Absorbed long-wave radiation and air temperature is illustrated in figure 3.7. The highest air temperature corresponds to highest long-wave atmospheric radiation. The most energy from long-wave atmospheric radiation is coming into the water in the warmest part of the day.

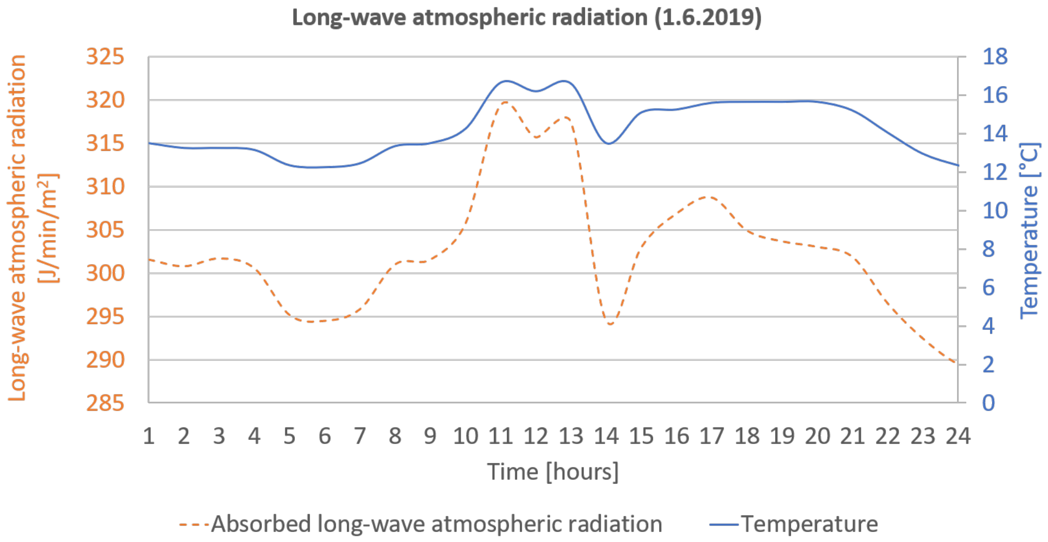

Figure 3.7: Air temperature and absorbed long-wave radiation for one day.

Long-wave back radiation

Since all terrestrial objects emit long-wave radiation, water not excluding, the water surface can loose a notable part of the energy through this long-wave back radiation. This process is dependent on the water temperature and can be calculated based on Stefan-Boltzmann law. Equation 3.8 can be modified by using emissivity and temperature of water instead of emissivity and temperature of air. However literature provides different values for water emissivity, all of them are in the range from 0.9 to 0.99. Used value in this project is 0.97 according to Ji, 2017 or Kalinowska, 2019.

Conduction

Heat transport between bodies with different temperatures is represented by conduction and convection. In the case of fully mixed WRP it is placed on the water-air interface. Conduction is caused by chaotic movement of particles which transfer kinetic energy by collisions. Equation 3.13 describes the conduction process and the governing parameters are water and surface temperature, wind speed, air pressure and Bowen ratio which is described in Ji, 2017 or Bowen, 1926.

$$H = c_b * \frac{p_a}{p_0} * f(u) * (T - T_a) \tag{3.13}$$

Where:

c_b=0.62	Bowen coefficient	[mb/°C]
p_a	Air pressure	[mb]
p_0=1013	Reference air pressure	[mb]
f(u)	Wind speed function	[m/s]
T	Water temperature	[°C]
T_a	Air temperature	[°C]

It is not possible to use measured wind speed directly. Ji, 2017 suggests to use wind speed function calculated as following:

$$f(u) = b_0 + b_1 * u + b_2 * u^2 \tag{3.14}$$

Where:

b_0	Empirical coefficent	[$W/m^2/mb$]
b_1	Empirical coefficent	[$W/m^3/mb*s$]
b_2	Empirical coefficent	[$W/m^4/mb*s^2$]
u	Measured wind speed	[m/s]

Usually there are 2 types of the wind speed functions in the literature where either b_1 or b_2 is zero. Thus wind speed function is linear or quadratic equation. Different coefficient from different authors are listed in the table 3.2.

Table 3.2: Empirical coefficient for wind speed function according to different authors.

b_0	b_1	b_2	Author
6.1	0	0.34	Ji, 2017
8.4	3.07	0	Meyer, 1917

Since these coefficients are empirical and site specific, both suggestions were used to examine the performance of the model. The values suggested by Meyer, 1917 was accepted as more accurate.

Energy loss or gain due to conduction is usually low since the difference between the water temperature and air temperature is not significant. In case that water is warmer than air, usually at night, WRP is losing energy. If water is colder than air, water is heated up and it gains energy.

Evaporation

In terms of non radiation fluxes, evaporation heat flux has the most significant effect on cooling water down. It considerably varies over time of the year and sites and it is depended on water temperature. Evaporation can be measured but with 1 minute time step the devices would have to be very accurate. There are some theoretical methods used for evaporation calculation. Amount of energy loss depends on wind speed function, described by equation 3.14, and on difference between saturation vapour pressure at the water surface and the actual vapour pressure of the air. (Kalinowska, 2019)

$$LE = f(u) * (e_s - e_a) \tag{3.15}$$

Where:

f(u)	Wind speed , (see eq. 3.14)	[W/(m^2*mb)]
e_s	Saturation water vapour pressure, (see eq. 3.12)	[mb]
e_a	Actual air vapour pressure, (see eq. 3.11)	[mb]

Saturation vapour pressure at the water surface can be calculated in the same way as saturation vapour pressure in the air. It is described by equation 3.12 above in section about long-wave atmospheric radiation. Coefficients r_1, r_2 and r_3 are the same as in table 3.1 but water temperature is used instead of air temperature. Actual vapour pressure is calculated in equation 3.11.

3.2.4 Modelled Water Temperature

Resultant net heat flux calculated from different types of heat flux described above illustrates how much energy water is gaining or losing. It varies over the day and seasons. Since positive atmospheric long-wave radiation is almost the same as negative long-wave back radiation, short-wave solar radiation has the biggest impact on the final net heat flux what is shown in figure 3.8. Since water temperature and air temperature do not significantly differ during this specific day 1.6.2019, conduction has the smallest impact on net heat flux. However also conduction can have a great impact on net heat flux, in case that heat wave is coming after colder period.

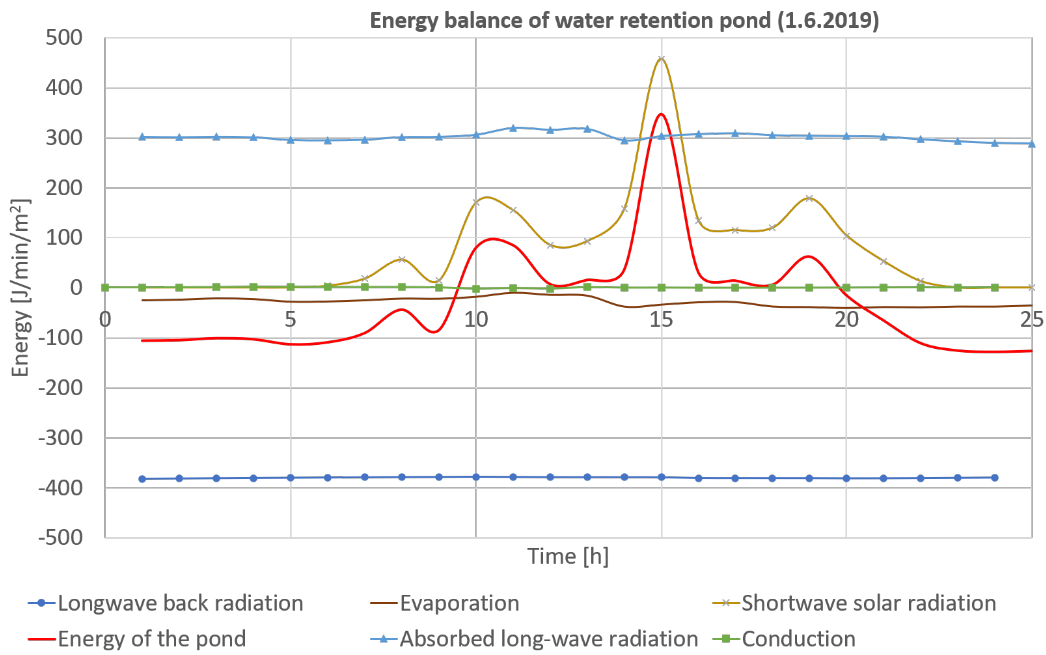

Figure 3.8: Net heat flux over 1 day

Modelled Water Temperature over Seasons

To make a model which can be used to predict net heat flux, respectively water temperature, over the seasons, is crucial to use time series over more than one year. Meteorological data over one year measured each minute were available from the meteorological station at Aalborg University and main focus was on the year 2018 where both winter and summer were very intense considering typical weather in Denmark and on the year 2019 as the newest data. Net heat flux from this period is illustrated in figure 3.9 for more detailed view. The red line shows how much energy the pond was losing or gaining. In case that the red line is in negative part of the plot the water retention pond is losing more energy than it is gaining. Heat flux due to evaporation has more significant impact than it could seem from the net heat flux over only one day.

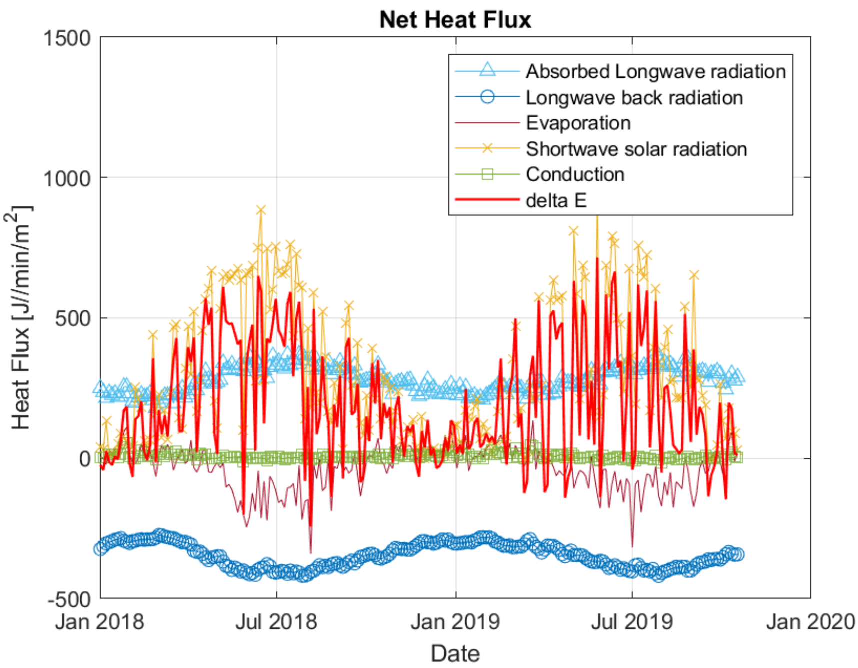

Figure 3.9: Net heat flux over 2018 and 2019

Modelled water temperature, computed according to equation 3.5 and 3.6, and measured temperature from 1.1 2018 until 15.10.2019 are illustrated in figure 3.10. The modelled temperature is considerably underestimated. On the other hand, this model has not been calibrated yet and since modelled temperature follows trend of measured temperature rather well, the model is accepted. The main error in the winter time can be caused by omitting the bottom heat flux which warm up the water in the winter.

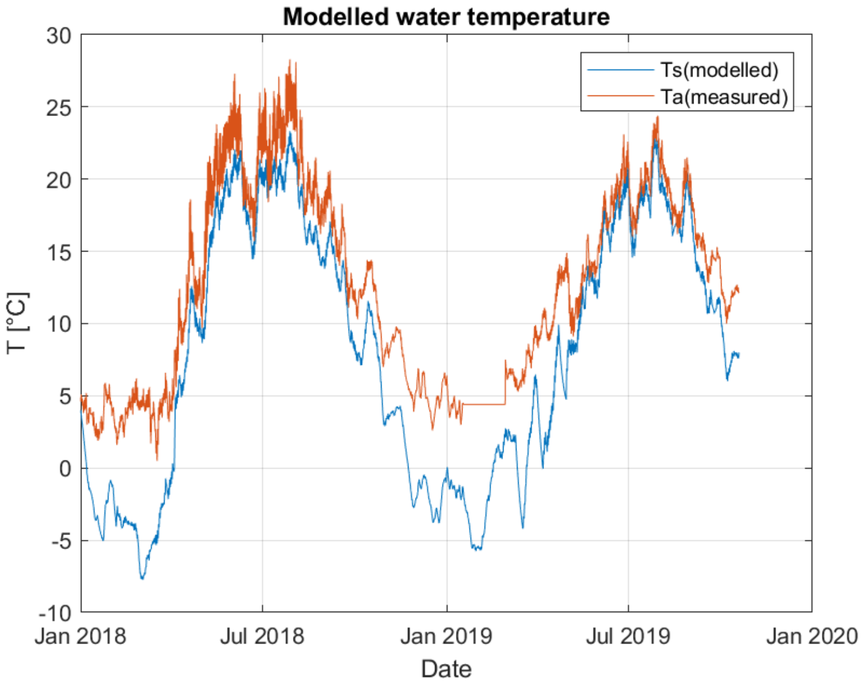

Figure 3.10: Modelled water temperature based on meteorological data

3.2.5 Control Quality of the Model

The control quality of the model was performed to see if all equations and parameters were set up correctly. It is used as kind of validation performed by following calculation. It is assumed, there is an isolated WRP with constant input parameters and no runoff water or discharge, thus volume of the pond is constant. The model with constant input is attached in electronic appendix 9.2.1. The equations described above in section 3.2.3 were used nonetheless all measured meteorological parameters as solar radiation, air temperature, humidity and wind speed were set to constant, see table 3.3. Since coming and emitting energy should be equal after some time, also the water temperature with constant input should have been equalized on one reasonable value.

Table 3.3: Constant input into the model.

Input	Value	Unit
Shortwave solar radiation	300	[J/s/m^2]
Air temperature	15	[°C]
Humidity	90	[%]
Wind	4.6	[m/s]
Soil temperature	10	[°C]
Initial water temperature	28	[°C]

Let’s say after longer hot weather period the water in the pond was heated on 28°C. After, a cold front came with constant air temperature 15 °C, with a bit cloudy sky thus the solar radiation is 300 J/s/m^2 and with gentle breeze. The figure 3.11 shows that equilibrium temperature 16.4 °C was reached after approximately 800 hours. It means that temperature decreased by 11.6 °C in 33 days. Since the fictive cold front was intense, the first two degrees were lost only in 1 day. Since there is no measurements, these results can not be compared with any. On the other hand, it fulfill the expectation about constant reasonable value. Also the water temperature decreased by 2°C in one day is considered as trustful and acceptable.

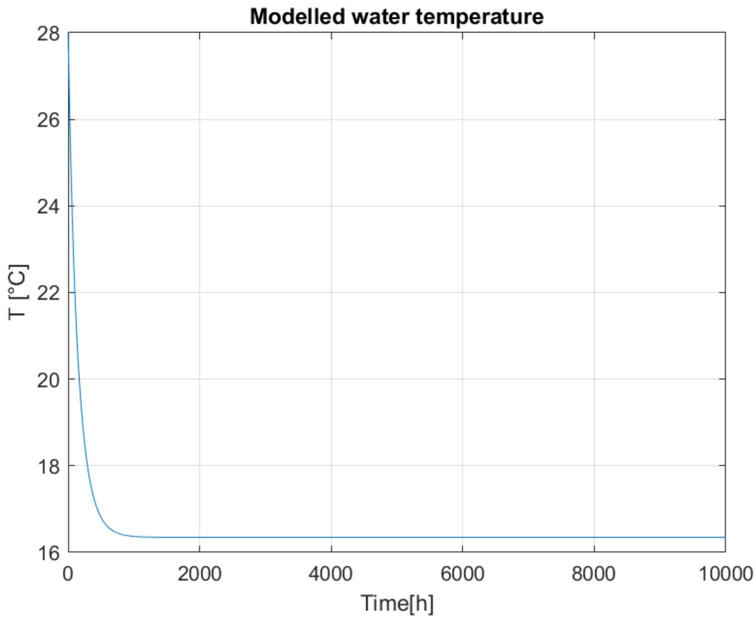

Figure 3.11: Modelled water temperature with constant input.

3.2.6 Model Calibration

To declare the model as reliable calibration has to be done. The calibration was performed fully manually. From the picture 3.10 is evident the modelled temperature is lower compare to the measured temperature. The first part of the calibration was made by trial and error method and eventually the modelled temperature was increased by 3°C. When calibrating the modelled temperature was moving up and down to achieve the best fit with measured data. Lower values of modelled data can be caused by using meteorological data sets from Aalborg which is 150 km far on the north from the water retention pond. Is possible the overall weather in Aalborg is a bit colder than in Beder-Malling.

Also the literature provides a lot of possible parameters to calculate all the heat fluxes, thus the parameters as albedo, coefficients used in wind function and coefficients used for air emissivity calculations were changing. However, the root mean square error and Nash-Sutcliffe model efficiency coefficient were used to examine the best combination of changed parameters, the model was not significantly sensitive to those changes and the NSE differs negligible (0.01-0.05). Since the model does not perform well in the winter time also an estimated bottom heat flux was added. This flux was calculated based on thermal conductivity and temperature of the soil underneath the pond according to equation 3.16.

$$S = k * \Delta T \tag{3.16}$$

Where:

S	Bottom Heat Flux	[J/s/m^2]
k	Thermal Conductivity	[W/(m^2*°C)]
Δ T	Difference between soil and water temperature	[°C]

Since there is no information or data about the soil, the both soil type and soil temperature was estimated and literature thermal conductivity was used. As thermal conductivity was used 4.26 W/m^2/°C (Hamdhan and Clarke, 2010).The temperature of the soil underneath the pond was estimated on 10°C. Nevertheless the soil temperature depends on the air temperature, solar radiation, soil type and the depth or location and for the more accurate model the soil temperature would have to be measured.

The figure 3.12 shows measured and modeled water temperature after calibration and adding the bottom heat flux during two years.

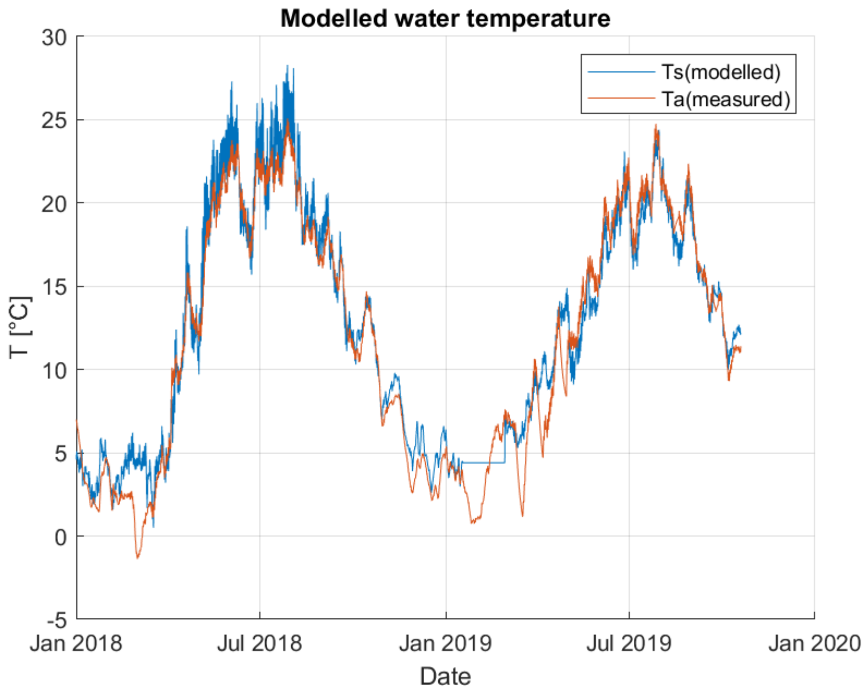

Figure 3.12: Measured and modelled calibrated water temperature during two years.

To find how much measured and modelled water temperature differ the Root Mean Square Error and Nash-Sutcliffe model efficiency coefficient were calculated for non calibrated, partial calibrated and fully calibrated model. By partial calibrated model is meant parameters calibration and adding the bottom heat flux without increased temperature. The Nash-Sutcliffe model efficiency coefficient (NSE) was calculated to examine the underestimation of the the modelled temperature. The calculated RMSE and NSE values are illustrated in the table 3.4.

Table 3.4: NSE coefficient and Root Mean Square Error for non calibrated model a for the trial calibrations

Calibration	NSE	R^2
Non calibrated	0.476	4.94
Model with bottom heat flux	0.65	4.02
Model with bottom heat flux and moved by 3°C	0.92	1.9

For non calibrated model the NSE is 0.476 and it means that the model without calibration can not be used.The model is just slightly more accurate than the mean of observed temperature.

The figures 3.13 and 3.14 show the modelled temperature vs the observed temperature before and after calibration.

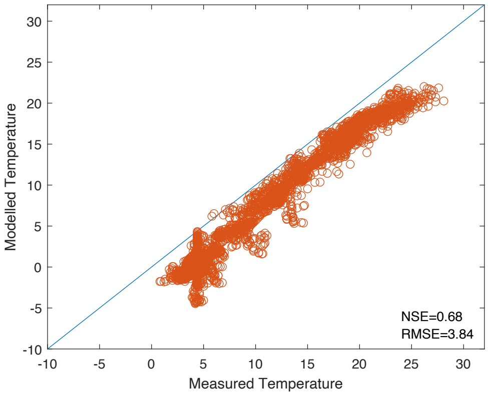

Figure 3.13: Modelled temperature vs Measured temperature NSE and RMSE.

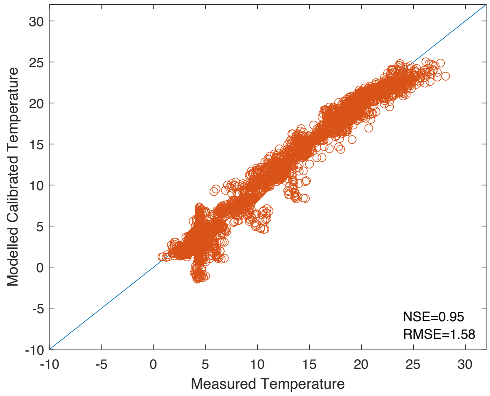

Figure 3.14: Calibrated temperature vs Measured Temperature

For each calibration trial the NSE coefficient was calculated and the best fit is temperature increased by 3°C where NSE is 0.92. The closer to 1 the more accurate model is. Since NSE coefficient higher than 0.75 was categorized by Moriasi *et al.*, 2007 as very good fit of model, the developed model can be declare as reliable and will be used further. Entire model can be found in electronic appendix 9.2.2. The model in appendix is already calibrated.

3.2.7 Model Validation

Validation is an important part of each model. The purpose of validation is examination how model works on different data sets.

The measurement in the pond next to Aalborg University has been set on the beginning of Decemeber, how it is illustrated in figure 3.15. The measuring device notices water level, temperature and pressure each ten minutes. Unfortunately in the meteorological data sets from Aalborg and from Vejle has had a gap of data for more than two months. Thus the measured data can not be used for validation.

Figure 3.15: Measuring device in the pond next to Aalborg University.

The model was applied into Hovedgroften pond from Beder-Malling to validate the model. This pond has not been used to develop model because of some uncertainties in measurement of water temperature, but for the validation the measurements are sufficient.

According to map dimensions of Hovedgroften pond are just slightly bigger than Bederbaek pond and also the discharge from Hovedgroften pond is assumed to be approximately the same as from Bederbaek pond. The main difference is in the catchment area which is for Hovedgroften pond 17.7 red. ha. It is approximately by 5 red.ha more than catchment area for Bederbaek pond AarhusVand, 2016. The same meteorological data sets are used for both ponds.

Figure 3.16 illustrates one year of water temperature measurements with modelled temperature before and after calibration. To illustrate only one year has been chosen to achieve more detailed view.

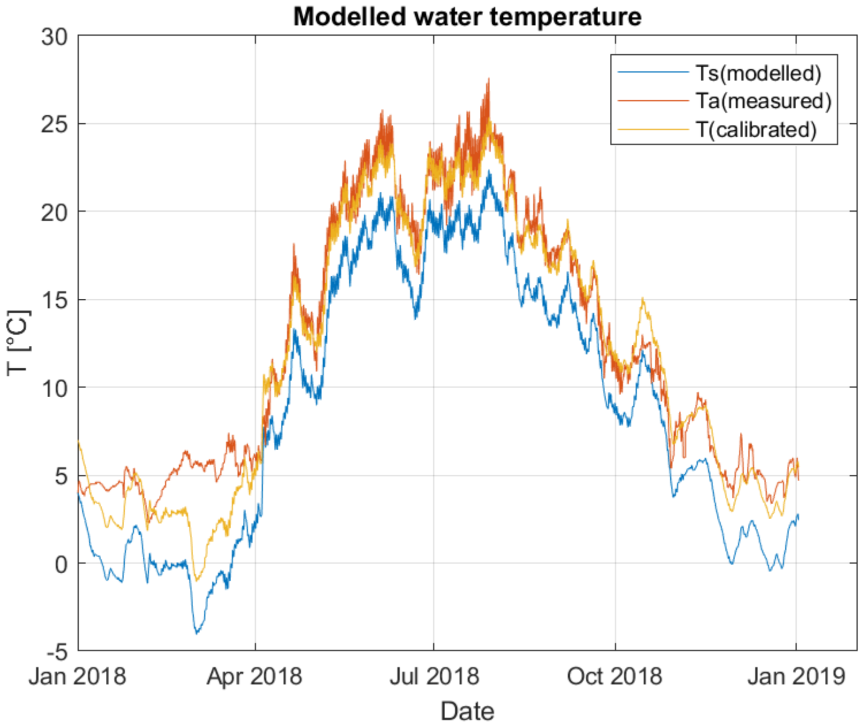

Figure 3.16: Measured and modelled water temperature before and after calibration.

Since Hovedgroften pond is in the same town with similar dimensions, the calibration has not been changed at all. The parameters affected by meteorological conditions are not changed and underestimated modelled temperature has been moved by 3°C as for Beder pond. The bottom heat flux is also added with the same estimated parameters.

To investigate how modelled temperature fits to measured temperature RMSE and NSE coefficients are calculated, see figures 3.17 and 3.18.

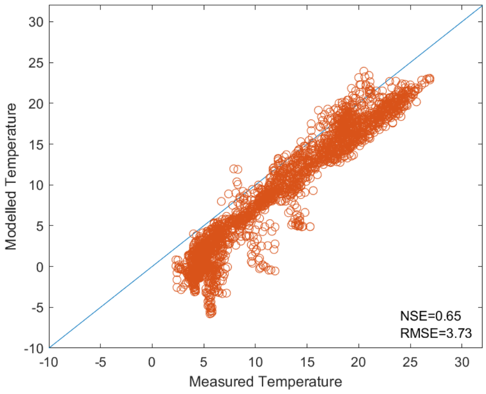

Figure 3.17: Non calibrated modelled temperature vs measured temperature.

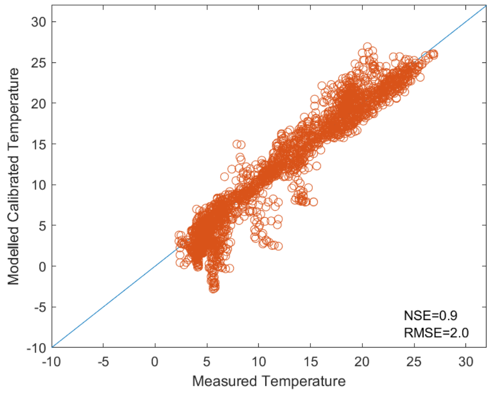

Figure 3.18: Calibrated modelled temperature vs measured temperature

The resultant NSE coefficient for calibrated model is just slightly lower than for Beder pond which means that the modelled temperature for Hovedgroften pond does not fit as good as for Beder pond but still performs pretty well. RMSE coefficient for calibrated model for Hovedgroften pond is just by 0.1 higher than for Beder.

The validated model with data sets for Hovedgroften pond is in electronic appendix 9.2.3. According to results presented above, the validation is considered as a sufficient and it is assumed that the model can be used for another pond in Denmark.

Application of the Model 4

Two ideas how the entire model can be applied are presented in this chapter. One of them is investigation how water temperature in the pond varies with different shape and dimensions of the pond and second one how water temperature reacts on runoff water inflows to the pond. When applying the model the changing parameters can be divided into two groups.

- Change in bottom radius, banks slope and maximum depth of the pond.
- Change in volume and temperature of runoff inflows to the pond.

4.1 Change of geometry

When investigating the effect of surface water area on water temperature, the model has been applied on ponds with different water surface area. Surface area should differ significantly to see the impact. The model of water temperature was developed based on the geometry of the Beder pond which is described in the chapter 2.2. Since the calculated volume of this pond is approximately 5000 m^3 and discharge rating curve is modelled for this volume, other ponds dimensions were determined based on the similar volume.

Since it is expected that temperature varies less with lower surface area, the twice deeper pond was applied in the first scenario. In the second scenario the depth was decreased by half resulting into bigger surface area. The bigger surface area, the higher temperature variation. The third scenario was applied with 4 meters depth. The table 4.1 sums the pond characteristics for all scenarios

The geometry of each pond was chosen to fulfill reasonable dimensions with just small difference in the volume.

Table 4.1: Pond characteristic for different scenarios

Parameter	Current pond	Scen.1	Scen.2	Scen.3	Unit
Depth	2.77	5.54	1.38	4	m
Bottom radius	23.7	17	35	20	m
Banks slope	5.5	3	10	5	-
Max surface area	4668	3462	7389	5026	m^2

Results

Developed and described model was used to predict the water temperature in each pond. Since each pond has a different bathygraphic curves which describe volume and water surface based on the depth, the modelled water temperature differs for each pond over seasons, what is shown in figure 4.1. The bathygraphic curves are used to calculate water level, how it is described in equation 3.2.

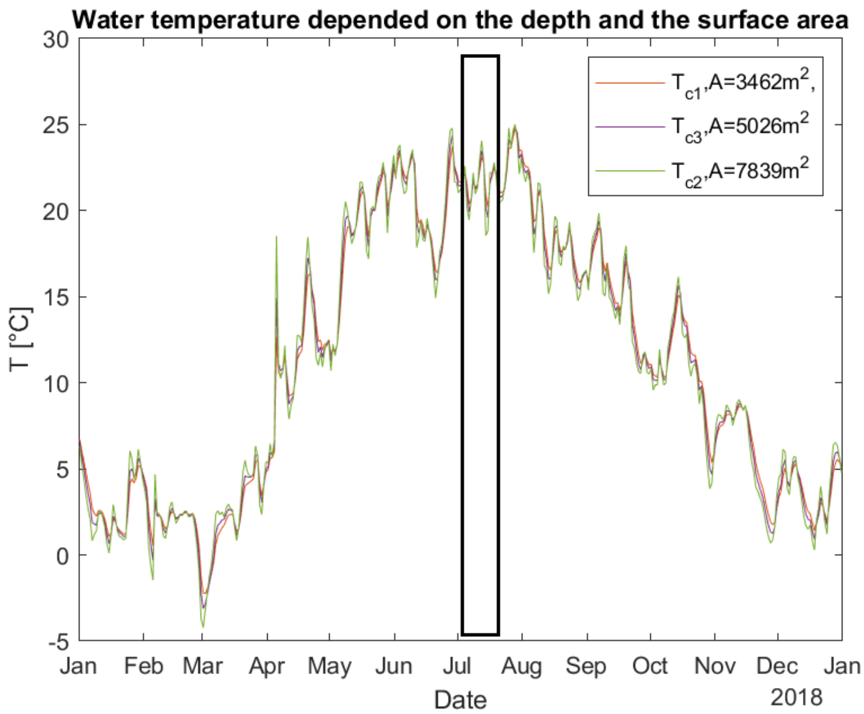

Figure 4.1: Modelled temperature for each scenario.

It is possible to zoom in on 5 days in the summer 2018 to present more detailed and clearer view, how it is presented in figure 4.2. It is easy to see the water temperature variation is the most significant in the pond with the biggest surface area both in day-night variation and weather-change variation. July 5^{th} a cold weather front came and the water temperature in the pond with biggest surface area dropped the most significantly. The temperature variation in that pond during the day and night is approximately 5°C. The water temperature in the deepest pond with the smallest water surface area differs in day and night only around 1.5°C, which is approximately 3 times less than in the pond with the biggest surface area. The cold weather front in 5^{th} July does not affect the water temperature so significantly compare to the pond with the biggest surface area.

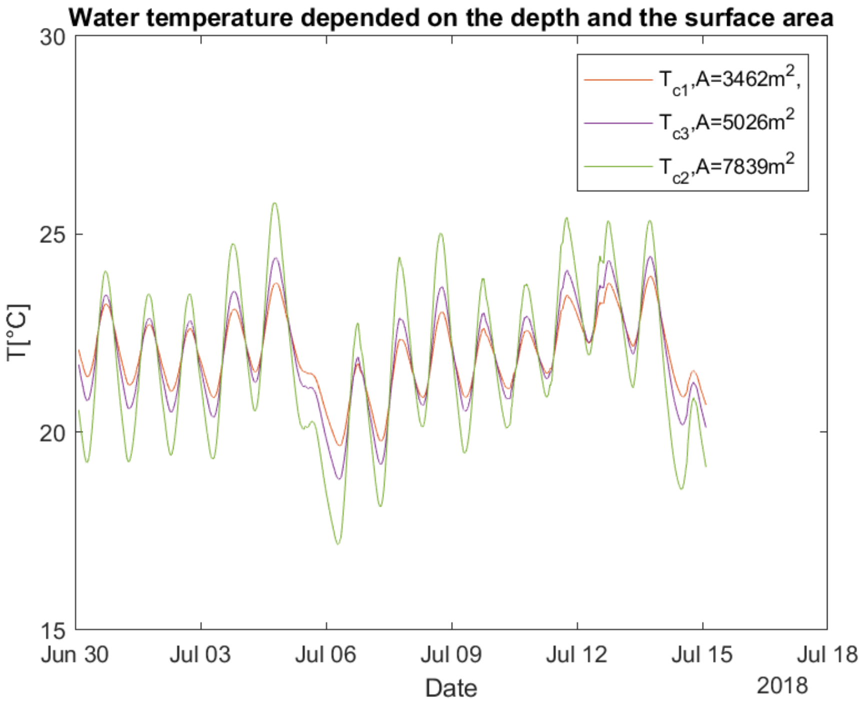

Figure 4.2: Modelled temperature for each scenario.

The model fulfills expectation about water temperature in the pond with different surface area. However, the assumption about non-stratified water would not have been true for the deepest pond with the smallest surface.

4.2 Change of Runoff Volume and Temperature

Since the purpose of the WRP is retain the runoff water to avoid polluting of adjacent stream, the temperature and volume of the runoff water inflows into the pond has to be investigated and implemented into the model. The runoff water temperature is implemented into the model by mixing equation 4.1.

$$T = \frac{T_1 * V_1 + T_2 * V_2}{V_1 + V_2} \tag{4.1}$$

Where:

T	Resulting temperature	[°C]
T_1	Temperature of the pond	[°C]
V_1	Volume of the pond	[m^3]
T_2	Temperature of the runoff water	[°C]
V_2	Volume of the runoff water	[m^3]

To see if this approach works, the constant input is applied. By constant input in table 4.2 is meant the constant runoff volume with the constant temperature during all seasons.

Table 4.2: Runoff water as constant input.

Input	Value	Unit
Inflow	400	[m^3/min]
Runoff temperature	8	[°C]

Figure 4.3 shows water temperature in the pond with and without effect of the runoff water temperature. The plot confirms expectation about increasing water temperature in the pond during the winter and decreasing during the summer. Since the input constant temperature is 8°C, which is during the autumn and spring similar to water temperature in the pond, the effect of the runoff temperature is not significant during these seasons. Since the expectation about the water temperature is fulfilled, the variation of the input can be applied.

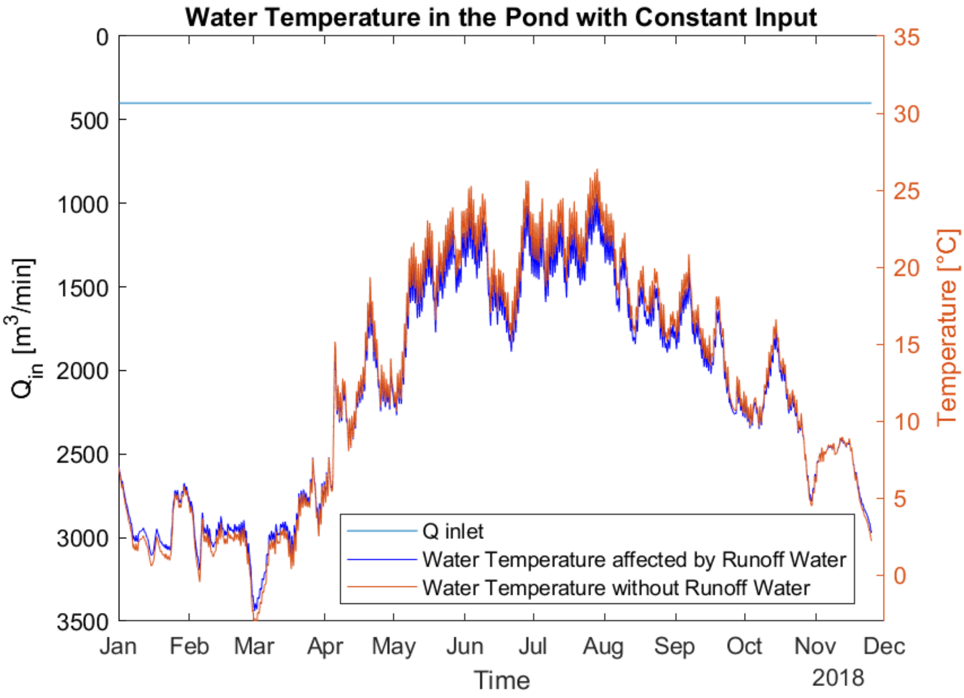

Figure 4.3: Runoff water temperature and the temperature of the air with runoff volume and temperature as constant.

4.2.1 Measured Precipitation and Estimated Runoff Temperature

Input preparation

The volume of the runoff water is determined based on precipitation and the catchment area, how it is described in the section 2.2. Any temperature measurements of runoff water are not available and the literature does not give any general value of the runoff temperature dependent on air temperature. On the other hand, there are the measurements of the water level and the water temperature in the pond, thus it is possible to estimate runoff water temperature based on these data.

The water level indicates the rain events and dry periods. In the case of rain event the water level gradually increases and in the certain point decreases again due to discharge into the stream, thus based on the water level and the pond dimension the volume of the runoff water were estimated. The temperature of the pond was written down before the discharge from the pond started and after the discharge ended.

This approach was applied into 30 larger rain events during the year 2018 and 2019. The runoff temperature was calculated according to mixing equation 4.2, where T_2 is expressed.

$$T_2 = \frac{T * (V_1 + V_2) - V_1 * T_1}{V_2} \tag{4.2}$$

Where:

T	Temperature of the pond at the end of rain event	[°C]
T_1	Temperature of the pond before rain event	[°C]
V_1	Volume of the pond	[m^3]
T_2	Temperature of the runoff water	[°C]
V_2	Volume of the runoff water	[m^3]

After the runoff water temperature is known for each rain event taking into account, the mean of the runoff water temperature for the each season of the year was calculated. The figure 4.4 shows the estimated runoff water temperature during the year for each event and the mean of these, which is used in further calculations. The table with noticed initial temperature, pond volume, runoff volume and calculated runoff temperature is attached in appendix 9.3 for 30 rain events.

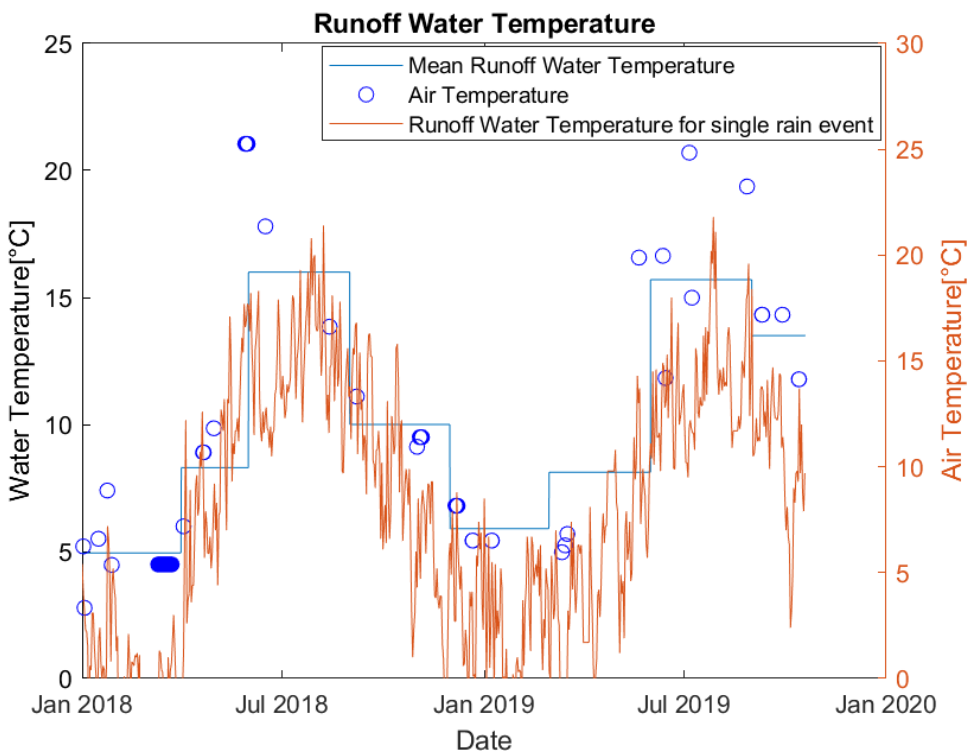

Figure 4.4: Runoff water temperature and the temperature of the air.

The runoff water temperature in June 2018 and 2019 for one event was estimated on 21°C. This values were omitted in the mean calculation because the air temperature is much lower around these rain events. Electronic appendix 9.2.4 contains the model of runoff temperature.

Results

The runoff temperature was applied into the model to see how the water temperature in the pond is affected by runoff water. The mixing equation,4.1, was used one more time to model the water temperature in the pond. Figure 4.5 shows the volume of inflow water and the corresponding temperature with and without effect of the runoff water temperature.

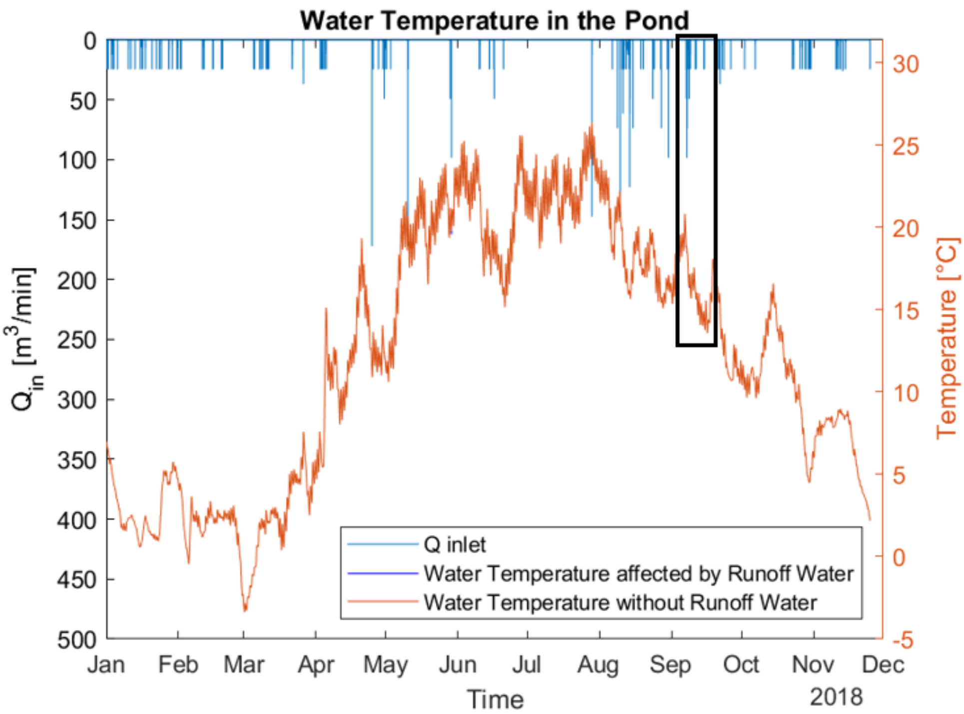

Figure 4.5: Temperature of the water in the pond affected and unaffected by runoff water

Since the temperature variations due to runoff temperature is much smaller than variation during the year is hard to see the thermal impact of runoff water, the figure 4.6 zooms into 7^{th} September when there was a heavy rain and the temperature of the pond dropped. The modelled temperature in the pond dropped just by a couple tenths of °C. This change of temperature is negligible.

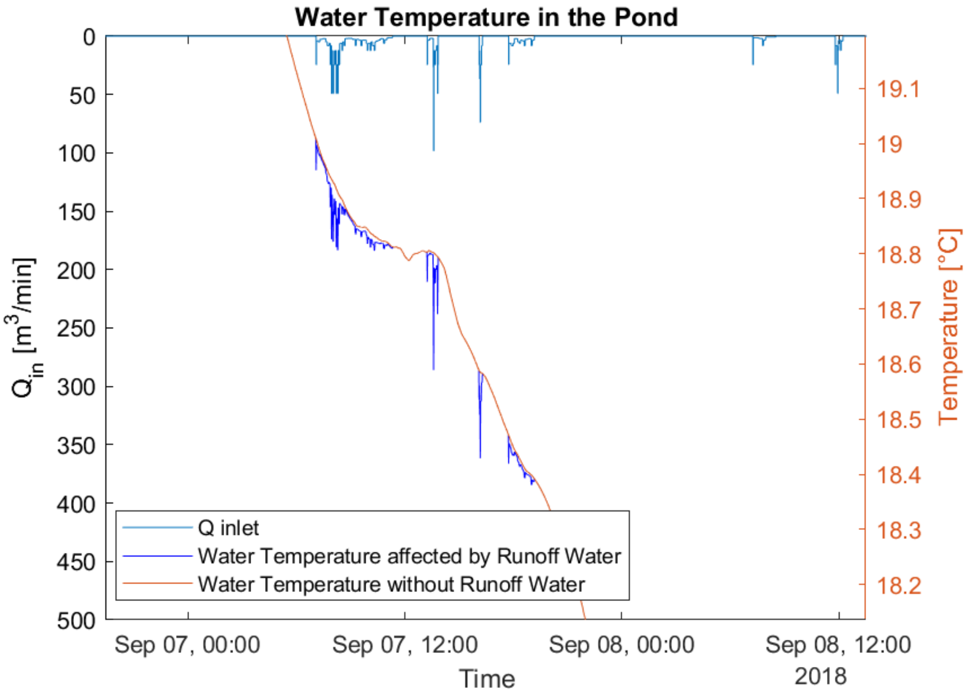

Figure 4.6: Temperature of the water in the pond affected and unaffected by runoff water during one day.

These results do not fit with observations which were used to estimate the runoff water temperature, where the change of water temperature in the pond due to runoff temperature was around 1°C. These uncertainties can be explained by using the mean of the runoff temperature and by poor quality of observations where the change of temperature was caused also by weather.

To see the effect of runoff temperature on the pond more accurate during the year, the figure 4.7 illustrates the difference between these two temperatures (with and without effect from runoff temperature).

The positive values are heating the pond up and negative values are cooling it down. The temperature of the runoff in the winter was estimated on 4.8°C in 2018 and 5.9°C, which is slightly higher than modelled water temperature in the pond. It means the modelled runoff during the winter usually heats water in the pond up. It fits also to observations where runoff heated the pond up during the winter and at the beginning of the spring.

However during the winter and autumn the rain events occurs more often than in the summer, the effect of the runoff water in the summer is more significant than during the winter. According to the plot the highest temperature difference is at the beginning of the summer 2018, where the runoff water cooled the pond down by 0.5 °C.

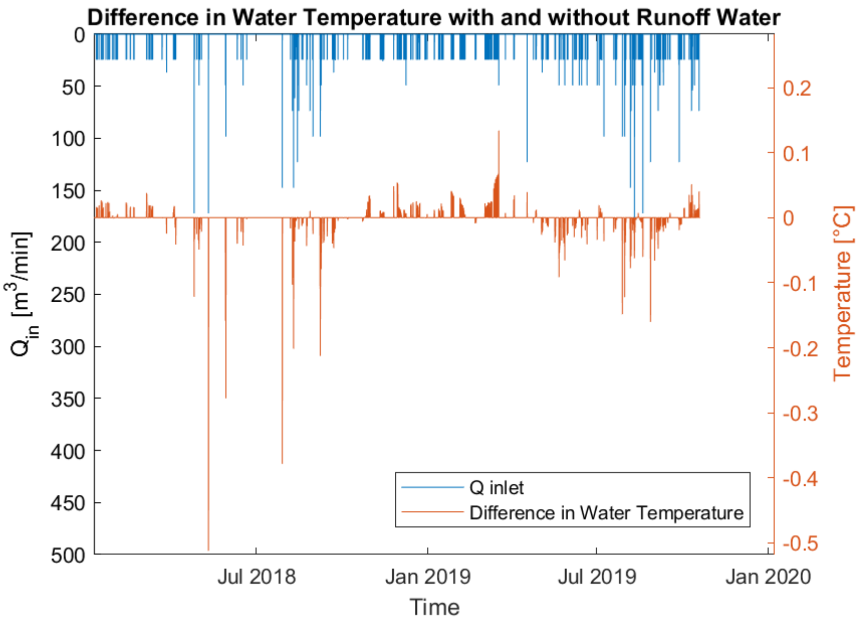

Figure 4.7: The difference in water temperature in the pond based on volume and temperature of the inflow.

It is necessary to mention that because of the lack of the data, the runoff water temperature was estimated as a constant for each season during the year and it does not reflect the runoff temperature variation during seasons. To achieve more accurate results the runoff temperature would have to be measured and more examination on that measurements performed.

4.2.2 Pond response to CDS rain with lower temperature

However according to the model the water in the pond is not affected significantly by runoff temperature, there are some consequence due to runoff water especially in case of the intensive rain events, which have the most significant effect on water temperature. Based on this observation, the CDS rain (Chicago Design Storm) with constant temperature was applied into the model.

CDS description

The CDS rain was designed as rain with return period of 50 years, based on the assumption that the pond has been correctly designed for 50 years. The climate change, respectively climate factor, has not been taken into account. The arbitrary climate factor for arbitrary return period could have been found by interpolation of climate factor for return period of 10 and 100 years. The rain duration was set to 240 minutes. The rain is constructed for the meteorological station in Aarhus. The intensity of the rain was obtained from spreadsheet from Skrift 30 (Spildevandskommiteen, 2016). The CDS rain is constructed in the summer, where the most intensive rain events are the most likely. The peak of the rain is later afternoon. The rain intensity is illustrated in figure 4.8. The initial loss due to evaporation, evapotranspiration and depression are not taking into account.

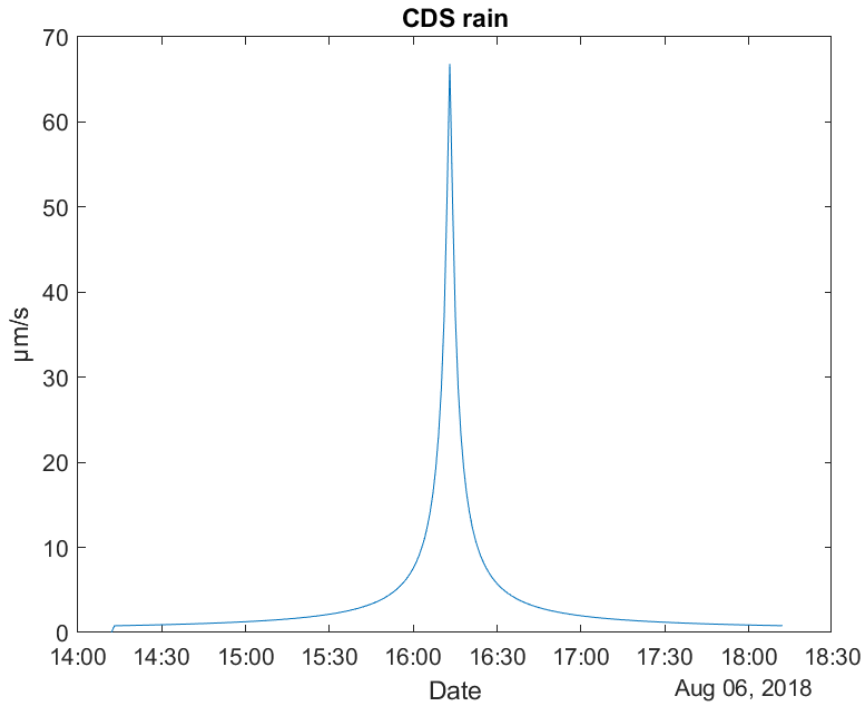

Figure 4.8: CDS rain intensity.

To estimate the runoff water temperature is difficult. There are a lot of unknown which can affect the temperature. Thus also in this case would have been necessary to make some measurements a observation of the rain temperature or of the runoff temperature. There are some assumption which can help to estimate the runoff water temperature. Since the intensive rain events sometimes bring even hails,it is assume that the temperature of the extreme rain event is much lower than air temperature. On the other hand, the runoff temperature can be heated by heat flux from the surfaces. The roof, roads or parking lots during the summer can be extremely hot. The runoff water from impervious area is usually collected into pipes and transported underground, where the water is cooled down again.

The temperature of the runoff water during the CDS rain was set to 12°C, which is approximately 5°C lower than air temperature. With estimated temperature, determined runoff volume and modelled water temperature and volume of the pond the mixing equation has been used.

Results

Figure 4.9 illustrates the volume of the inflow, water temperature in the pond without runoff water and how water temperature in to pond drops in case of CDS rain.

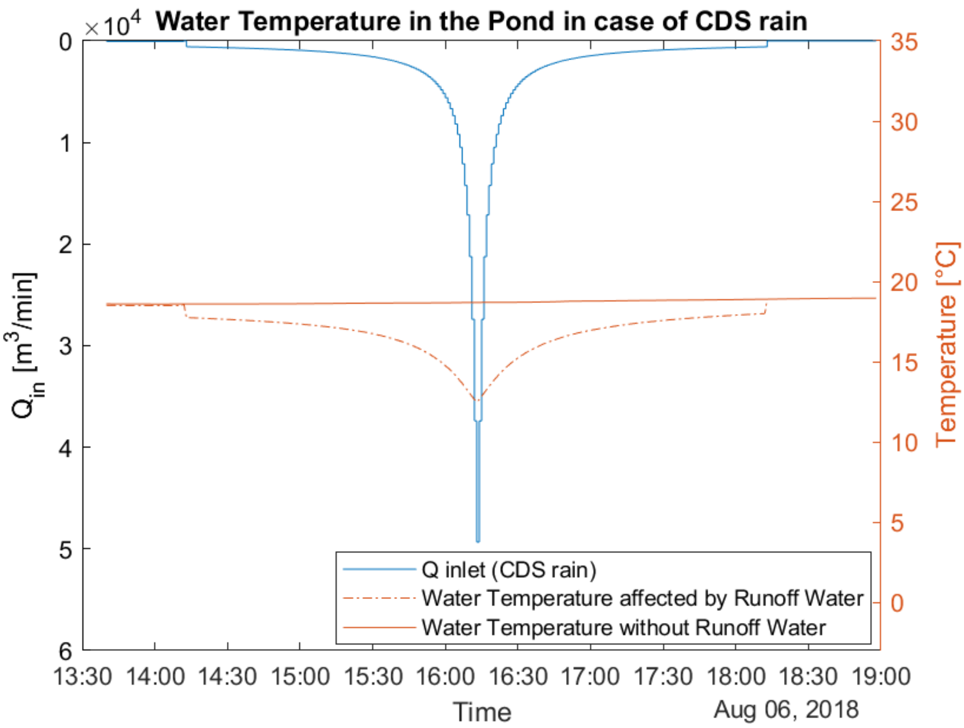

Figure 4.9: Water temperature in the pond during CDS rain.

The temperature of the water in the pond dropped by 8°C because of the CDS rain. It means that in case of heavy rain with relatively low temperature, the water in the pond can be significantly affected. The change in temperature depends on the volume and temperature of the water coming into the pond and on the volume and temperature of the pond.

In case that the runoff water would not have been retain in the water retention pond, the temperature change in the stream could be even more rapid. The water temperature in the stream and also the flow in the stream is lower than in the pond, thus the volume and temperature of runoff water would have had more significant effect on water temperature in the stream.

If it is assumed that water retention pond has been designed for CDS rain with 50 years return period, the water discharged from the pond to the stream can be released slowly and decrease the temperature shock for organisms living in the stream.

5 Stream Water Temperature

5.1 Impact of water temperature on aquatic organism

The effect of the released water from the pond into the stream can be harmful for organisms living in the stream. The streams around Aarhus are used by migrating sea trouts and brown trouts were found in the stream Giber Å, which is fed by adjacent stream next to Bederbaek pond. (Ulnits, 2000). Brown trouts as another living organism have temperature limits where they can survive. These limits often changes during a lifetime. (Santiago, 2017). The water temperature affects metabolic rate, breathing rate, development period and also migrating habits. The space of environmental condition, where aquatic organism can persist is called fundamental niche. There is a sub-level of fundamental niche called realized niche. Thermal realized niche is preferred temperature, where the fish spend most of the time. (Santiago, 2017)

The thermal tolerance of the brown trout differs with development stage of the fish. According to Elliott and Elliott, 2010 maximum embryo survival is between 0-13°C. The embryos are hidden in gravel in a stream bed. Alevin stage after embryo stage is more resistance to water temperature variation. (Elliott and Elliott, 2010)

However brown trouts are able to growth between 2-19.5°C, optimum temperature for growth of adult brown trout is dependent on the type of food. Brown trout fed by invertebrates grows optimally between 13.1-14.1°C, these ones which are fed by fish like warmer temperature between 16.6-17.4°C (Elliott and Hurley, 2000) and optimum temperature for growing of brown trout fed by pellets is 11.6-19.1°C (Forseth *et al.*, 2009).

5.2 Model of stream water temperature

The water temperature in the stream during a summer is colder than water in the pond and it is not affected so significantly by weather. To investigate the effect of the discharged water from the pond to the stream is necessary to know water temperature and flow upstream, water temperature in the pond and volume of the water releasing from the pond into the stream. The mixing equation, see 4.1, can be used to calculate the water temperature in the discharge point.

5.2.1 Temperature determination

The upstream temperature measurement is available for 8 months from November 2018 to June 2019. The temperature was measured every ten minutes and the data were provided by Thomsen, 2020 and it is illustrated in figure 5.1.

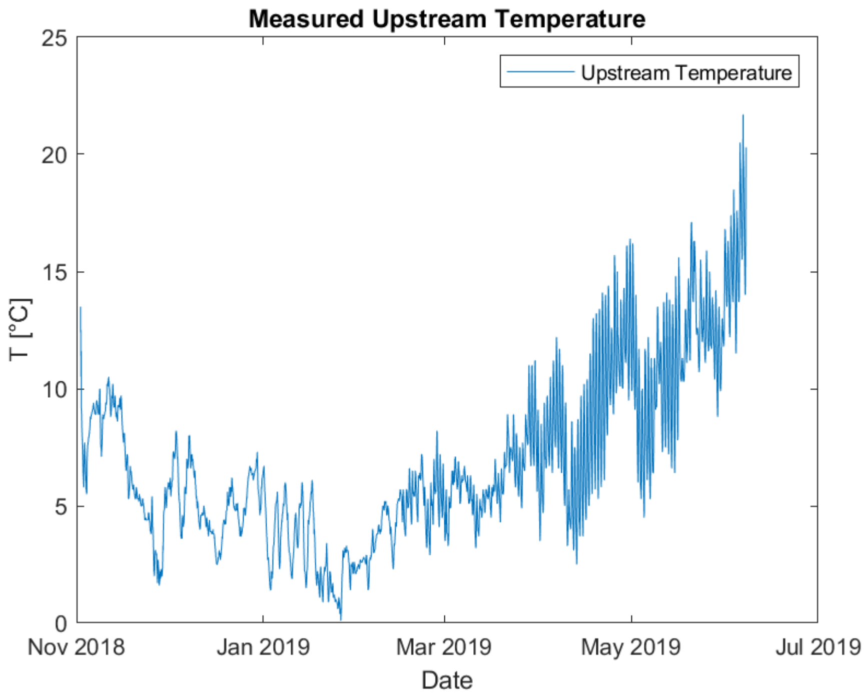

Figure 5.1: Water temperature measured upstream.

During the autumn and the winter the day-night variation is not as significant as in the spring and the summer beginning. With increasing sunlight time the temperature variation during the night and the day is much more visible also the overall trend rises with the higher air temperature.

The modelled temperature is used as the temperature of the released water from the pond. Unfortunately the available data from the stream are from the winter and the spring when the model of the water temperature in the pond does not perform as good as in the summer. The modelled temperature is underestimated by approximately 3°C during the winter, see figure 5.2.

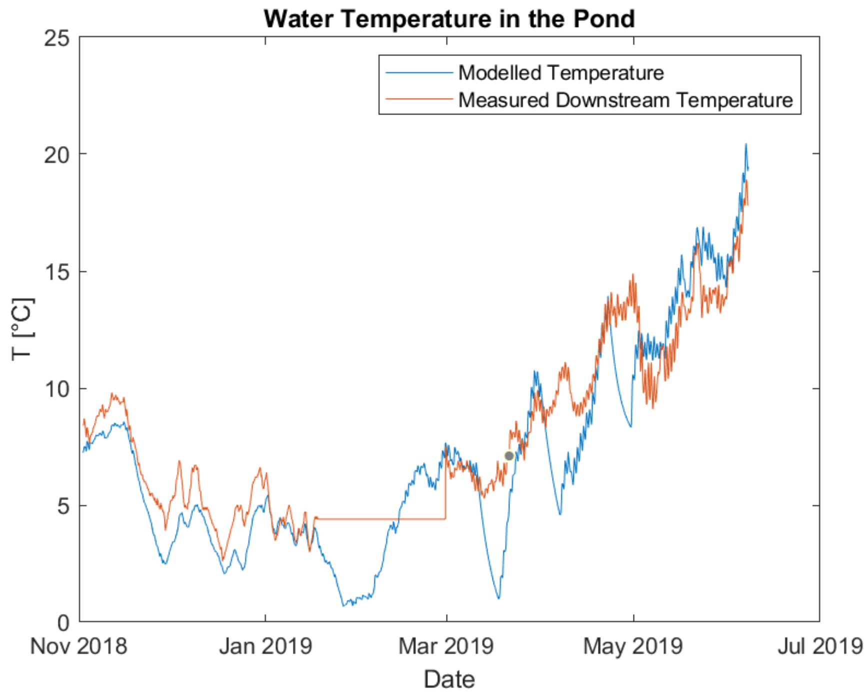

Figure 5.2: Measured a modelled water temperature in the pond.

The reason for these uncertainties can be set of meteorological data which were measured at Aalborg University which is 150 km far from Beder. However weather trend in both place is consider as fairly similar, there can be some time period when weather in Aalborg is significantly different from weather in Beder-Malling. The modelled temperature was increased by 2°C to achieve the more accurate results of the water temperature in the stream.

5.2.2 Flow in the Stream

Except temperature, the flow has to be also determined. The flow in the stream was calculated according to experimental equation 5.1 from Thomsen, 2020, where is necessary to know water level in the stream. However the equation is valid for absolute water level, the sensor measures relative water level. To use the equation 5.1 the distance from the bottom to sensor was estimate to be 5 cm. The water level and temperature was measured every ten minutes.

$$Q_{stream} = 1.37 * (h - 6)^{1.845} \quad (5.1)$$

Where:

Q_{stream}	Flow in the stream	[l/s]
h	Water level in the stream	[cm]

Discharge from the pond to the stream is calculated outflow in the section 3.1.1. The outlfow from the pond is equal to the inflow into the stream. Both, the flow in the stream and the discharge from the pond, are graphically illustrated in figure 5.3 and 5.4. The figure on the right side shows the discharge from the pond included fixed discharge of 4.5 l/s (AarhusVand, 2016). The discharge from the figure on the left will be used to determine the impact of the rain events when the water level, respectively discharge, increases.

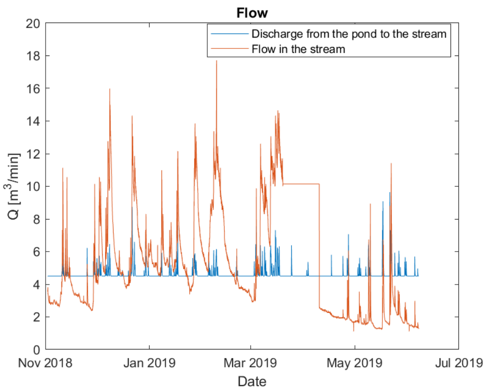

Figure 5.3: Stream flow and discharge from the pond including fixed discharge 4.5 l/s.

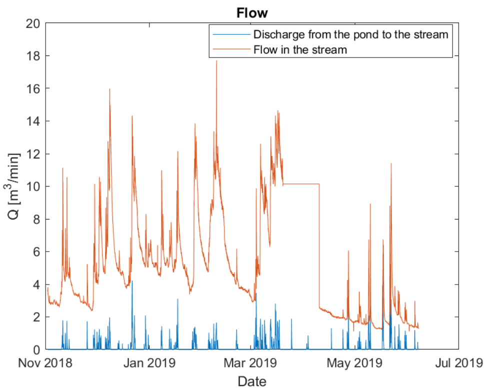

Figure 5.4: Stream flow and discharge from the pond excluding fixed discharge 4.5 l/s.

In both cases the discharge from the pond during the winter is smaller than flow in the stream. On the other hand with warmer weather the flow in the stream decreases and the discharge has more significant impact. It is assumed that during the summer the decreasing trend of the flow would continue.

5.2.3 Results

However, the modelled water temperature in the stream is slightly underestimated as measured temperature during the winter and slightly overrated during the spring, the model follows the trend of measurements, how it can be seen in figure 5.5. To investigate how model performs over the year is not possible. Only 8 months of measurements with 20 days of lack of the data in the spring is not sufficient. Since, the model of the water temperature in the pond performs better in the summer and the autumn, at least during one year of upstream measurement would be necessary.

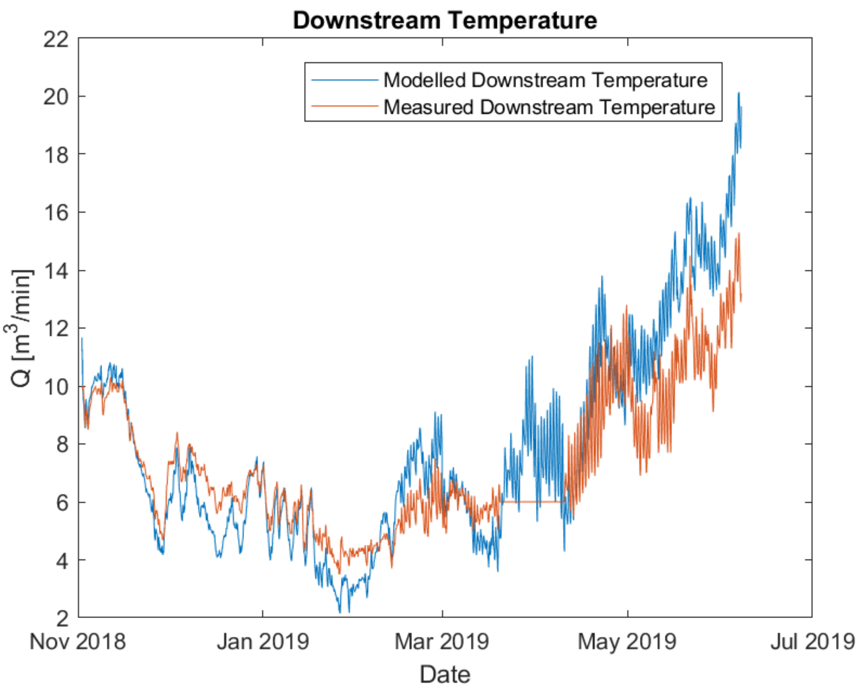

Figure 5.5: Measured a modelled water temperature in the stream.

The RMSE and NSE coefficients were found for the modelled and measured water temperature in the discharge point. Figure 5.6 graphically illustrates both coefficients. According to the plot the modelled downstream temperature is overrated compare to measured downstream temperature during the spring. The uncertainties can be explained by different weather in Aalborg and Beder-Malling. Furthermore, the discharge point is shaded by trees so the solar radiation has a smaller impact in real situation than in modelled situation where no shading factor is applied.

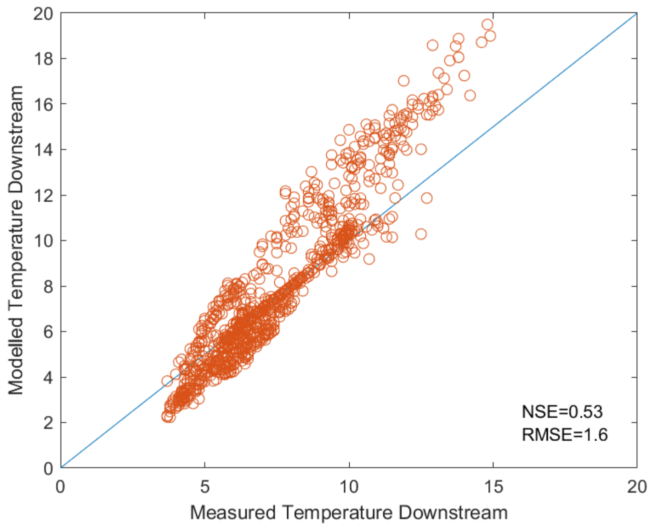

Figure 5.6: NSE and RMSE coefficients for measured a modelled water temperature in the stream.

The Effect of the Discharge from the Pond on the Stream Temperature

The effect of the discharged water on the stream is illustrated in figure 5.7. The discharged water usually heats the stream up . The stream temperature during the winter increases by approximately 2°C. On the other hand discharge from the pond reduces the daily amplitude and heats the water up in the spring.

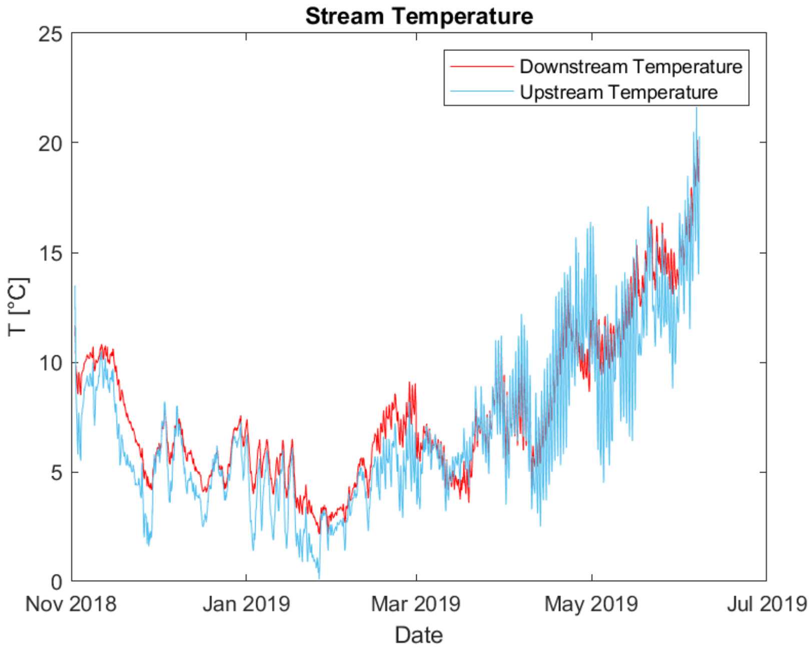

Figure 5.7: The measured upstream and modelled downstream temperature.

Trout embryos during the winter can survive between 0-13°C according to Elliott and Elliott, 2010, thus slightly increased temperature during the winter does not significantly affect embryos . During the spring embryos grow up into alevin stage, where the temperature niche is even wider. On the other hand, the optimal water temperature for trouts fed by invertebrates is between 13.1-14.1 °C (Elliott and Hurley, 2000), thus the water temperature in discharge point during May could be too high for optimum trout growth. Figure 5.8 shows how discharged water increased water temperature in the stream. Downstream water temperature at the end of May is slightly higher than optimal temperature for trouts fed by invertebrates.

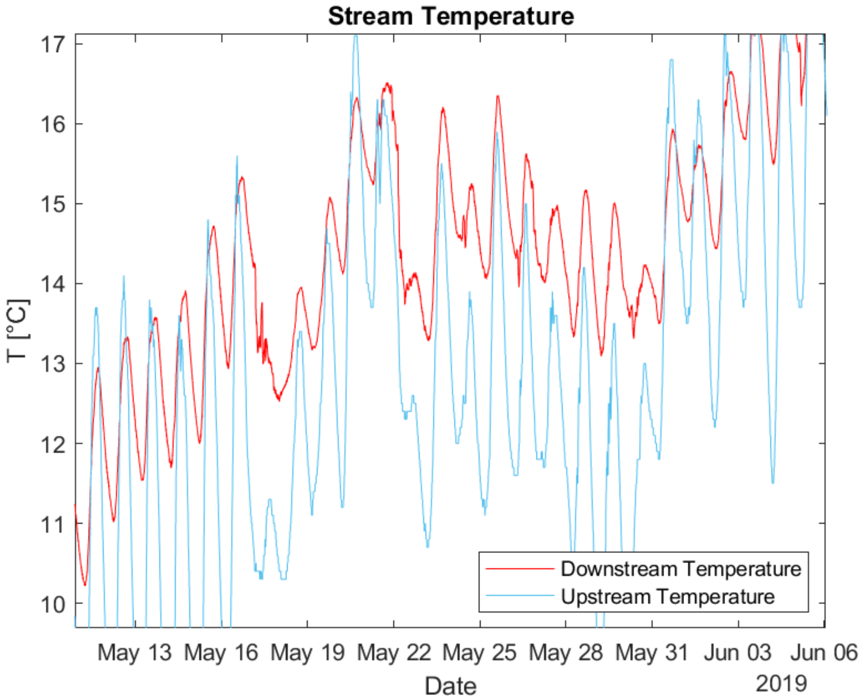

Figure 5.8: The measured upstream and modelled downstream temperature.

The Effect of the Discharge from the Pond on the Stream Temperature during the Rain events

The discharge during and immediately after rain events increases based on water level in the pond. The effect of these discharge events was examined. The temperature in the discharge point with and without effect of the rain events was compared. To obtain clearer view the significant discharge event was picked up. Figure 5.9 shows this event and the change in the temperature is evident. The water from the pond heats the stream by more than 0.5°C. This change in temperature does not significantly affect trouts population. On the other hand, the retention time during the spring is shorter than during the summer and water in pond does not have so much time to heat up. The effect of discharge during summer would have had more significant impact.

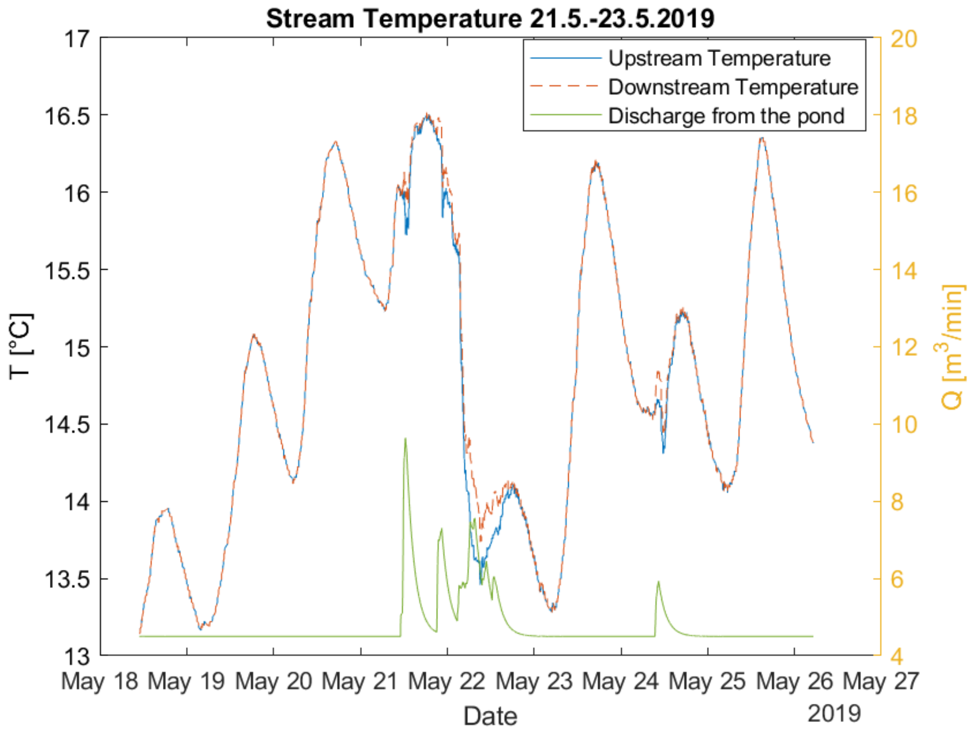

Figure 5.9: The measured upstream and modelled downstream temperature due to the discharge after rain events.

Figure 5.10 shows the difference between modelled downstream temperature with and without fixed discharge. Since the stream has a higher flow during the winter the effect of the discharge after rain events has a smaller impact on the stream. During the spring the discharge after rain events can increase the stream temperature by up to 0.7°C. It is assumed that during the summer the difference in the water temperature would have been even higher.

The model of stream water temperature can be found in electronic appendix 9.2.5.

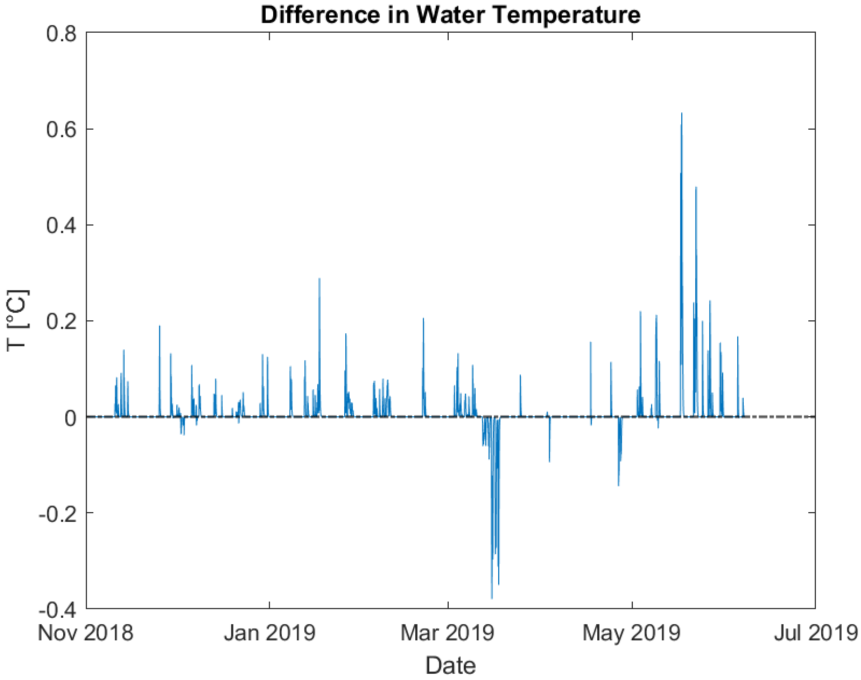

Figure 5.10: Difference between upstream and downstream temperature.

6 Discussion

During this master thesis, the model of water temperature in the pond was developed and effect of discharge into the stream was examined. The model was developed based on few assumptions, which can make an uncertainties. These and another uncertainties are discussed below.

Shape of the pond

One of the assumptions was about the shape of the pond which was used to develop the model. The pond has an irregular kidney shape meanwhile in the model is used circular shape of the pond. This assumption affected the calculated water level, respectively water surface area, in the pond. The uncertainties about the shape is possible to eliminate by measuring water surface area every 10 cm of the depth of the pond. These details can be read from drawing in CAD program.

Bottom heat flux

According to Bengtsson *et al.*, 2012 bottom heat flux has a significant impact only in ice covered lakes. The air temperature in Denmark during the winter fluctuate around 0°C, thus ponds are not covered by ice all winter. However the model was set up without the bottom heat flux, during the calibration was added because of poor performance of the model during the winter. With this finding it is suggested to collect more data about soil underneath the pond and perform some measurements of the soil temperature during the winter to achieve more accurate results.

With the modelled temperature during the winter is also connected the next assumption of non stratified water. The water temperature in winter time is still underestimated even after the bottom heat flux is added. The biased can be explained by colder weather in Aalborg, where meteorological station is located or by the fact, that water is stratified during the winter. The water with the highest density (4°C) stays close to bottom and the top water layer is the coldest one. The water temperature is modelled on the water-air interface meanwhile the measurements of temperature are performed approximately 20 cm under the permanent water level. As the result the modelled temperature is lower compare to measured temperature.

Heat Fluxes Calculation

Heat fluxes calculations have been challenging. There are a lot of ways how to calculate these. The literature has been studied and it was found out that net heat flux calculation is generally based on solar radiation, air temperature, humidity, wind speed, water temperature and air pressure. A lot of empirical parameters enter into these calculation. Since solar radiation has the greatest impact on a resultant net heat flux, the reflection coefficient and shading factor have to be considered. The reflection coefficient albedo was set up as one value on 0.07 after calibrations. However the albedo is not constant during the day and during the seasons. The amount of solar radiation is reflected based on the angle of the radiation. The smaller the angle, the higher the albedo, measured from the water level. On the other hand, during literature study, most of the authors used only one value with satisfied results. With the solar radiation is also connected another factor - shading factor. It can have a great impact on water temperature because it decreases amount of solar radiation. The shading factor should be added for ponds with big trees around or with steep banks.

Validation of the model

The model was validated on Hovedgroften pond located close to Bederbaek pond. Hovedgroften pond was really similar to Bederbaek pond with the same time period of measurements and the similar dimension and the shape. The initial purpose was using the pond in Aalborg, where meteorological data sets are from. Performing validation on the pond in Aalborg would have been more convincing, since the pond would have been closer to the meteorological station and uncertainties in weather would have been eliminated. Also it would have been interesting to see how the model reacts on different time periods and dimensions. Also the shape of Aalborg pond is more circular so the shape uncertainties would have been reduced. Unfortunately, there was a lack of the data for 4 months, thus the model was successfully applied on Hovedgroften pond.

Runoff Temperature

The runoff temperature has been examined to see how runoff water can affect the pond temperature. The runoff temperature was determined based on water level and temperature measurements for 30 rain events. The mean for each season was applied into the model afterwards. Since the runoff temperature depends on a lot of unknown as rain temperature, impervious area temperature, the length of transport pipes, the runoff temperature should have been measured. CDS rain with estimated temperature has been applied into the model and the water temperature in the pond was decreased significantly by 8°C. It was assumed that all water will be retain in the pond. In case that there would have been no water retention pond, the runoff water would flow directly into the stream. Since the stream is colder and there is less water the temperature change would have been even higher.

7 Conclusion

The water temperature in the water retention pond has been modelled to investigate how pond temperature is affected by water surface area and runoff water.

The water temperature in the pond is affected by solar radiation. The water surface area of the pond affects the water temperature. The water temperature in the pond with 2.2 times bigger surface area has approximately three times bigger amplitude during the day. The impact of runoff water is significant in case of CDS rain with 50 years return period, where the water temperature dropped by 8°C. The modelled impact of the runoff water on the pond temperature during year 2018 and 2019 was max up to 0.5°C. The runoff temperature has been estimated and to achieve more accurate results is necessary to measure runoff water temperature.

The model has been used to examine how discharged water from the pond affects the adjacent stream and organisms living in the stream. Since streams around Aarhus are used by migrating sea trouts, as the most vulnerable organism in stream the trout population has been chosen.

Stream temperature during the winter is usually heated up by discharge water from the pond. The modelled temperature in the discharge point is approximately higher up to 2°C than temperature upstream during winter time. Since the embryos of migrating sea trouts and brown trouts can survive in water temperature between 0-13°C the effect of discharge water is not harmful for trout embryos. The problem can occur at the end of spring, when the stream temperature increases due to meteorological condition. Furthermore, the discharge from the pond increases the daily peak of stream temperature and reduces the daily lowest value. The downstream temperature at the end of May is slightly higher than optimal temperature for trouts fed by invertebrates. Trouts still can grow but slower than in optimum temperature. It is assumed that during summer the stream temperature increases and the discharge from the pond has even greater impact, due to higher water temperature and due to lower flow in the stream.

On the other hand the discharge from the pond after rain event increases the stream temperature maximum by 0.7°C. This change can be a problem in case that stream temperature already achieves temperature higher than 20°C, which is upper limit for trouts growth. It is necessary to measure upstream temperature at least during one year to investigate the impact of the discharged water on trout population during the summer, when upper limit of temperature for trout growth can be achieved.

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8

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Appendix

9

9.1 Pond Layout

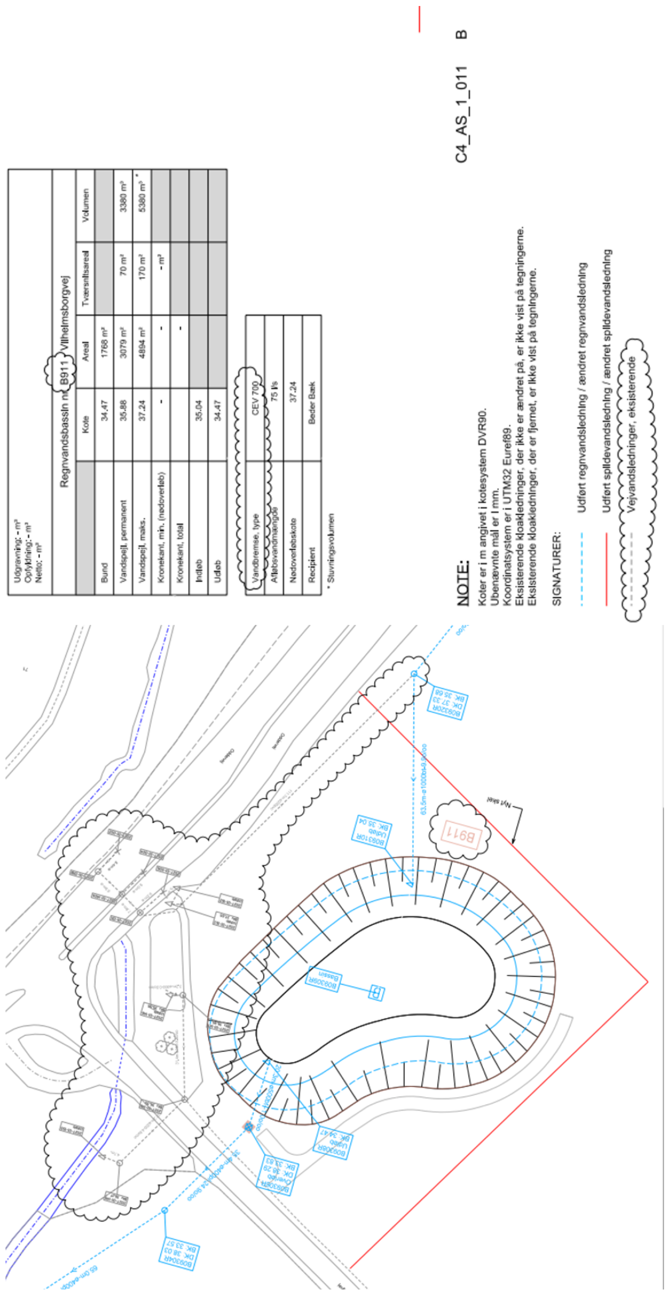

Figure 9.1: Layout of the Bederbaek water retention pond

9.2 Electronic Appendix

9.2.1 Control Quality Model

9.2.2 Model of Water Temperature in the Water Retention Pond

9.2.3 Model of Water Temperature in the Water Retention Pond - Validation

9.2.4 Model of Runoff Temperature

9.2.5 Model of Water Temperature in the Stream

9.3 Runoff Temperature Determination

Year 2018											
winter 2018						spring 2018					
Ti	Ti	Vi	Vr	Vrunoff	T	Ti	Ti	Vi	Vr	Vrunoff	T
3.8	4.2	7256.1	10128	2871.9	5.21	4.9	5.1	4541.8	5551.2	1009.4	6.00
4.7	4.8	4155.6	4747.5	591.9	5.50	11.4	9.7	3371.6	11338	7966.4	8.98
3.6	3.2	6274.1	10387	4112.9	2.59	12.1	10.5	3371.6	11694	8322.4	9.85
2.5	3.6	3371.6	7519.7	4148.1	4.49	22.1	21.4	3371.6	10183	6811.4	discard
2.2	2.9	4115.8	4754	638.2	7.41						
4.2	4.3	4044.2	6359.1	2314.9	4.47						
mean					**4.95**						**8.28**
summer 2018						autumn 2018					
Ti	Ti	Vi	Vr	Vrunoff	T	Ti	Ti	Vi	Vr	Vrunoff	T
19	18	3371.6	10354	6982.4	17.81	19	16.6	7905.4	11358	3452.6	11.10
19.8	18	3371.6	4612.4	1240.8	13.85	8.4	8.7	3371.6	4612.4	1240.8	9.52
						8.4	8.8	3371.6	7519.7	4148.1	9.13
mean					**15.83**						**9.92**

Year 2019											
winter 2019						spring 2019					
Ti	Ti	Vi	Vr	Vrunoff	T	Ti	Ti	Vi	Vr	Vrunoff	T
4.6	5	3371.6	6382.5	3010.9	5.45	15.7	16.2	5143	11954	6811	16.58
6.6	6.7	3371.6	5694	2322.4	6.85	5.6	5.3	4474	8641.2	4167.2	4.98
4.6	5	3371.6	6468.4	3096.8	5.44	6.1	5.6	4201	10168	5967	5.25
						6.9	6	3371.6	13334	9962.4	5.70
mean					**5.91**						**8.12**
summer 2019						autumn 2019					
Ti	Ti	Vi	Vr	Vrunoff	T	Ti	Ti	Vi	Vr	Vrunoff	T
17.3	18	3371.6	3820.9	449.3	discard	16.1	15.3	5830.5	10623	4792.5	14.33
17.3	16	4255	8153	3898	15.00	14.9	14.5	3371.6	11134	7762.4	14.33
20.6	20	4096.8	11779	7682.2	19.37	12.1	11.9	3736	10271	6535	11.79
17.1	17	3933	5039.6	1106.6	16.64						
19.6	18	3371.6	4113	741.4	11.83						
mean					**15.71**						**13.48**

	heating up
	cooling down

Ti	intitial temperature
Ti	pond temperature
Vi	pond volume
Vr	runoff volume
T	runoff temperature

Figure 9.2: Observation of the water volume and water temperature before and after rain event.