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Investigation of the Relationship between Sea Level Fluctuations and the Electrical Conductivity of Wastewater

Development of an Empirical Model for the Study Area of Gothenburg

Master's Thesis in Infrastructure and Environmental Engineering and Water Resources Engineering and Management

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Master's Thesis BOMX02-16-67
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Abstract

Different researchers have shown that rising global sea levels have to be expected in the course of climate change. Long-life infrastructures such as sewer systems therefore face new challenges in coastal regions. The influence of rising sea level on sewer systems has been acknowledged but has not yet been described in detail or even quantified. In the present study, a correlation between sea level fluctuations and wastewater conductivity will be investigated. By implementing mixture calculations this correlation will be used to develop an empirical model to predict wastewater conductivity out of sea level data and flow measurements. The results of these calculations for the municipality of Gothenburg show that the theoretical seawater inflow would not influence the treatment capacity of the wastewater treatment plant (WWTP) negatively. However, it became evident that seawater inflow is an existing process in coastal regions like Gothenburg. Smaller WWTPs might not be able to compensate these inflows. The developed model can therefore be a useful tool to estimate possible weaknesses of a system. Future research lies mainly in the improvement and increase in robustness of the model. By combining the improved model with climate scenarios, future challenges can be identified and the planning process for sewer systems can be improved.

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Abbreviations

COD	Chemical Oxygen Demand
CSO	Combined sewer overflow
MLR	Multiple linear regression
PCA	Principal component analysis
PE	Population equivalents
PLS	Partial least squares regression
SMHI	Swedish Meteorological and Hydrological Institute
WWTP	Wastewater Treatment Plant

Notations

ρ_f	Density of freshwater
ρ_s	Density of seawater
Q_{comb}	Combined wastewater flow
Q_{DW}	Dry weather flow
Q_f	Freshwater flow
Q_{Inf}	Excess water flow
Q_{sea}	Seawater flow
Q_{sea_sl}	Predicted seawater inflow based on the sea level
Q_{ww}	"Pure" wastewater flow
z	Distance below sea level to sea/freshwater interphase
Δh	Groundwater table above sea level
σ_{calc}	Calculated conductivity
σ_{comb}	Conductivity of combined wastewater
σ_f	Conductivity of freshwater
σ_{inf}	Conductivity of excess water
σ_m	Mean conductivity
σ_{pred}	Predicted conductivity
σ_{sea}	Conductivity of seawater
σ_{ww}	Conductivity of "pure" wastewater

1. Introduction

On the UN Climate Change Conference in Paris 2015, 195 countries acknowledged a global change in climate and the need to act against it. Mitigation and prevention measures have been approved to face rising global temperatures, climate extremes and an increasing rate of natural disasters such as floods, storms and heat waves (European Commission 2016; CRED & UNISDR 2015). Furthermore, the increase in the average global temperature is expected to result in a rise in global sea level. Melting ice masses and the thermal expansion of seawater are presumed to increase the sea level on an accelerated rate since the 1990s (SMHI 2014). Adding to an expected intensification in precipitation, this situation brings significant challenges for coastal regions. Increased erosion, seawater intrusion and flooding are consequences urban areas close to the sea have to cope with (Hurlimann et al. 2014).

Since the timescale in which mitigation measures and environmental protection agreements show effect on the climatic conditions are quite long, coastal communities have to deal with the effects of climate change in the coming decades. Urban areas have to adapt to increased sea levels in spacial planning especially for long-life infrastructures (Deyle et al. 2007). The sewer system of an urban area is part of this infrastructure. With pipes and tunnels lasting up to 100 years the systems have to be planned and designed incorporating future predictions.

The available literature is acknowledging the issues the municipalities are going to face regarding their wastewater management (Simmonsson et al. 2011; Schirmer et al. 2013). However, specific investigations how these effects might be quantified have not been conducted. Located on the west coast of Sweden, Gothenburg is one municipality facing these issues. Within the present study the effects of sea level fluctuations on the wastewater composition will be investigated and quantified.

1.1. Study Area

Gothenburg is the second largest city of Sweden with approximately 600,000 inhabitants in the metropolitan area. It is located in the county of Västra Götaland at the west coast of Sweden. With its location at the coast and the division by the river "Göta Älv" the city has been dealing with increased climatic impacts over the last years. In 2006 and 2011 the combination of high sea level and severe precipitation led to major floods within Gothenburg (Sörensen & Bengtsson 2014).

The sewer system of Gothenburg consists mainly of a separate system conveying wastewater and stormwater in separated pipe networks. Only 20% of the system are combined conveying both flows towards the "Rya" wastewater treatment plant (WWTP) on the northern side of Göta Älv (Sörensen & Bengtsson 2014). Gryaab AB is the municipal company operating the Rya WWTP and the tunnel system of Gothenburg with about 120 km (Gryaab AB 2016).

Treating the wastewater of about 830,000 PE the Rya WWTP is one of the largest plants in Scandinavia (Gryaab AB 2016; Mattsson et al. 2009). Its treatment process consists of a non-nitrifying activated sludge tank with simultaneous phosphorous removal. Supplementary to the denitrification in the activated sludge tank, post-denitrification takes place in a moving bed biofilm reactor. In trickling filters the post-nitrification is realized (Mattsson et al. 2012; Wilén et al. 2012).

1.2. Aim and Objectives

Previous investigations have suggested that elevated sea levels have an impact on the electrical conductivity of the wastewater in Gothenburg (Davidsson & Mattsson 2014). To be able to plan and adjust for future challenges coming with climate change the aim of this study is to prove and quantify this connection for the Rya WWTP in Gothenburg.

To gain an understanding of the processes related to a change in the conductivity several parameters and their interdependencies will be investigated and described. By identifying the influence of each parameter on the wastewater conductivity it would be possible to predict how future changes in the system will affect the wastewater composition.

The objectives of this study are to identify and quantify the seawater inflow into the sewer system. By combining the found influences on the wastewater conductivity and the understanding of the entry of seawater, a correlation between sea level and wastewater conductivity can be established. This correlation is then used to develop a model predicting the wastewater conductivity out of sea level and flow data.

1.3. Delimitation

Within the present study the reasons and ways of saltwater infiltration and inflow into the sewer system of Gothenburg are investigated. Examining the effects of elevated salinity in the wastewater on the treatment processes is not part of this study.

Furthermore, the different causes of sea level rise will be discussed only secondarily. If precipitation, air pressure or global temperature increase are causing changes in the sea level is considered to be subsidiary for the correlation between sea level and wastewater conductivity.

2. Background

The following chapters introduce the key concepts which are relevant to analyze the correlation between sea level and wastewater conductivity. To adapt or establish a method to investigate a correlation between the sea level fluctuations and the conductivity of the wastewater the existing literature has been reviewed. Additionally, the possible effects of high salinity in wastewater are presented to understand the relevance of the investigated correlation. To establish a reliable model, the composition of the wastewater and the ways on which saltwater is entering the sewer have to be investigated as well.

2.1. Literature Review

International publications and specialized literature were examined with emphasis on the influence of sea level fluctuations on the wastewater conductivity. As mentioned in the beginning the possible effects of elevated sea levels on the wastewater composition have been mentioned by different researchers (Simmonsson et al. 2011; Deyle et al. 2007; Hurlimann et al. 2014). Even though influences of sea level rise on the urban sewer system are presumed, their impact has not yet been studied in detail. The same is true for approaches or methods to describe or quantify a supposed seawater inflow into the sewers.

2.2. Electrical conductivity of wastewater

The focus of this study lies in the electrical conductivity of wastewater and its interdependencies with other parameters. Throughout the present thesis the term conductivity is frequently used. If not stated otherwise this refers to the electrical conductivity.

The electrical conductivity of water shows its ability to pass an electrical current and is therefore reported in μS/cm. It is directly linked to the ionic strength of a solution. The ionic strength includes the concentration of ions present in the solution as well as their valence (Stephenson & Judd 2008). Since the solubility of ions in water increases with increasing temperature, the conductivity is strongly dependent on the water temperature (Barron & Ashton 2007). Therefore, conductivity is usually reported at 25°C (σ_{25}), which removes the large influence of the water temperature (Radtke et al. 2005).

Most available conductivity meters today are programmed to report σ_{25} using linear or non-linear compensation factors (McCleskey et al. 2012).

Table 2-1 shows average conductivity values for different water sources. Both units µS/cm, mS/m and the estimated corresponding NaCl concentration are shown. Dealing with relatively high values for conductivity regarding seawater it was considered more practical to use the unit mS/m within this study.

Table 2-1 Typical conductivity values for different water sources

Water source	**Conductivity [µS/cm]** (Stephenson & Judd 2008)	**Conductivity [mS/m]**	**Corresponding NaCl conc [g/l] according to** Schuman (2012)
Seawater	50,000	5,000	34.23
Potable Water	1,000	100	0.2
Distilled Water	50	5	-

As seen in the table the values for conductivity vary up to a large extend. Water inflows into the sewer system can therefore have different effects. On one hand an inflow of low conductivity water like rain- or groundwater dilutes the wastewater and therefore reduces the conductivity. On the other hand, even a slight inflow of seawater might increase the conductivity significantly due to its high content of ions.

An increased conductivity in the wastewater can have crucial effects on the different steps within the treatment process. In an immersed membrane bioreactor with activated sludge, especially shock loads are influencing the efficiency negatively. Salinity shocks of 5 g/l (approx. 790 mS/m) were proven to affect the COD removal and membrane permeability negatively. As soon as the salt load is removed both characteristics are restored (Reid et al. 2006). Khengaoui et al. (2015) were able to show that the COD removal efficiency of biological filtration decreases continuously with increasing salinity. According to Campos et al. (2002) the nitrification is influenced by salinity as well. NaCl concentrations greater than 13.7 g/l (approx. 2043 mS/m) lead to a complete failure of nitrification in an activated sludge unit (Campos et al. 2002).

Nevertheless, Zita & Hermansson (1994) showed that small increases in ionic strength can improve the stability of bioflocculation in a biological treatment step. However exceeding a certain ionic concentration leads to a disruption of the flocs and therefore to increased suspended solids.

Due to the possible impacts of high salinity on the treatment processes the knowledge about the specific salt concentration due to environmental conditions might get crucial in the future. Relating the conductivity of wastewater to the sea level rise in future scenarios gives the opportunity to adapt the treatment processes for these influences.

2.3. Excess water

The combined flow towards a WWTP consists mainly of three components. The wastewater out of domestic, industrial and commercial activity should contribute with the largest share. The amount of stormwater varies highly if it is conveyed with the wastewater or separately. The third share is called excess or parasite water depending on the literature. It consists of infiltration and inflow. Infiltration water is the amount of additional groundwater entering the sewer system. Since large parts of a sewer system are located below the groundwater table, water is able to enter the sewers through cracks or poor joints. With proceeding age of the pipe network the number of these weak spots increases and leads to larger amounts of infiltration water. The direct inflow contains the water from misconnected rainwater collection systems or flooded overflows and manholes (Butler & Davies 2004).

Since the excess water usually does not require any treatment, the aim is to keep its amount as low as possible. Otherwise the capacity of the sewer system and the WWTP can be exceeded leading to surcharges of wastewater (Karpf & Krebs 2011). Therefore, the specific amounts of water entering the sewer system are of large importance for the design and operation of the WWTP. The higher the flows conveyed towards the plant the more treatment capacity has to be provided (Butler & Davies 2004).

To avoid misunderstandings the notations used in the present study are summarized in Table 2-2.

Table 2-2 Notation and description for different flows

Type of Inflow	Notation	Description
Combined	Q_{comb}	Total flow measured at the WWTP
Wastewater	Q_{ww}	“pure” wastewater flow discharged at households
Infiltration water	Q_{inf}	Amount of excess water consisting of fresh- and seawater inflow ($Q_{inf} = Q_{comb} - Q_{ww}$)
Freshwater	Q_f	Freshwater share of Q_{inf} including rain- and groundwater
Seawater	Q_{sea}	Seawater share of Q_{inf}
Dry weather flow	Q_{DW}	Average daily flow without any rain events (Butler & Davies 2004)

2.4. Sea Level

The sea level is underlying natural fluctuations caused by the moon cycle (tides), atmospheric pressure, precipitation and wind. In Gothenburg the main influence on the sea level is the fluctuating atmospheric pressure. A pressure range of 950 hPa to 1050 hPa causes the sea level to alternate between +63 cm and -37 cm (SMHI 2014). In addition to that, the tidal fluctuations have an influence of max. 24 cm (Port of Gothenburg 2009).

Due to climatic changes and increased global temperatures a continuous rise in sea level has been noticed in the past. Melting ice masses and expanding seawater lead to an increased average global sea level. In northern Scandinavia this process is compensated by land rise (SMHI 2014). The land masses of northern Europe have been compressed during the last ice age. The continuous expansion of these masses leads to an uplift of land which is still noticeable today (Meier et al. 2006). However, southern Sweden experiences the rising sea level to a certain extent. According to the Swedish Meteorological and Hydrological Institute (SMHI) the sea level increased by 15 cm since 1886. Over the last 30 years the rise even accelerated to 3mm per year (SMHI 2014). Depending on the underlying model and considered scenarios there are different sea level projections until 2100. Nevertheless, the trend of an accelerated increase in sea level over the past decades is acknowledged in different studies.

The future projections vary highly between 0.1 m to 1 m of sea level rise within the present century (Deyle et al. 2007; Meehl et al. 2007; Bolin et al. 2014; Persson et al. 2007; Meier et al. 2006). An increased sea level can have different effects on a coastal area. Communities near the sea have to face higher magnitude and frequency of flood events, storm surges, increased erosion and saltwater intrusion (Hurlimann et al. 2014). One process important for this study is the intrusion of saltwater into the groundwater layer. Due to the difference in density the saltwater is subverting the freshwater. These layers are stable and can be estimated in coastal regions. Enhanced groundwater extraction and the rise in sea level can alter the equilibrium and therefore lead to further saltwater intrusion (Figure 2-1) (Johnson 2007).

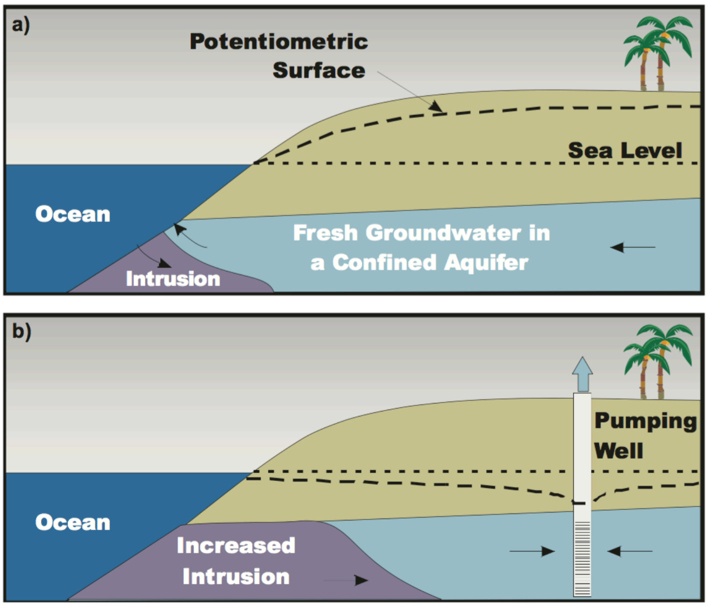

Figure 2-1 Seawater intrusion (Johnson 2007)

- **a) Natural/stable condition**
- **b) Increased intrusion due to groundwater extraction**

It is assumed that the seawater intrusion can affect the composition of wastewater conveyed towards the WWTP. With proceeding intrusion more sewage pipes are influenced by salty groundwater. Hence, the infiltrating water increases the conductivity of the wastewater (Deyle et al. 2007).

3. Methodology

As the literature review has shown a method to describe and quantify a supposed seawater inflow into the sewer system of a city has not yet been established. The approach presented in this study is therefore based on general hydrological concepts used in wastewater management and urban hydrology.

3.1. Available Data

Different data sets have been available during the present study. The measurement locations are presented in the map below. The process data provided by Gryaab AB contained the conductivity in mS/m and the amount of combined wastewater flow (Q_{comb}) in m^3/s at the inlet of the WWTP. The wastewater temperature was measured at the plant's outlet. Additionally, water level measurements [cm] for different locations along the Göta Älv were available (Figure 3-1). Furthermore, some data on the property of sea- and wastewater was provided by Gryaab AB.

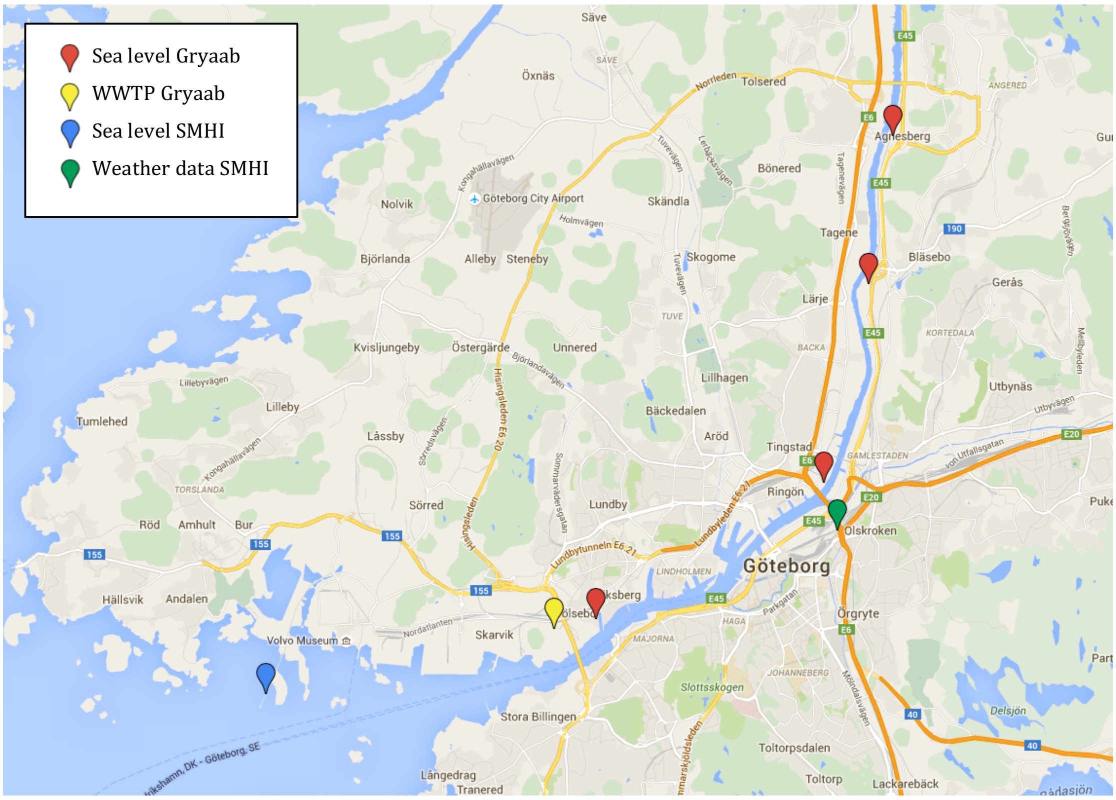

Figure 3-1 Measurement locations Gothenburg (Google Maps 2016)

Meteorological and hydrological data like precipitation [mm], atmospheric pressure [hPa], air temperature [°C] and the sea level fluctuations [cm] were extracted from the open data base of SMHI (SMHI 2016). Most of the data was available in an hourly resolution for a time series larger than ten years. For the investigations within this study the time frame from 2005 till 2015 was chosen due to a high data density.

3.2. Data evaluation

The available data was first investigated by a statistical analysis. Different parameters were examined for linear correlations according to Pearson (Mukaka 2012). Additionally, the interconnections of several parameters were analyzed by using a partial least squares (PLS) regression model.

PLS is combining features from the principal component analysis (PCA) and multiple linear regression (MLR) (Abdi 2003), thus resulting in a more robust approach (Geladi & Kowalski 1986). It is used to predict a variable Y (e.g. conductivity) from a set of variables X. This results in a set of latent variables showing the influence of each X variable on the variable of interest (Y) (Abdi 2003). For the calculation of the PLS regression the software "solo" by EVRI was used (Eigenvector Research Inc. 2016). The data was auto-scaled and cross-validated in contiguous blocks. For further information on PCA and PLS please refer to the referenced literature as well as Bro & Smilde (2014) and Godoy et al. (2014).

Additionally, the correlations were investigated in a univariate analysis. The parameters were plotted against each other to examine their interdependencies and possibilities to improve the correlations. Some data series had to be treated regarding the influences of time gaps and dilution. The processed data was then examined once again statistically and in the univariate analysis.

Subsequently, the composition of the wastewater was studied in more detail. To identify the wastewater flow, the method of the sliding minimum (Kretschmer et al. 2008) was applied and combined with additional data from Gryaab AB about the supplied drinking water. The different shares of inflowing water could be identified by assuming that the electrical conductivity is directly proportional to the concentration of ions in the water (Alhumoud et al. 2010). The rule of mixtures can be adapted to identify flows (Q_i) and their specific conductivity (σ_i) (Equation 3-1) (Askeland et al. 2011).

$$Q_{mix} * \sigma_{mix} = Q_1 * \sigma_1 + Q_2 * \sigma_2$$ **Equation 3-1**

By analyzing the contribution of the different flows and their specific conductivities further correlations could be identified. These correlations were used to establish an empirical model to predict the wastewater conductivity out of the measured sea level.

In a sensitivity analysis it was determined how the output of the model changes with adjustments in the input parameters (Qin et al. 2016). The model developed in the present study was tested regarding its robustness for changes in the freshwater and wastewater conductivity as well as the wastewater flow.

4. Evaluation of raw data

To start investigating the amounts of seawater entering the sewer system of Gothenburg the ways on which the water is entering had to be identified. By examining the behavior of the parameters over time and towards each other a general understanding of the behavior and interconnections of the parameters could be gained. Additionally, the data was inserted into a PLS model.

4.1. Ways of entry

As mentioned above salty groundwater, caused by seawater intrusion, can lead to the infiltration of water with high conductivity into the sewer system. Another possibility is the direct inflow over combined sewer overflows (CSOs) or other flooded entries.

The hydrogeological map of Gothenburg shows that the groundwater tables are quite high with at least one meter above sea level (SGU 2008). This high gradient towards Göta Älv and the sea makes a seawater intrusion unlikely. An approximation according to the equation of Ghyben-Herzberg (Equation 4-1) confirms that the saltwater interface can be expected around 40 m (for Δh=1 m) below the sea level. Therefore, the seawater intrusion is not considered as a driver for the entry of seawater into the sewer system.

$$z = \frac{\rho_f}{\rho_s - \rho_f} * \Delta h \approx 40 * \Delta h$$ **Equation 4-1**

Where

z	=	distance below sea level to sea/freshwater interphase
Δh	=	groundwater table above sea level
ρ_f	=	density of freshwater ($\rho_f \approx 1000\ kg/m^3$)
ρ_s	=	density of saltwater ($\rho_s \approx 1025\ kg/m^3$)

This leaves the direct inflow through openings like CSOs or manholes as main way of entry. Hence, the saltwater inflow can be expected to show effect on a rather small time scale. Therefore an investigation of hourly measurements appears reasonable.

4.2. Long term trends

To start the investigations, the parameters have been examined regarding their behavior over time. To get an overview over the long term trends the parameters have been plotted over the course of at least one year. Later on they will be investigated for shorter time frames.

As shown in Figure 4-1 the sea level is highly fluctuating at the coast of Gothenburg. Since several locations were available to retrieve the water level along Göta Älv and the sea they were investigated regarding their fluctuations in water level. Figure 4-1 shows that the trend in all locations is similar. Fluctuations in the sea level are therefore noticeable quite far upstream of the Göta Älv.

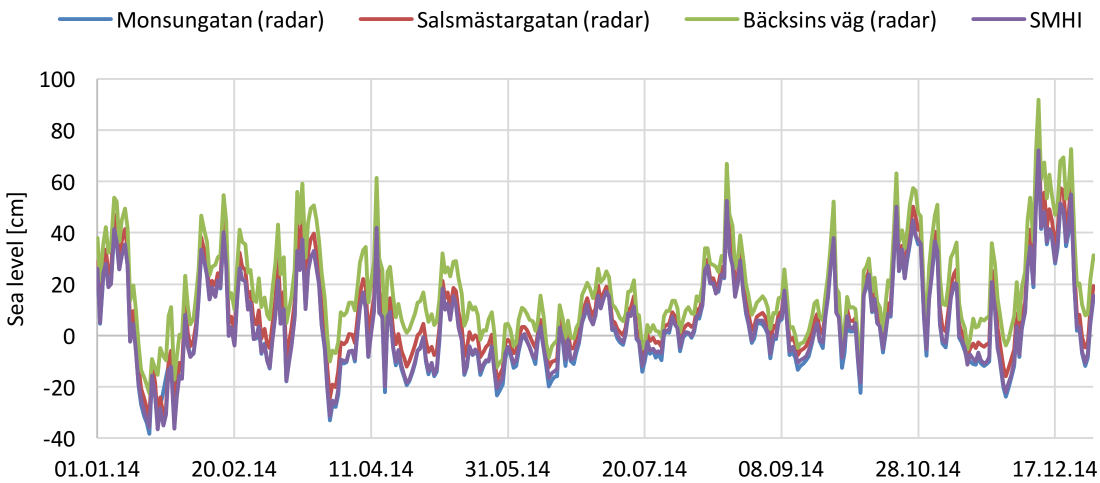

Figure 4-1 Sea level fluctuations at different measurement locations for 2014

To reduce the load of data, which had to be handled, the data set from SMHI was chosen for further investigations since it showed a more consistent measurement, fewer outliers and therefore required less treatment of the data.

The increasing trend of the sea level stated by SMHI (2014) was as well evident in the available data. The sea level is fluctuating during the course of the year as well as during the day. Due to the large amount of data a short time series is presented in the appendix (Figure A- 1). As main driver for these fluctuations SMHI (2014) states the atmospheric pressure. This suggestion is supported by the data available for this study. Figure 4-2 shows the increasing sea level with dropping atmospheric pressure.

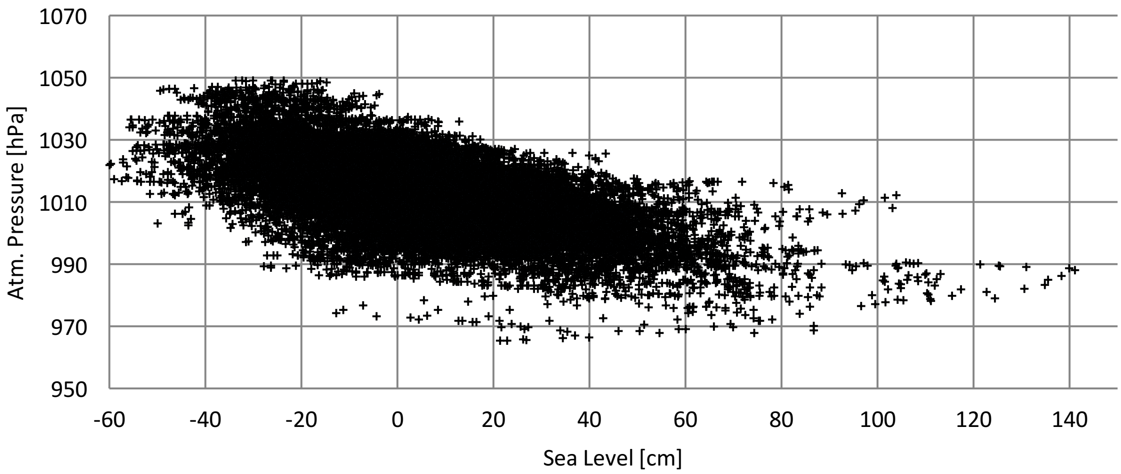

Figure 4-2 Sea level vs. atm. pressure (hourly) 2010 – 2015

As presented in the appendix (Figure A- 2) water temperature and conductivity show seasonal fluctuations. Since the conductivity measurements are reported in σ_{25} this pattern in the conductivity requires further investigation in the univariate analysis.

4.3. Short term observations

Investigating the behavior of the parameters over shorter time periods some alleged correlation between the conductivity and sea level becomes visible. Figure 4-3 shows both parameters from the 8.9.12 till 16.9.12 in daily averages. The conductivity seems to follow the rising sea level until the 13.9.12.

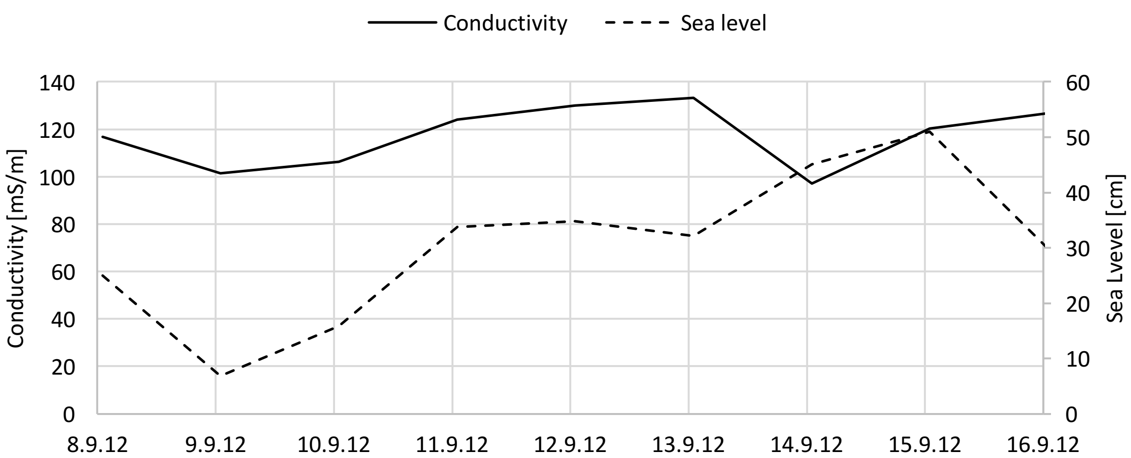

Figure 4-3 Conductivity and sea level 8.9.12 – 16.9.12 (daily)

As shown in Figure 4-4 a rain event on the 13.9.12 leads to an increase in flow and apparently to a decrease in conductivity even though the sea level keeps rising.

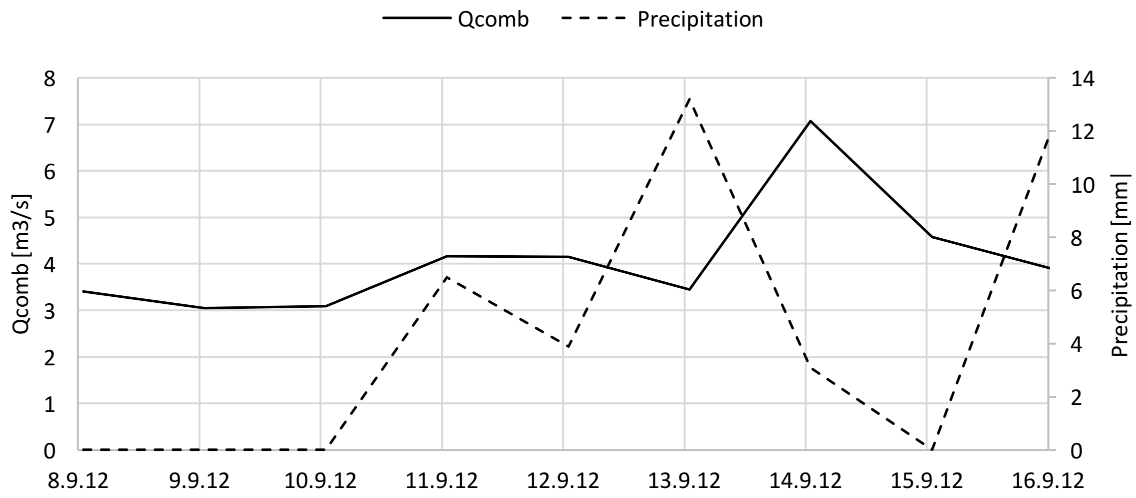

Figure 4-4 Q_{comb} and precipitation 8.9.12 - 16.9.12

That only a small number of these occasions could be found within the investigated ten years suggests that the correlation might not be as obvious as suggested by Figure 4-3. The conductivity of wastewater underlies several influences, which have to be examined in more detail.

4.4. Disturbance due to snowfall

Investigating specific time series two main seasonal impacts on the parameters could be found. The first one is the seasonal variation of the conductivity mentioned above. The second effect was found investigating shorter time series. On 19th January 2016 Gothenburg experienced heavy snow fall, shown by the precipitation peak in Figure 4-5. This event shows neither an impact on the inflow towards the WWTP nor the conductivity (Figure 4-6). As soon as the air temperature rises above 0°C in the evening of 23rd January the conductivity and inflow are increasing as well.

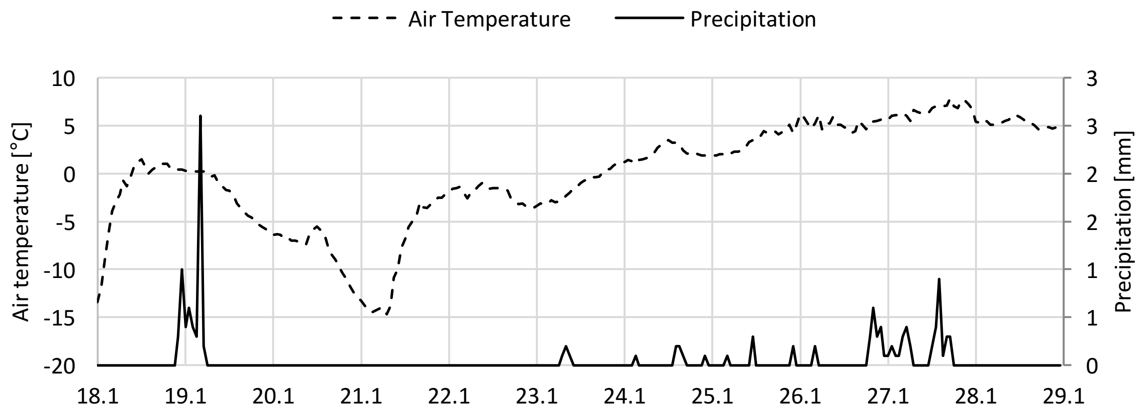

Figure 4-5 Air temperature and precipitation 18.1.16 - 28.1.16 (hourly)

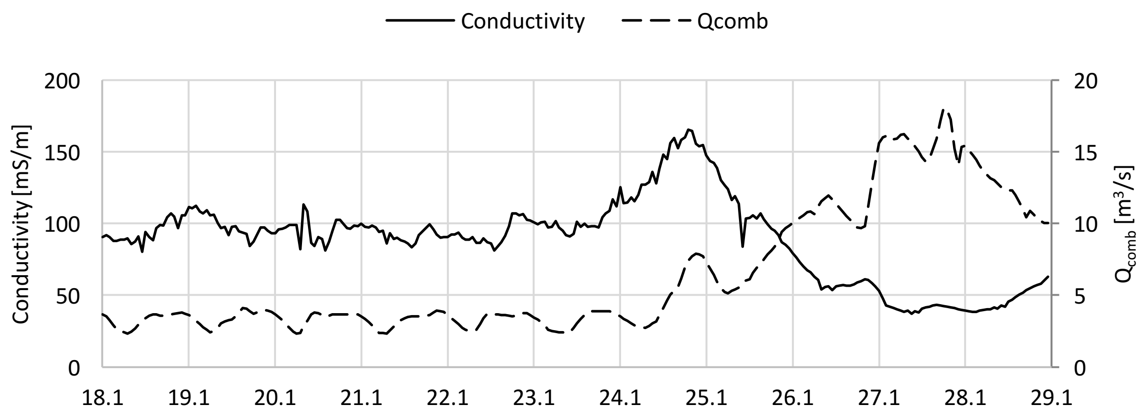

Figure 4-6 Conductivity and Q_{comb} 18.1.16 – 28.1.16 (hourly)

Since the streets of Gothenburg have been salted heavily in the week after the snow fall it can be assumed that the salt on the streets influences the wastewater properties as soon as it is washed off the streets with the melting snow.

Two effects can be seen as problematic for the further investigations. Firstly, the extreme time delay between the snow fall and the conveyance of runoff in the wastewater flow. Since this time gap is dependent on the air temperature it is not possible to consider it in a standardized approach. The second disturbance is caused by the impact of the street salt on the wastewater conductivity. This influence will alter the correlation between sea level and conductivity. These two observations justify the exclusion of the data for the cold months October till March in all further investigations.

4.5. Interdependencies of the investigated parameters

To gain an understanding and an overview of the different parameters and their correlations the data was investigated statistically. The Pearson correlation coefficients were calculated and compared additionally to a partial least squares regression (PLS). Both procedures allow further understanding of the correlation between specific parameters. After the statistical analysis the individual correlations were investigated in a univariate analysis.

4.5.1. Statistical analysis

The loadings of the PLS model show the influence of each parameter (variable) on the latent variable (LV). This LV is used in the PLS to predict the wastewater conductivity. Similar to the Pearson coefficient negative loadings indicate a negative influence and vice versa (Bro & Smilde 2014).

The model was fed with the available data excluding the winter months as described above. The loadings show a quite high negative influence of the combined wastewater flow (Figure 4-7). Secondly, the water temperature exerts a high positive influence. Precipitation and sea level show low negative influences.

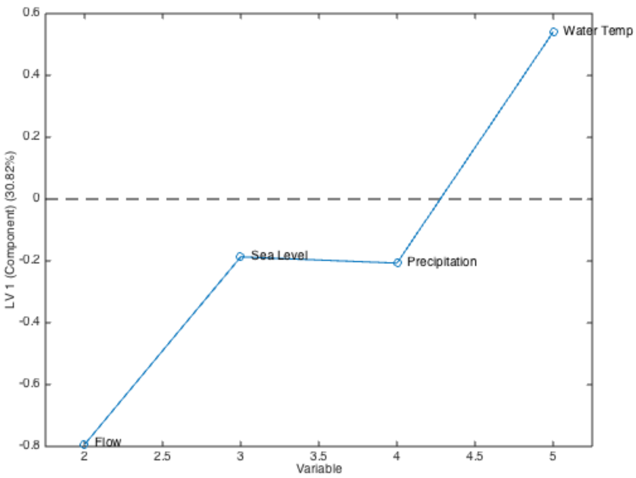

Figure 4-7 PLS loadings for untreated summer data (X-axis: number of the variable, Y-axis influence on the conductivity)

Quite similar trends are present in the comparison of the correlation coefficients. Table 4-1 shows a "heat map" of the coefficient for each parameter combination. Dark red indicates a strong negative and dark green a strong positive correlation. Both statistical methods show the high influence of the flow and water temperature in the investigated data. However an influence of the sea level is not visible in this approach.

Table 4-1 Correlation coefficients for different years (color coded from red = -1 to green = 1)

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	∅
Conductivity/ Q_{comb}	-0.32	-0.49	-0.58	-0.59	-0.39	-0.55	-0.53	-0.57	-0.52	-0.52	-0.64	-0.52
Conductivity/ Sea level	0.13	0.00	-0.04	-0.07	0.06	-0.04	-0.20	0.01	0.05	-0.12	-0.16	-0.03
Conductivity/ Water temp.	0.22	0.36	0.30	0.16	0.28	0.33	0.26	0.35	0.53	0.48	0.47	0.34
Conductivity/ Precipitation	0.02	-0.06	-0.08	-0.12	0.00	-0.18	-0.07	-0.05	-0.02	-0.03	-0.08	-0.06
Q_{comb}/ Sea level	0.27	0.29	0.36	0.31	0.38	0.37	0.50	0.29	0.26	0.32	0.35	0.34
Q_{comb}/ Water temp.	-0.06	-0.38	-0.02	-0.16	-0.02	0.00	-0.01	-0.15	-0.20	-0.25	-0.25	-0.14
Q_{comb}/ Precipitation	0.12	0.10	0.21	0.26	0.13	0.47	0.21	0.15	0.09	0.10	0.20	0.19
Sea level/ Water temp.	0.21	0.12	0.24	0.24	0.30	0.40	0.16	0.26	0.31	0.16	0.07	0.22
Sea level/ Precipitation	0.09	0.07	0.10	0.12	0.11	0.10	0.13	0.08	0.05	0.12	0.12	0.10
Precipitation/ Water temp.	0.05	0.01	0.02	0.06	0.02	0.08	0.08	0.01	0.01	0.02	0.02	0.04

4.5.2. Univariate analysis

To be able to describe the correlations, the parameters were investigated in a univariate comparison. As already indicated in the statistical analysis the influence of the sea level on the conductivity is not evident in the untreated data (Figure 4-8).

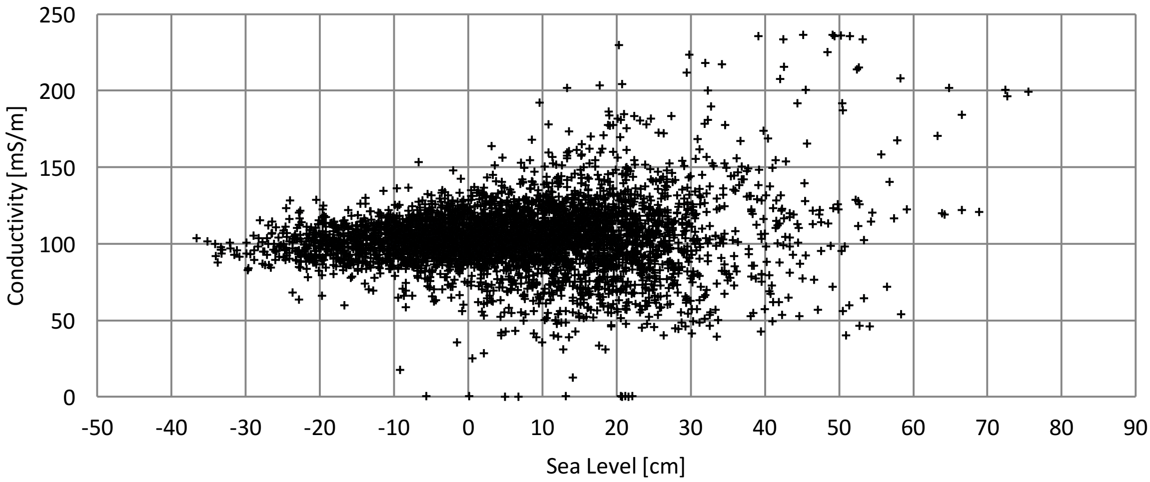

Figure 4-8 Hourly sea level vs. conductivity summer 2005

At low sea levels the cloud appears to be narrow, suggesting a correlation. With rising sea levels however, the data scatters drastically. Within the investigated ten years no pattern could be identified. Since some impact by the sea level was noted by Davidsson & Mattsson (2014) it can be suggested that this impact is hidden by other influences and disturbances. By examining the correlations of the other parameters some of these disturbances become evident.

Looking at the plot of the sea level against the inflow in daily averages a strong positive correlation can be seen (Figure 4-9). With rising sea level, the conveyed flow towards the WWTP increases. However, coloring the data points for a conductivity above 130 mS/m shows that the increase in flow is not likely to be caused by inflowing seawater. The high conductivity events are almost exclusively bound to the low flow measurements. It is more likely that the correlation between flow and sea level is triggered by the atmospheric pressure. Low atmospheric pressure lets the sea level rise and the probability of precipitation events increases (SMHI 2014). That high conductivity events are most likely connected to low flow events indicates the dilution due to an inflow of low conductivity water.

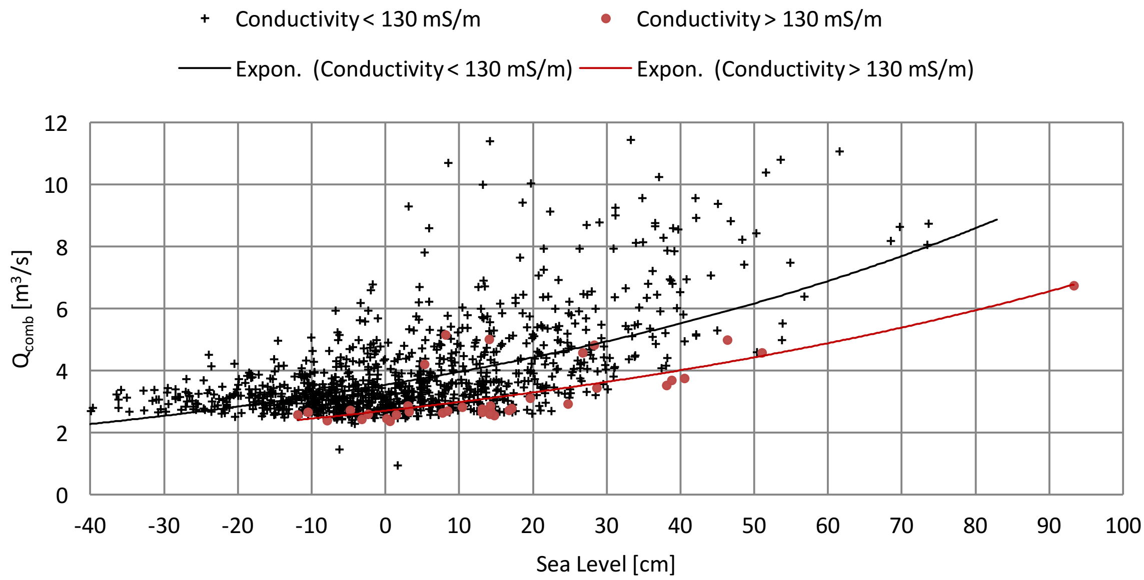

Figure 4-9 Daily sea level vs. Q_{comb} at different conductivity conditions

Investigating hourly measurements different patterns become evident. Figure 4-10 shows the wastewater conductivity against the water temperature. It is visible that with increasing temperature the conductivity rises as well. The data points have been grouped according to the amount of flow. The correlation between flow and conductivity becomes evident again. Lower flow events are more likely to be linked to high conductivity events and vice versa. It also appears like high flow events are stronger related to higher wastewater temperatures. In other investigated years high flow events scatter over the whole temperature spectrum as shown in the appendix (Figure A- 3). Therefore, it is not indicated that the correlation between conductivity and water temperature is connected to the amount of flow.

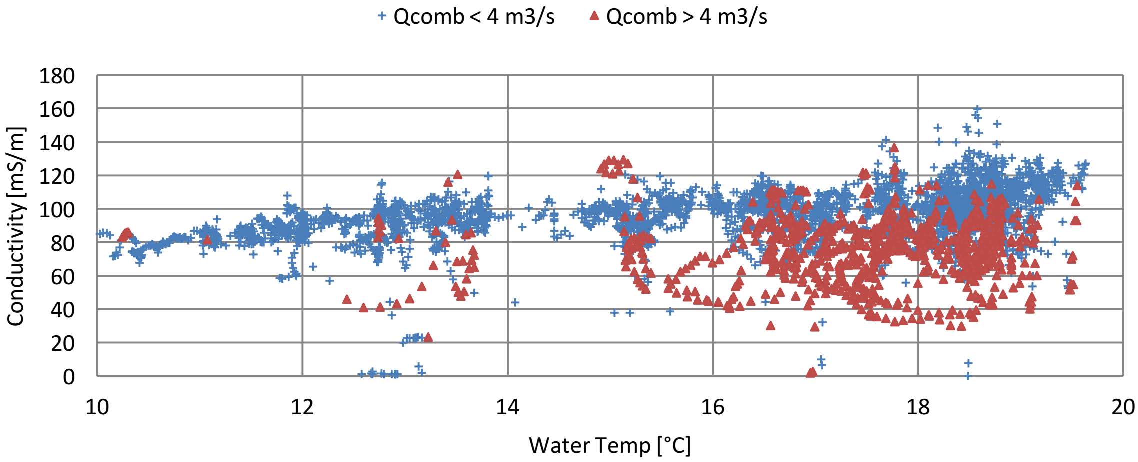

Figure 4-10 Hourly water temperature vs. conductivity summer 2010

Figure 4-11 shows the combined flow plotted against the water temperature grouped for different times of the year. Hereby seasonal patterns become visible. It can be seen that the overall water temperatures are higher towards the end of the summer. Additionally, it is visible that the temperature during April is very sensitive towards the flow. With increasing flow, the water temperature decreases drastically. This is not the case for the period from May till September. This leads to the assumption that the infiltrating water is much colder during April leading to low temperatures during high flow events. With increasing temperatures of the ground and surface waters the impact of the inflowing water on the wastewater temperature reduces. Same as in Figure 4-9 the findings in Figure 4-11 suggest dilution processes.

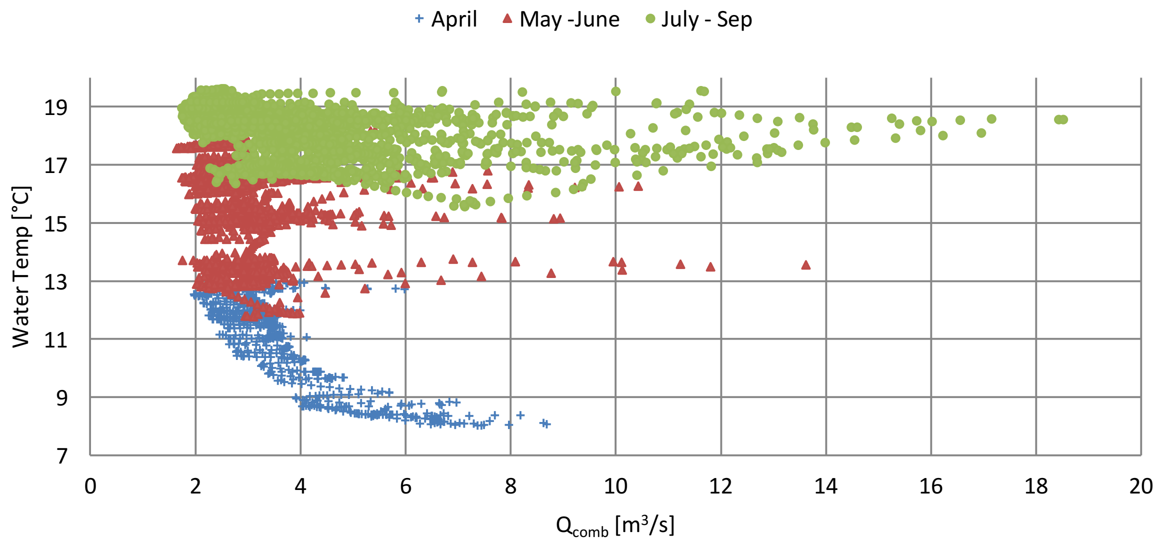

Figure 4-11 Hourly flow vs. water temperature for different periods of the year summer 2010

It becomes evident that water temperature as well as conductivity are strongly related to the mixing of the wastewater with infiltration and inflow. This process of dilution becomes even more obvious by looking at the plot for the conductivity and flow. With increasing flow the conductivity decreases drastically (Figure 4-12).

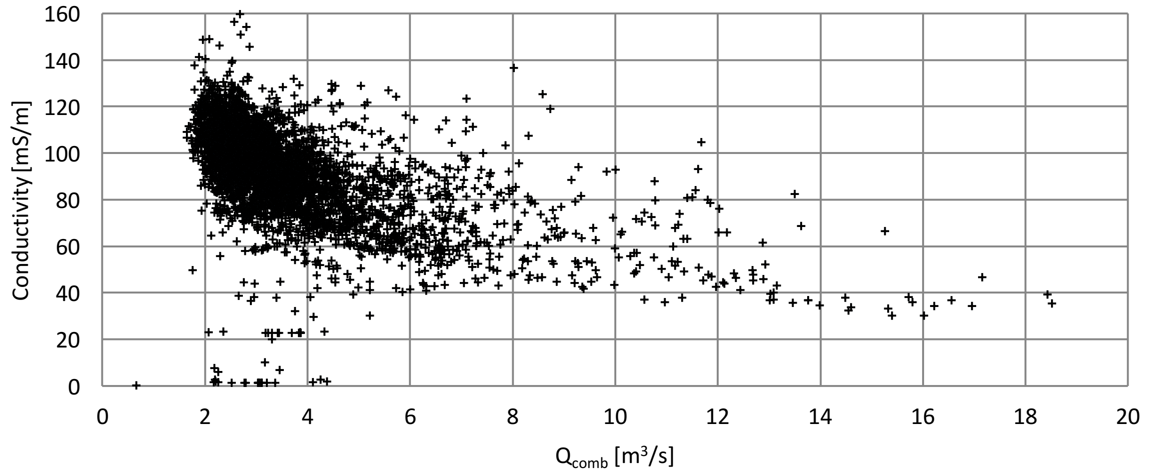

Figure 4-12 Hourly flow vs. conductivity summer 2010

The most likely cause for dilution during high flow events is precipitation. However, the correlation between rainfall and flow is contradictory to that expectation. Figure 4-13 shows that the data at its present state suggests high flow events to be less likely connected to rain events.

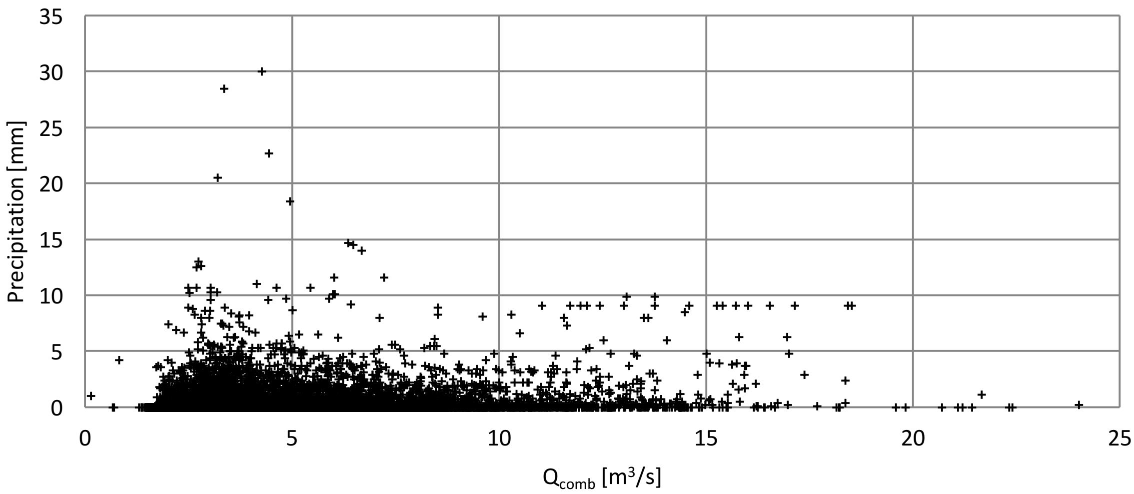

Figure 4-13 Flow vs. precipitation 2005 – 2015 (hourly)

The univariate investigation has shown, that the data has to be treated to compensate for certain disturbances. The process of dilution is evident in several of the presented correlations. However, this cannot be supported by the untreated precipitation data. Considering the time the rainwater has to travel to reach the WWTP a time gap has to be expected between the recorded rainfall in the city and the measured flow data at the WWTP. Additional processes of wetting and storage reduce the impact of the early and small rain occasions.

4.6. Data Treatment

Due to the time delays mentioned above a clear correlation between flow/precipitation or conductivity/precipitation could not be established within the previous approach. Furthermore, it was not possible to prove the correlation between sea level and conductivity due to the complex relationships between the parameters. To account for the influences of time and dilution, different approaches were carried out to enhance the correlations.

4.6.1. Influence of time

Due to the measurement locations there are two parameters where a delay in the measurement and their effect at the WWTP can be expected. These are the precipitation and the sea level. Both are measured at a certain distance from the WWTP where the other parameters are recorded. It appears logical that a rain event does not show an immediate effect on e.g. the flow pattern. Due to wetting and storage processes the first measured amounts of rain do not necessarily end up in the sewer system. Additionally, the water has to travel a certain time to reach the WWTP. To compensate for both effects the rainfall data was accumulated over certain time periods as well as shifted forward in time. This way the significance of later measurements is enhanced and the travel time is considered as well. Table 4-2 shows the correlation coefficients for the flow against the accumulated and shifted rainfall data.

Table 4-2 Correlation coefficients for accumulated rainfall and time shift (color coded from red = 0 to green = 1)

Time shift / Accu-mulation	complete 10 years	only summer	1h time shift	2h time shift	3h time shift	4h time shift	5h time shift	6h time shift
Q_{comb}/0h	0.19	0.19	0.19	0.37	0.26	0.26	0.26	0.41
Q_{comb}/2h	0.25	0.26	0.36	0.48	0.55	0.55	0.50	0.44
Q_{comb}/4h	0.37	0.43	0.54	0.61	0.62	0.59	0.53	0.48
Q_{comb}/6h	0.47	0.56	0.62	0.64	0.64	0.59	0.54	0.49
Q_{comb}/8h	0.52	0.62	0.64	0.65	0.63	0.59	0.54	0.49
Q_{comb}/10h	0.55	0.64	0.64	0.65	0.65	0.63	0.58	0.53
Q_{comb}/12h	0.65	0.64	0.64	0.57	0.54	0.50	0.42	0.39

The color coding in the table shows how the correlation between flow and precipitation is enhanced by accumulating the rainfall data. This can be improved even more by excluding the data from the winter months. The best correlation seems to be around a six to ten-hour accumulation and a delay of two hours. For he later correlations the combination of six hours of accumulation and a two-hour delay was chosen. This treated precipitation data is annotated as precipitation' in the following. As shown in Figure 4-14 the behavior of the flow towards the precipitation' appears to be more logical after the treatment. High flow events can now be connected to precipitation events.

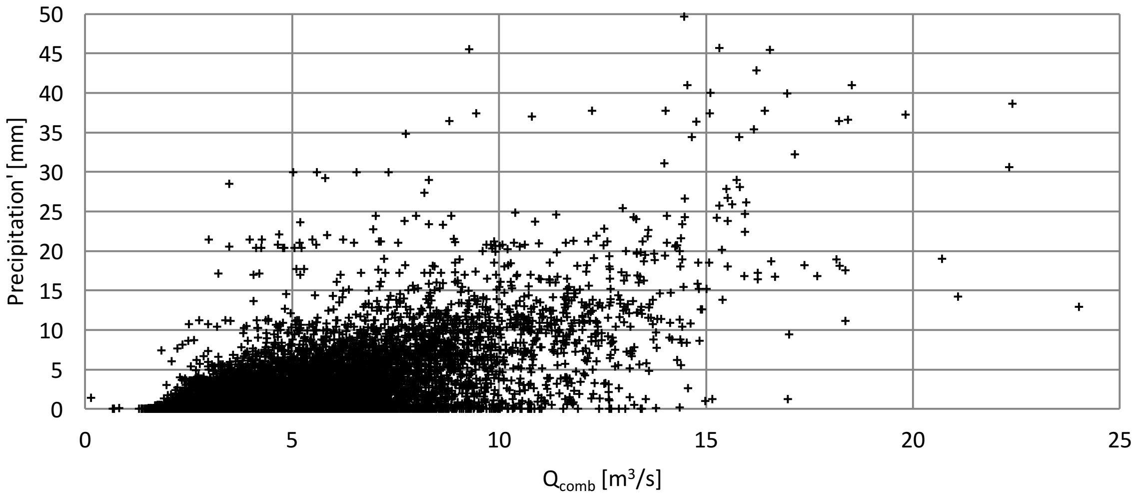

Figure 4-14 Flow vs. accumulated and shifted precipitation (Precipitation')

Not only the relationship between flow and precipitation got improved by this approach.Table 4-3 shows the average correlation coefficients for conductivity, flow, sea level and water temperature towards the precipitation before and after the data treatment. The slightly negative correlation between conductivity and precipitation got enhanced by the processing of the data. The same is true for the positive correlation between sea level and precipitation. The correlation between precipitation and water temperature remained unchanged. This might be due to the processes seen in Figure 4-11. Only in April an increased inflow showed effect on the water temperature. The rest of the summer the temperatures remained quite stable.

Table 4-3 Average correlation coefficients before and after the treatment of the data

	Precipitation	Precipitation'
Conductivity	-0.06	-0.28
Q_{comb}	0.19	0.67
Sea level	0.10	0.18
Water temp.	0.04	0.04

The enhanced negative correlation between conductivity and precipitation' supports the expected dilution of the wastewater during a rain event. Another parameter which is expected to show effect with a delay is the sea level. The entering seawater has to travel a certain way as well until it reaches the WWTP and shows effect on the conductivity. Since the conductivity is strongly connected to the water temperature and flow it was decided to shift the sea level data forward in time. Hereby the other correlations remain untouched.

Regarding the sea level, the time shift does not improve its correlation to any of the other parameters significantly. It is therefore not considered in the further investigations. Same as shifting the measurements in time building the moving average over different time periods did not show any effect on the correlation between sea level and conductivity (Table 4-4). However, the other correlations became improved up to an averaging period of six hours. Due to lower influence of peak values the curves got smoothened and therefore enhanced the correlations.

Table 4-4 Correlation coefficients after applying the moving average over different time spans

	raw data	2h	4h	6h	8h
Conductivity/Sea level	-0.02	-0.02	-0.02	-0.02	-0.02
Flow/Sea level	0.35	0.35	0.37	0.39	-0.55
Precipitation/Sea level	0.10	0.11	0.13	0.15	-0.14
Water temperature/Sea level	0.22	0.22	0.22	0.23	0.33

The enhanced negative influence of the precipitation' data also shows effect in the PLS model (Figure 4-15).

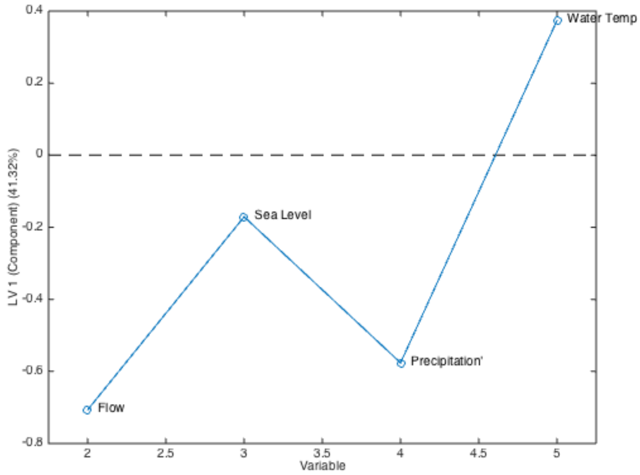

Figure 4-15 Loadings of PLS model with treated precipitation data (Precipitation')

The expected influence of the sea level could not yet be proven. The present state of the study even suggests a negative correlation between conductivity and sea level. This would indicate a decreasing conductivity with rising sea level.

4.6.2. Dilution

Investigating the connection between flow and conductivity has shown that increasing flow leads to decreasing conductivity. This behavior suggests, that the wastewater is diluted during high flow events. A water inflow with a low conductivity like rain or groundwater is reducing the conductivity of the combined flow.

As described above it is expected to have several different inflows contributing to the combined wastewater flow. They can be divided in three shares of interest within this study. The wastewater flow delivers a certain base flow. The excess out of inflow and infiltration is contributing with a large share of freshwater (Q_f) and a smaller saltwater inflow (Q_{sea}).

As mentioned in the methodology it is assumed that the conductivity is directly proportional to the ion concentration in the wastewater. Therefore, the equation to calculate concentrations in mixtures can be adapted for the conductivities in the combined flow (Equation 4-2).

$$Q_{comb} * \sigma_{comb} = Q_{ww} * \sigma_{ww} + Q_f * \sigma_f + Q_{sea} * \sigma_{sea} \qquad \textbf{Equation 4-2}$$

For further investigations additional assumptions had to be made. The assumptions used for all further calculations and the according references are summarized in Table 4-5.

Table 4-5 Assumptions for mixture calculations

Notation	Description	Assumption	Unit	Source/Comment
Conductivity				
σ_{ww}	Wastewater	70	[mS/m]	(Gryaab AB 2011)
σ_{f}	Freshwater	3	[mS/m]	(Sjöstedt 2015)
σ_{sea}	Seawater	2,500	[mS/m]	Estimate according to (Davidsson & Mattsson 2014)
σ_{DW}	Dry weather	100	[mS/m]	Average for Q_{DW} = 3 m³/s
Flow				
Q_{ww}	Wastewater	1.7	[m³/s]	Both estimated according to the sliding minimum over 21 days; supported by data from Gryaab AB
Q_{DW}	Dry weather	3	[m³/s]	

For the wastewater flow (Q_{ww}) the investigation of exemplary years showed and average of Q_{ww} = 1.7 m^3/s. In the same approach a dry weather flow of approximately 3 m^3/s could be identified. This is assumed to be a continuous flow throughout the day. The assumption of a conductivity of 3 mS/m for the freshwater inflow is based on measurements taken in rainwater near Lund in southern Sweden. Since the exact composition of the freshwater share is not known, it is assumed that rainwater contributes with the largest share. As for the conductivity of seawater, Davidsson & Mattsson (2014) have investigated the conductivity along the coast and Göta Älv (Table 4-6).

Table 4-6 Measured conductivity at different locations along the coast of Gothenburg and Göta Älv (Davidsson & Mattsson 2014)

Measurement location	Conductivity [mS/m]
Fiskebäck	2760
Lilla Varholmen	2850
Arendal	2236
Färjenäs	423
Eriksberg	312
Lindholmen	102
Ringön	28

At the coast conductivities between 2,236 and 2,760 mS/m were recorded. Moving upstream of Göta Älv the conductivity decreases drastically to values below 100 mS/m. Since the seawater inflow is of interest within this study an average of 2,500 mS/m has been chosen as an adequate assumption. In a first estimate the dry weather flow was diluted with rain water (Equation 4-3).

$$Q_{comb} * \sigma_{comb} = Q_{DW} * \sigma_{DW} + Q_f * \sigma_f \qquad \textbf{Equation 4-3}$$

Figure 4-16 shows that for low flow events this assumption seems to work. With increasing flow however, the conductivity is underestimated.

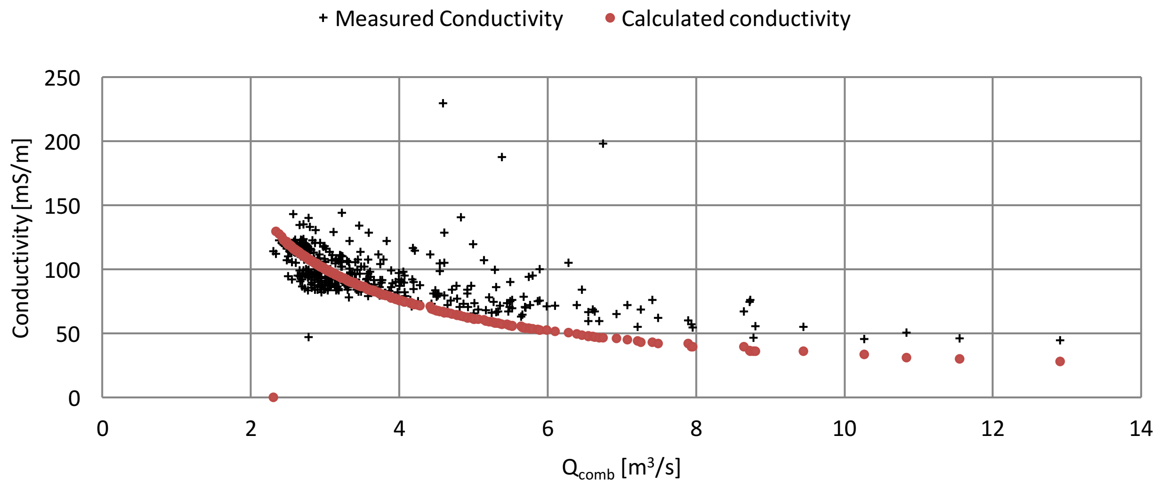

Figure 4-16 Measured (daily average) and calculated conductivity summer 2013

These results suggest that the inflowing water at high flow events has a higher conductivity than the assumed 3 mS/m for the rainwater. According to Davidsson & Mattsson (2014) this increased conductivity is related to high sea levels. Therefore, it is assumed that inflowing seawater is responsible for the increased conductivity.

Because Q_f and Q_{sea} are still unknown they are treated as one incoming flow (Q_{inf}) with a certain conductivity (σ_{inf}). By adapting Equation 4-2 this conductivity can be calculated with the available data.

For $Q_{inf} = Q_{comb} - Q_{ww}$:

$$\sigma_{inf} = (Q_{comb} * \sigma_{comb} - Q_{ww} * \sigma_{ww})/Q_{inf} \qquad \textbf{Equation 4-4}$$

This inflow conductivity is expected to increase or decrease the wastewater conductivity depending on its composition. Following the same approach, the share of sea- and freshwater water can now be calculated.

$$Q_{inf} * \sigma_{inf} = Q_{sea} * \sigma_{sea} + Q_f * \sigma_f$$ **Equation 4-5**

Assuming $Q_f = Q_{inf} - Q_{sea}$ Equation 4-5 can be transformed into the following.

$$Q_{sea} = \frac{Q_{inf} * (\sigma_{inf} - \sigma_f)}{\sigma_{sea} - \sigma_f}$$ **Equation 4-6**

Using the different flows and the assumed conductivities, the conductivity of the combined flow can be calculated quite accurately. However, this procedure needs a measured conductivity to start with and therefore is not suitable to predict the combined conductivity. Nevertheless, this approach produces new parameters which can be investigated regarding their correlations towards the sea level and wastewater conductivity.

4.7. Seawater inflow

The calculated seawater flow (Q_{sea}) shows a positive correlation with the wastewater conductivity (Figure 4-18).

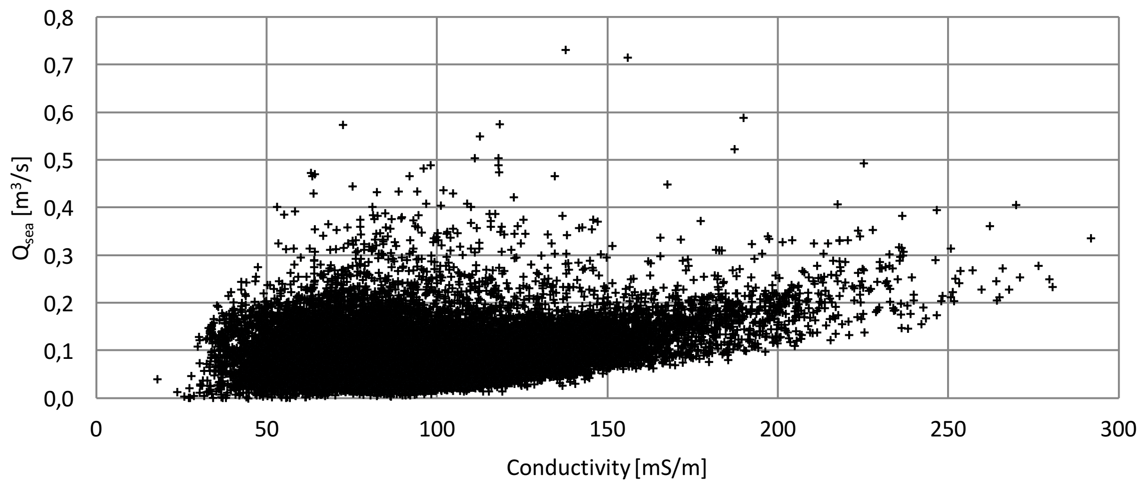

Figure 4-17 Calculated Q_{sea} vs. conductivity 2005 – 2015 (hourly)

This correlation can be improved by taking the six hourly averages of the parameters (Figure 4-18). Indicated by the improved correlations in Section 4.6, the six hourly average seems to be a reasonable time frame to reduce the influence of peak values. Neglecting the precipitation events completely was considered, however discarded since the rain water inflow is incorporated in the calculations. The calculation of Q_{sea} for the years 2005 till 2015 revealed an average seawater inflow of 0.083 m^3/s. On average the seawater therefore contributes with 2.3 % to the average combined wastewater flow of 3.58 m^3/s.

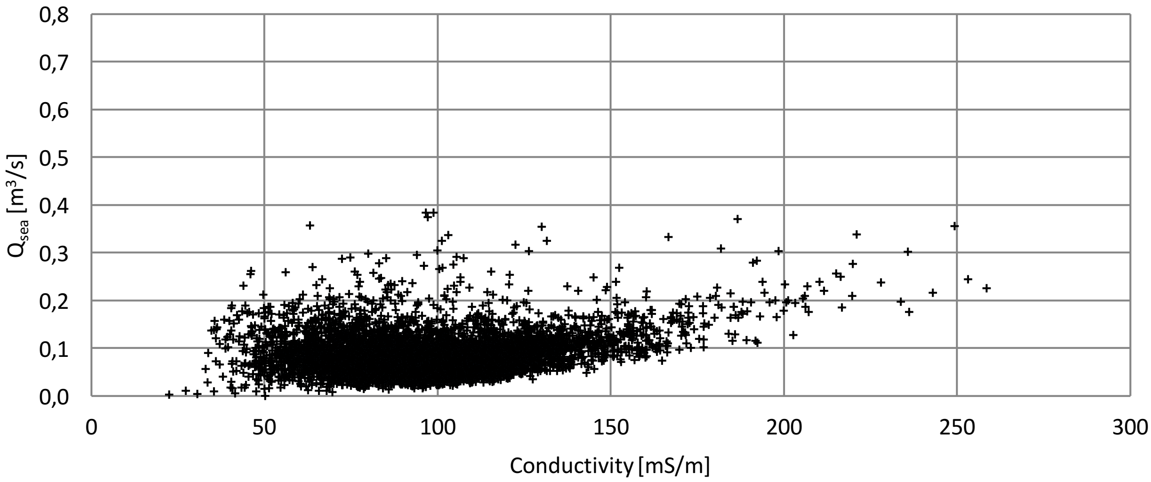

Figure 4-18 Calculated Q_{sea} vs. conductivity 2005 – 2015 (six hourly average)

Knowing the amount and conductivity of the combined wastewater the seawater inflow can now be quantified. To be able to predict the Q_{sea} from the measured sea level an empirical model had to be developed.

5. Development of the empirical model

The empirical model is aimed to predict the combined conductivity out of sea level measurements and flow data. In the following the development of this model and the sensitivity analysis are presented. Additionally, the model was validated by applying it to shorter time frames with known leaks.

5.1. Prediction of combined conductivity

By plotting the new parameter Q_{sea} against the sea level a positive linear correlation becomes visible. Indicated by the improved correlation between Q_{sea} and the conductivity the six hourly average was taken for the parameters throughout all the following calculations.

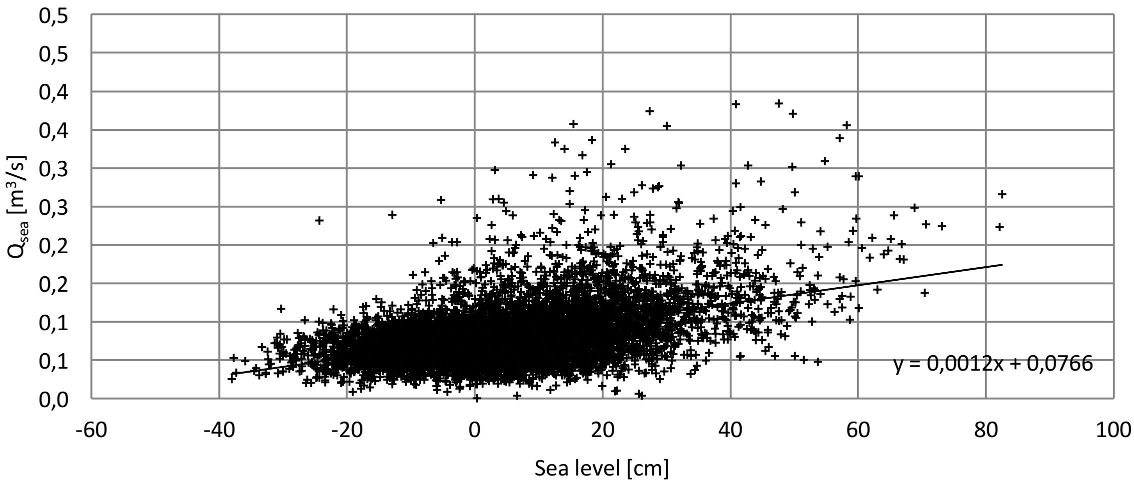

Figure 5-1 Sea level vs. calculated Q_{sea} (6h average)

Q_{sea} is incorporating the influences of flow and sea level on the conductivity. Therefore, it is a reasonable approach to base the prediction of the conductivity on Q_{sea}. Using the function of its trendline allows to calculate Q_{sea_sl} out of the sea level (sl).

$$Q_{sea\_sl} = 0.0012 * sl + 0.0766 \qquad \textbf{Equation 5-1}$$

Now Q_{sea_sl} can be estimated independently from the measured conductivity. This allows to transform Equation 4-2 to predict the conductivity to be expected at the WWTP out of the flow data and specific conductivity assumptions (Equation 5-2).

$$\sigma_{pred} = \frac{Q_{ww} * \sigma_{ww} + Q_{sea\_sl} * \sigma_{sea} + Q_f * \sigma_f}{Q_{comb}} \qquad \textbf{Equation 5-2}$$

This predicted and the actually measured conductivity are shown in Figure 5-2. Since the Q_{sea_sl} is estimated out of the related sea level it does not strictly depend on the combined flow. Therefore, the predicted conductivity gives a range of values for a certain Q_{comb}. This results in a diffused prediction curve. By applying this approach, an average Q_{sea_sl} = 0.08 m^3/s was estimated for the period 2005 – 2015. This corresponds quite closely to the seawater inflow calculated in Section 4.7.

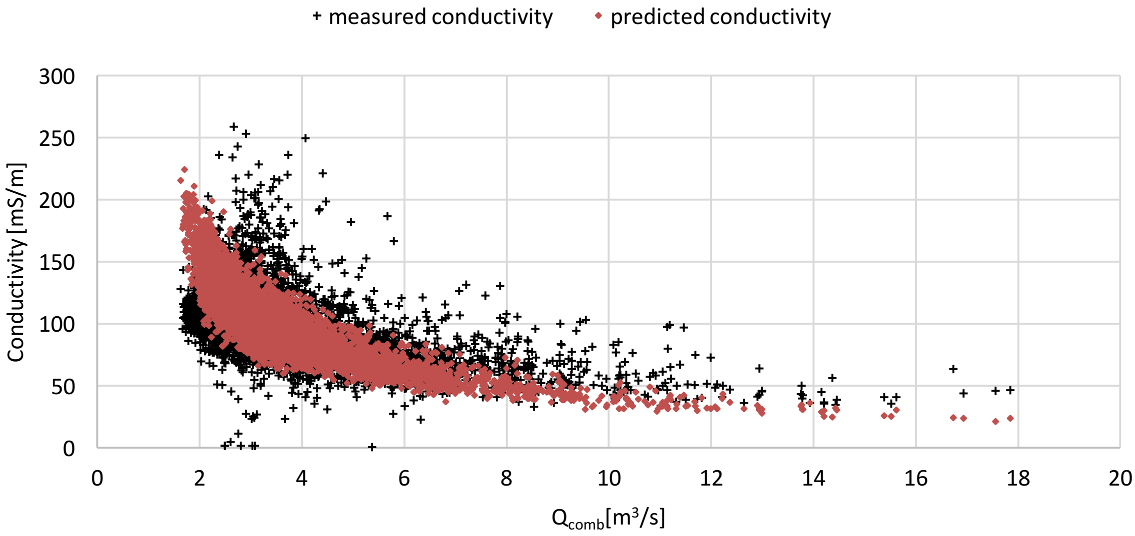

Figure 5-2 Q_{comb} vs. predicted and measured conductivity (6h averages) 2005 - 2015

The scatter clouds almost match at low flow conditions. However, during low flow the high conductivity events are not represented very well in the prediction. The same is true for high flow events. Starting at approximately 7 m^3/s the conductivity is constantly underestimated in the prediction. This divergence can be seen in Figure 5-3. The $d\sigma$ represents the difference between measured and predicted conductivity ($d\sigma = \sigma_{measured} - \sigma_{predicted}$). It can be seen that during low flow the model tends to overestimate the actual conductivity. During high flow events the $d\sigma$ shows a quite constant underestimation of approximately 20 - 50 mS/m.

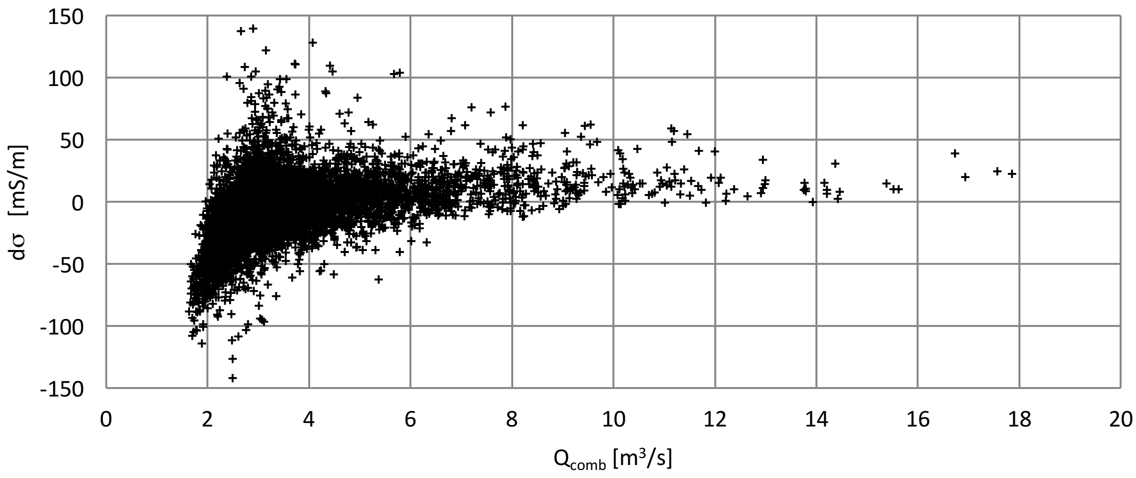

Figure 5-3 Q_{comb} vs. dσ 2005 – 2015

The dσ between predicted and actually measured conductivity increases also with the actual wastewater conductivity (Figure 5-4). Up to a conductivity of 150 mS/m the prediction rather overestimates the conductivity. Above 150 mS/m the offset increases drastically in an almost linear trend.

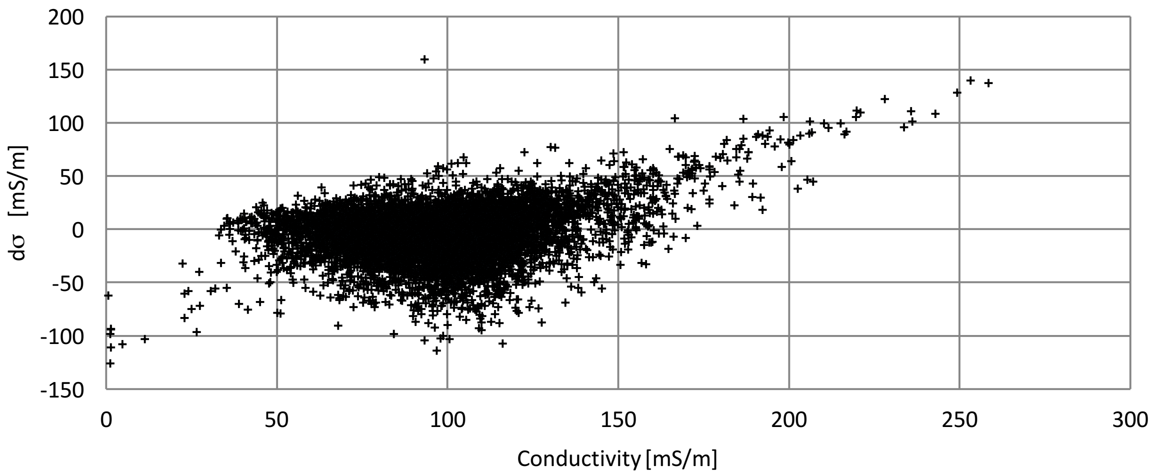

Figure 5-4 Measured conductivity vs. dσ 2005 - 2015

The large offset and the clear shape in the error distribution over the measured conductivity as well as the flow indicate that there are some impacts not considered properly within this model. This could be caused by the sewer system not being a static system. It is constantly improved, repaired and new leaks occur. Hence, over a time period of ten years lots of changes take place. To avoid too many of these occasions influencing the model, it is indicated to investigate shorter time periods.

5.2. Application of the model on specific time frames

With the help of the department for waste and water management (Kretslopp och Vatten) from city of Gothenburg two time periods were chosen, in which leaks were detected. One is close to the center of the city in 2011 and the other out at the coast towards the sea in 2014 (Torststensson 2016). In the following chapter the approach described above will be applied to both time series. The aim is to reduce the offset in the prediction and finally quantify the seawater inflow into the sewer during these time series. Those periods were chosen to be able to test the approach with reasonable assumptions for the seawater conductivity.

5.2.1. Leak at Lilla Varholmen in 2014

A quite recent leak was located in the area of Lilla Varholmen west of Gothenburg out in the Kattegat (Figure 5-5). In this case a pipe with connection to the sea broke and lead seawater towards a nearby pumping station. Thereby seawater was pumped towards the WWTP. The leak was fixed in the end of July 2014 (Torststensson 2016).

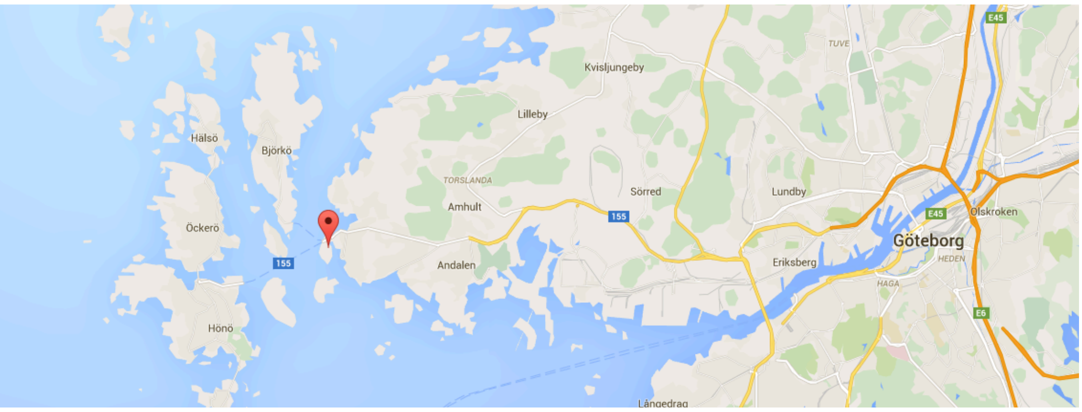

Figure 5-5 Location of the leak in 2014 (Google Maps 2016)

Table 4-6 shows that the conductivity of the seawater in that area can be expected to be around 2,800 mS/m. Entering this into Equation 4-6 produces the correlation of Q_{sea} and sea level as shown in Figure 5-6. To predict the combined conductivity out of the sea level the trendline for this correlation was taken.

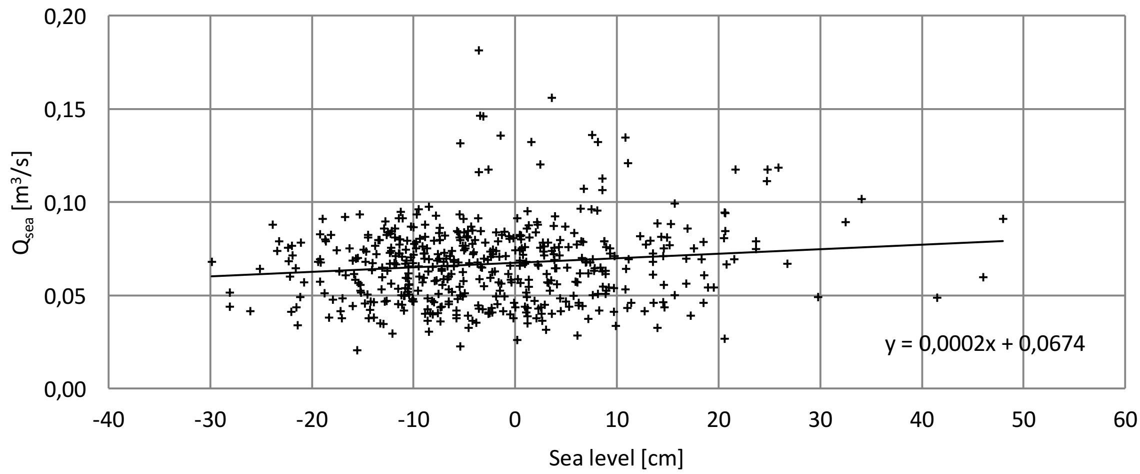

Figure 5-6 Qsea vs. sea level April till July 2014

The calculation with the new equation for Q_{sea_sl} resulted in the following prediction (Figure 5-7).

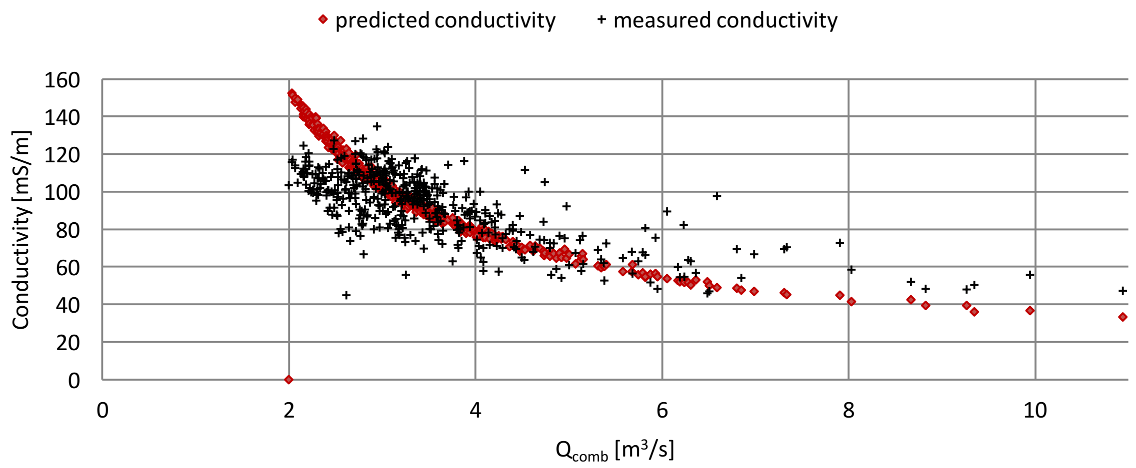

Figure 5-7 Q_{comb} vs. measured and predicted conductivity (6h average) April till July 2014

The prediction of the conductivity got improved by taking shorter time series. Due to the known leak and less influences over time the error in the calculations decreased. Plotting dσ against the measured conductivity shows that the scatter cloud lost its "arrow" shape and became more random. The magnitude of the error decreased significantly as well (Figure 5-8).

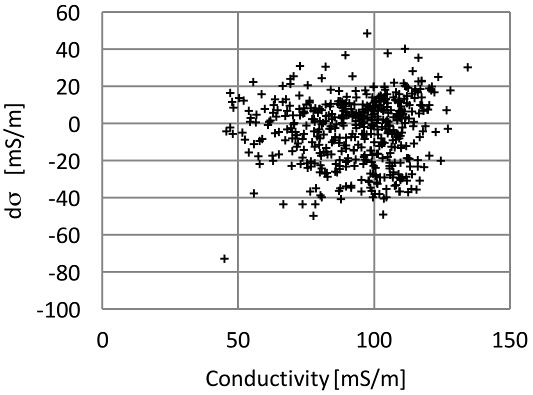

Figure 5-8 Conductivity vs. dσ April till July 2014

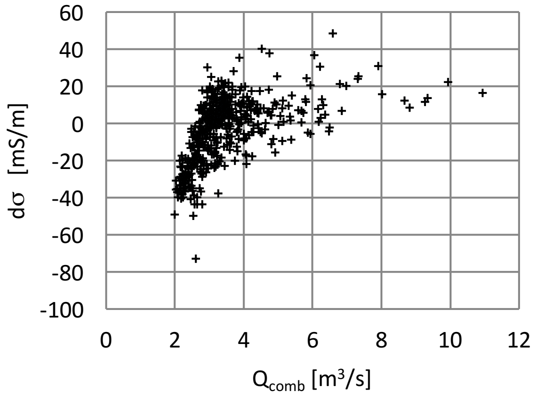

Figure 5-9 Q_{comb} vs. dσ April till July 2014

Looking at the plot of dσ against the combined flow the shape of the cloud is still present (Figure 5-9). However, the error is reduced in magnitude in positive as well as negative direction. That the error in the positive direction got reduced, indicates that the model tends less towards underestimation of the conductivity. During low flow events the results for the predicted conductivity still tend to be higher than the actual conductivity.

By applying this model on the short time period from April till July in 2014 an average seawater inflow of Q_{sea_sl} = 0.07 m^3/s could be identified. The seawater is therefore contributing with 2% of the average Q_{comb} of 3.5 m^3/s.

5.2.2. Leak in the city center in 2011

The second leak investigated within this study was located in one of the canals in the city center of Gothenburg and occurred in the time from April till June 2011. In this case the weir of a CSO was too low so that the water from the canal was flowing back into the system (Torststensson 2016).

Figure 5-10 Location of the leak in 2011 (Google Maps 2016)

Due to its location close to Lindholmen the conductivity of the water in the canal was assumed to be 100 mS/m according to Table 4-6. Following the same empirical approach presented above, the equation for the prediction of Q_{sea_sl} was developed (Figure 5-11).

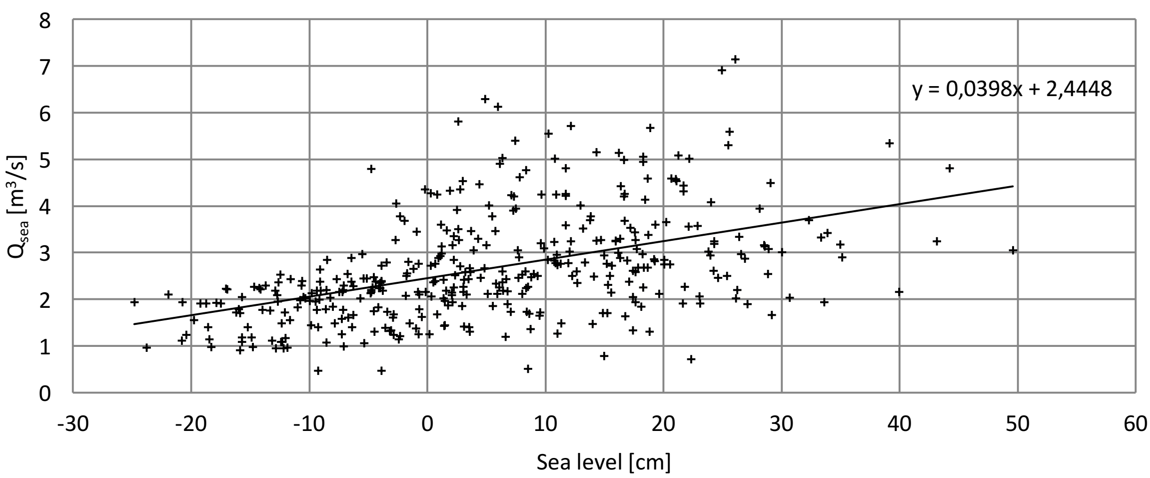

Figure 5-11 Sea level vs. Q_{sea} for April till June 2011

With this assumption a quite accurate prediction of the wastewater conductivity was possible. Even at higher flows the offset seems to be low (Figure 5-12).

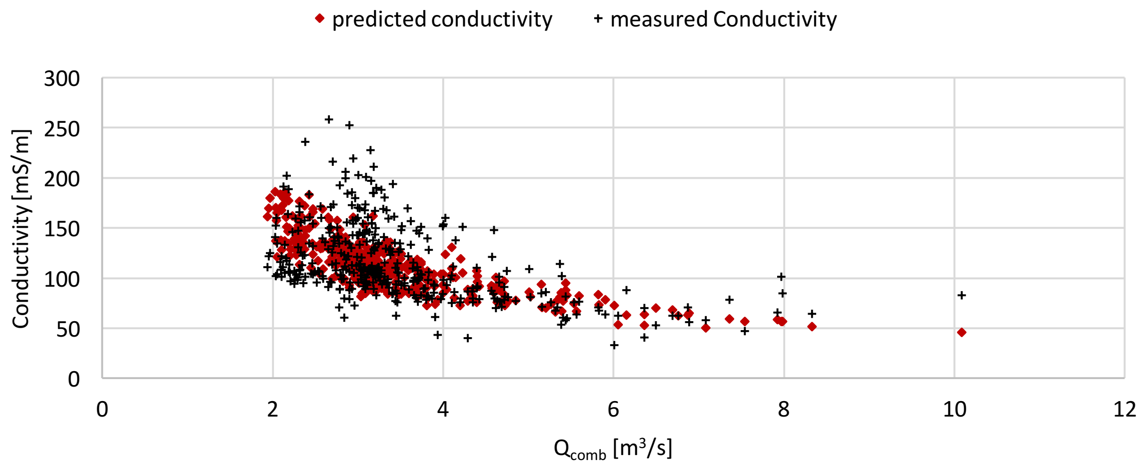

Figure 5-12 Q_{comb} vs. predicted and measured conductivity (April till June 2011)

Nevertheless, the scatter clouds of the error distribution presented in Figure 5-13 and Figure 5-14 show the same patterns as in the long term prediction in Section 5.1.

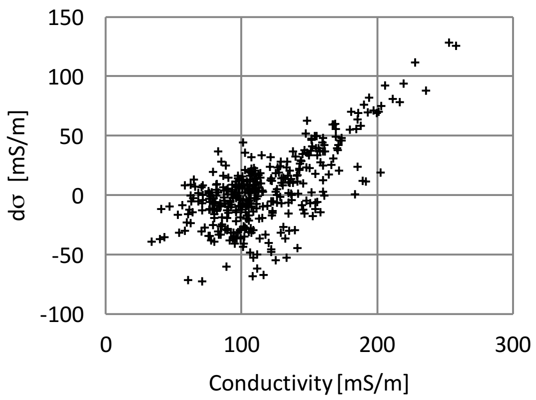

Figure 5-13 Conductivity vs. dσ April till June 2011

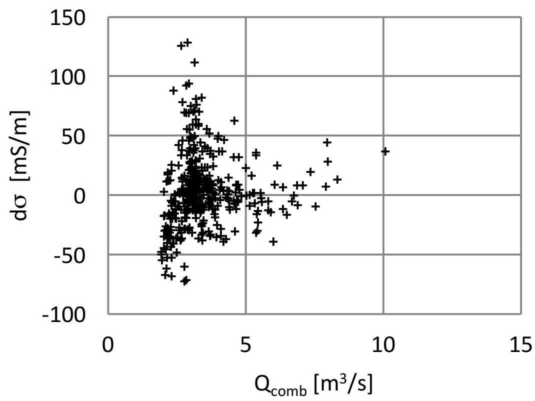

Figure 5-14 Q_{comb} vs. dσ April till June 2011

Indicated by the very high Q_{sea_sl} in Figure 5-11 a more detailed investigation of the outcome had to be conducted. Figure 5-15 shows dQ (= Q_{comb} - Q_{sea_sl}) plotted against the combined flow. This difference is increasing linearly with increasing Q_{comb}. The prediction for this time series creates quite a large number of negative dQ at low flow conditions. This means that the calculated seawater inflow is larger than the actually measured combined wastewater flow.

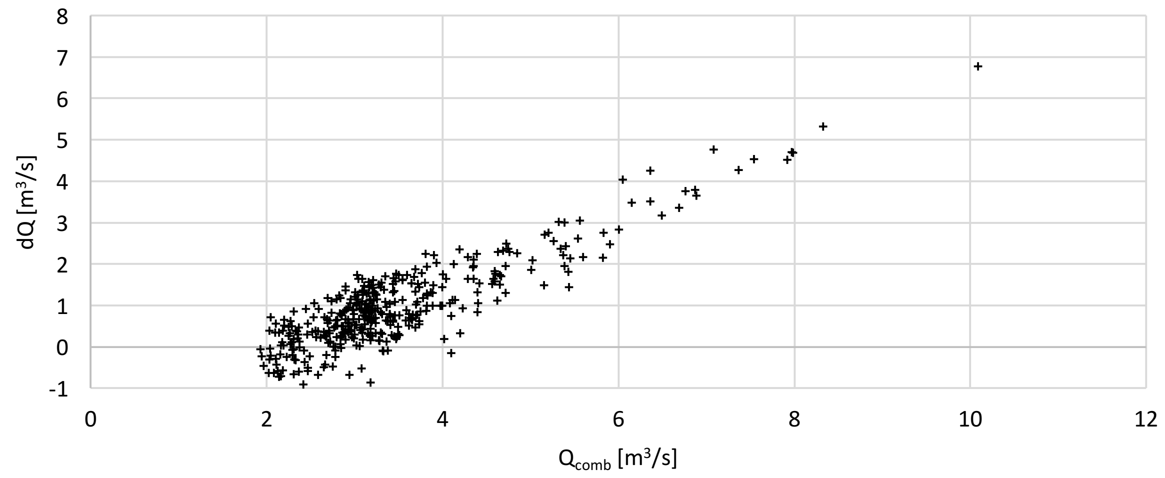

Figure 5-15 Q_{comb} vs. dQ April till June 2011

This behavior indicates that the assumptions have to be examined. With a σ_{sea} = 100 mS/m the conductivity of the inflowing seawater is very close to the wastewater conductivity of σ_{ww} = 70 mS/m. With a freshwater share contributing with an even lower conductivity, the conductivity of the mixture could actually not exceed 100 mS/m. In the calculation (Equation 5-2) this is achieved by very high Q_{sea_sl} values. An investigation with different σ_{sea} was considered not to be feasible within this study since it is not accountable where the higher conductivity is coming from. Further investigations of the conductivity in the canals could lead to a more realistic result. This means in particular, that higher conductivities would lead to lower and therefore more reasonable seawater inflows.

5.3. Sensitivity analysis

The patterns in the offset suggest that some influences are not considered entirely in the calculations. In a sensitivity analysis the two main assumptions were tested regarding their influence on the outcome of the calculations. Since there was only very rough data available on the conductivity of freshwater and wastewater these parameters had to be assumed. The same is true for the seawater conductivity. In this case however, the calculations in Section 5.2.2 have shown that a change in seawater conductivity is compensated by a change in Q_{sea}. Therefore, the calculated conductivity does not show sensitivity towards the σ_{sea}. The model was also tested against changes in the wastewater flow Q_{WW}.

Since the prediction could be improved by investigating shorter time periods the sensitivity analysis is applied to the time period April till July 2014. To test the sensitivity of the model the freshwater conductivity was increased up to 30 mS/m whereas the other parameters remained constant as presented in Table 4-5. Figure 5-16 shows the predicted conductivity against the combined flow. For greater clarity only the trendlines for the changes in σ_f are shown in the graph.

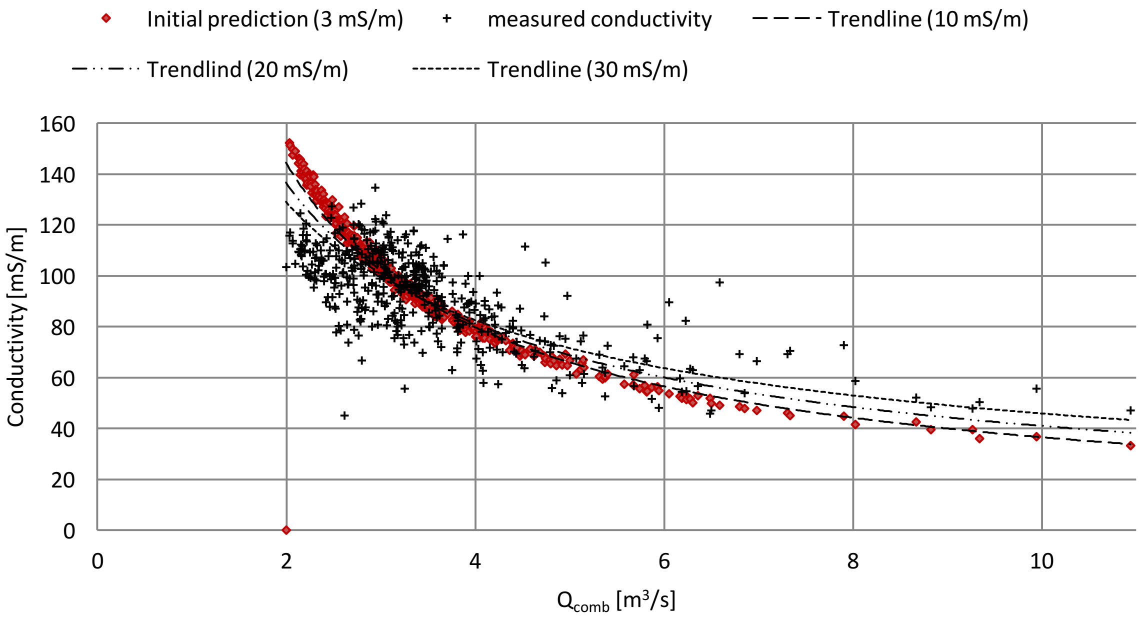

Figure 5-16 Q_{comb} vs. conductivity for different σ_f

As shown in Figure 5-16 the increase in the freshwater conductivity lowers the offset for the prediction during high flow events. During low flow events the predicted conductivity gets reduced and therefore tends less towards overestimation. This can be related to the increased influence of the freshwater in Equation 4-6. Table 5-1 shows the average dσ for the changes in the freshwater conductivity. The constantly decreasing error supports the improvement of the model due to raised σ_f.

Table 5-1 Average dσ for different freshwater conductivities (σ_f)

σ_f	3 mS/m	10 mS/m	15 mS/m	20 mS/m	25 mS/m	30 mS/m
Ø dσ [mS/m]	-3.24	-2.49	-1.31	-1.73	-1.30	-0.98

A change in the wastewater conductivity σ_{ww} showed very little to no impact on the prediction as shown in the appendix (Figure A- 4). A general change in the wastewater flow Q_{ww} showed effect on the outcome of the calculations (Figure A- 5). This, however, resulted in an increased error in the prediction of the combined conductivity.

6. Discussion

Some findings had to be interpreted in the previous chapters in order to maintain clarity over the implemented procedure. However, the main results and the methodology will be discussed in the following.

6.1. Results

Within this study it was possible to show that an assumed entrance of seawater into the sewer system is most likely related to a direct inflow. The estimations in Section 4.1 have shown that the flow direction of the groundwater is clearly directed towards the sea and Göta Älv. This led to the expectation of a direct impact of inflowing seawater. However, the influence of the sea level on the conductivity of wastewater was not evident in the statistical analysis of the data.

Even though some investigated time series showed an alleged correlation the complex and interdepending influences of the different parameters on the conductivity blurred the influence of inflowing seawater. By treating the data and reducing the investigated time series it was possible to resolve some of the influences on the wastewater conductivity. Especially the treatment of the precipitation data showed effect on the calculations. An accumulation over six to ten hours and a time shift two hours forward was found to give the best correlations towards flow and conductivity. This correlation shows that a rain event effects the WWTP after two hours of precipitation. The flow peak is reached within six to ten hours.

Figure 4-11 indicates a seasonal dependency of the water temperature. During certain periods of the year the wastewater shows a specific temperature range. Here might also lie the strong positive correlation of the conductivity and the water temperature. In April the inflow and infiltration water is much colder and therefore leads not only to dilution but also cools down the wastewater. During periods with lower water temperature one can therefore expect lower conductivities. Other explanations for a seasonal dependency of the wastewater conductivity were found in the literature. One suggestion are different industrial or commercial discharges during different periods of the year. The agricultural activity might increase in spring and summer and that results in a different composition of the combined flow (Water Environment Federation 2007).

Another explanation could be greater microbial activity due to higher water temperatures in summer. This could result in a larger amount of suspended solids and therefore an increase in conductivity (Idiata 2015; Harter & Rollins 2008).

With a detailed investigation of the contributing flows it was possible to calculate the combined conductivity. Two ways of calculating the seawater inflow have been presented in this study. Both resulted in a seawater inflow of approximately 0.08 m^3/s over the investigated time span from 2005 till 2015. This seawater inflow shows a positive linear correlation towards the sea level.

With the assumed conductivity of 2,500 mS/m the Q_{sea} contributes with a salinity of approximately 17 g/l (NaCl) (Schuman 2012) to the combined flow. Since the seawater inflow contributes with only 2 % to the average combined flow it becomes diluted significantly by the waste- and freshwater. A therefore reduced conductivity is unlikely to have an influence on the treatment process. The same is true for the results investigating shorter time series. The inflowing conductivity of 2,800 mS/m for the leak in 2014 corresponds to approximately 18 g/l NaCl (Schuman 2012). With a calculated inflow of 0.07 m^3/s it can be expected that the dilution is sufficient to reduce the impact on the treatment as well. The results of the presented calculations show that inflowing seawater does not have a very big influence on the wastewater composition in Gothenburg at the current state. However, smaller municipalities or regions with higher seawater conductivities might be influenced in a larger extent.

Even though the calculations for the leak in 2011 got disturbed by other significant influences the characteristics of this leak show that an increasing sea level brings additional challenges for the sewage system of Gothenburg. Existing structures like CSOs get flooded more frequently and lead seawater back towards the WWTP.

6.2. Methodology

Within the present study large data sets have been handled. The process data from Gryaab AB and the meteorological measurements from SMHI showed extensive coverage and resolution. To process this large amount of data a statistical analysis was initially conducted. While the correlation coefficients according to Pearson give the linear correlation between two parameters the PLS is able two show the influence of parameters on the wastewater conductivity. However, these methods did not reveal a direct influence of the sea level on the conductivity.

To be able to investigate the influence of the sea level in more detail several assumptions had to be made. The main assumption to start with was the direct proportionality of the ion concentration and conductivity. Since the electrical conductivity depends not only on the ion concentration but also on the valence of these ions (Stephenson & Judd 2008) this assumption inherits some uncertainties. Nevertheless, the electrical conductivity is widely used in marine research to estimate other parameters of seawater like salinity and density (UNESCO 1983; Pawlowicz 2015). Since the exact composition of the combined wastewater flow is unknown and might change over time this assumption can be considered as an appropriate estimate.

Two approaches were carried out to approximate the wastewater conductivity. The first one is based on the measured combined flow and its conductivity. By taking further assumptions regarding the properties of the specific flow shares the composition of the combined flow could be calculated. Based on these calculations an empirical approach was established to base the calculations on the measured sea level. Giving a much rougher estimate of Q_{sea} this approach only requires the combined flow and sea level measurements. The empirical approach resulted in quite large errors with a defined distribution. Even though this error could be reduced by applying six hourly averages and shorter time series it stayed evident. A more detailed investigation of the underlying assumptions showed possible areas of improvement.

The sensitivity analysis revealed that the freshwater conductivity might have been set too low. The conductivity of σ_f = 3 mS/m was taken from measurements in rainwater in southern Sweden. While this measurement relates to pure rainwater it can be expected that runoff is transporting dirt and dust from rooftops and streets. This would increase the load of suspended solids and most likely the conductivity (Idiata 2015; Harter & Rollins 2008).

Additionally, surface waters and groundwater are contributing to the freshwater inflow as well. Even though their conductivity can be expected to be low in southern Sweden they supposedly increase the freshwater conductivity slightly. Groundwater for example contributes with around 50 mS/m (Lidén & Saglamoglu 2012). Further investigations regarding the composition and conductivity of runoff and infiltration water in Gothenburg might therefore be indicated to improve the model. The same is true for the conductivity of wastewater discharged from households. The available data consisted of spot samples at very few locations. However, the sensitivity analysis has shown that changes in σ_{ww} do not affect the model significantly. Its influence seems to be outweighed by the high seawater conductivity and large share of freshwater inflow.

The wastewater flow was calculated out of the available flow data by applying the sliding minimum over 21 days. This approach results in an estimated wastewater flow of 1.7 m^3/s throughout the day. This constant flow during the day does not represent the flow patterns in reality. During the course of the day peak flows can be expected. Whereas the wastewater share at night will be significantly lower (Butler & Davies 2004). Here might lie one reason for the shape in the error distributions (e.g. Figure 5-3). During low flow events the influence of the wastewater flow becomes greater, however, this share is not represented properly with a constant flow. The sensitivity analysis has shown that changes in Q_{ww} can have an impact on the calculations. However, the approach of a uniform flow might not be adequate. Adjusting the model to be more flexible regarding flow patterns could help to improve the outcome of the model greatly.

The calculations in Section 5.2.2 have shown that an adequate assumption for the seawater conductivity is crucial. Even though the prediction of the combined conductivity was quite accurate it was based on very high theoretical seawater inflows. Different reasons can be suggested within the scope of this study. The conductivity in the Göta Älv is probably underlying constant changes due to the fluctuations in sea level. The data from the different water level measurement locations has shown that fluctuations in sea level are noticeable quite far upstream of Göta Älv (Figure 4-1). Therefore, the calculation with a static conductivity from a spot sample does not appear suitable. Another explanation could lie in the size of Gothenburg's sewer system. With its 830,000 PE it is quite large and the origin of the water is difficult to allocate. An additional leak or industrial wastewater will have great influence on the water composition.

A more detailed investigation of the contributing waters and their conductivity would help to improve the model to a large extend. One contribution not considered within this study is the wastewater produced by industries or commercial sites. Depending on their production and local treatment the discharged wastewater can contribute with significant loads of salt. Considering the size of the system it was not within the range of this study to account for this share of water.

It becomes evident that most assumptions and uncertainties are related to the unknown properties of the contributing water sources. With little time and financial effort, it would be possible to gather more information on the conductivity of different waters. A more detailed and resource demanding approach would be an isotope analysis. This would mainly help to identify the contributing sources and their loadings. By investigating the isotopes deuterium (δD) and oxygen^{18} ($\delta^{18}O$) one can determine the water sources of a mixture and also calculate up to which extent they contribute to the flow (Affolter et al. 2015; Peng et al. 2014; Wurl 2009).

The model presented in this thesis enables the user to identify saltwater inflows by applying dilution calculations. Furthermore, the saltwater share can be quantified based on the sea level. With an extensive data set for all required parameters a rough estimate is possible over longer time series. For a more detailed investigation the time span has to be limited to reduce the influence of changes in the system. A prediction into the future based on climate scenarios, however, would be very uncertain at the current state. Since it is not known how and where the seawater is going to enter the sewer system, these predictions would have to be based on further assumptions.

7. Conclusion

This study was aimed to identify and quantify the influences on wastewater conductivity with emphasis on the sea level fluctuations. By identifying the ways of entry, applying statistical tools and a detailed analysis of the composition of flows these aims could be reached. The calculated seawater inflows show a strong positive correlation towards sea level fluctuations. Based on several assumptions the amount of seawater entering the sewer system could be quantified theoretically as well. Due to a number of assumptions and limitations within the present study the model contains some uncertainties. The influences on the wastewater conductivity have proven to be very complex and interconnected. By excluding the winter months and focusing on shorter time series the uncertainties could be partly reduced. However, an influence of other natural waters and industrial wastewater can be expected. The dominant part of the contributing water sources was found to be the rainwater. With a time delay of two hours and a peak in flow after six to ten hours the flow patterns could be identified. However, the specific properties of this share have to be investigated in more detail. It is therefore indicated to expand the investigations in future studies. The following research questions could be identified within the present study:

- Identification and quantification of water sources to get a deeper understanding of the contributing flows (isotope analysis)
- Apply the model to a smaller more defined area: By reducing the influences on the wastewater conductivity the correlation and model could be improved
- Further investigations regarding the properties of different water sources: A more detailed survey over the conductivity of the contributing waters and their mixing behavior would help to increase the robustness of the model
- Application of the improved model on climate scenarios to estimate future impacts of climate change

Even though the amount of entering seawater might not influence the treatment facilities in Gothenburg it became evident that a seawater inflow exists. The properties of the investigated leaks have shown that they become even more likely with increasing sea levels. The system in Gothenburg benefits from its size and therefore large buffer capacity. Other regions with smaller WWTPs, a higher salt content in their seawater, seawater intrusion or longer coastlines might experience a larger influence of rising sea levels. The presented model can be a helpful tool to estimate the impacts on specific regions and prepare for future challenges.

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Appendix

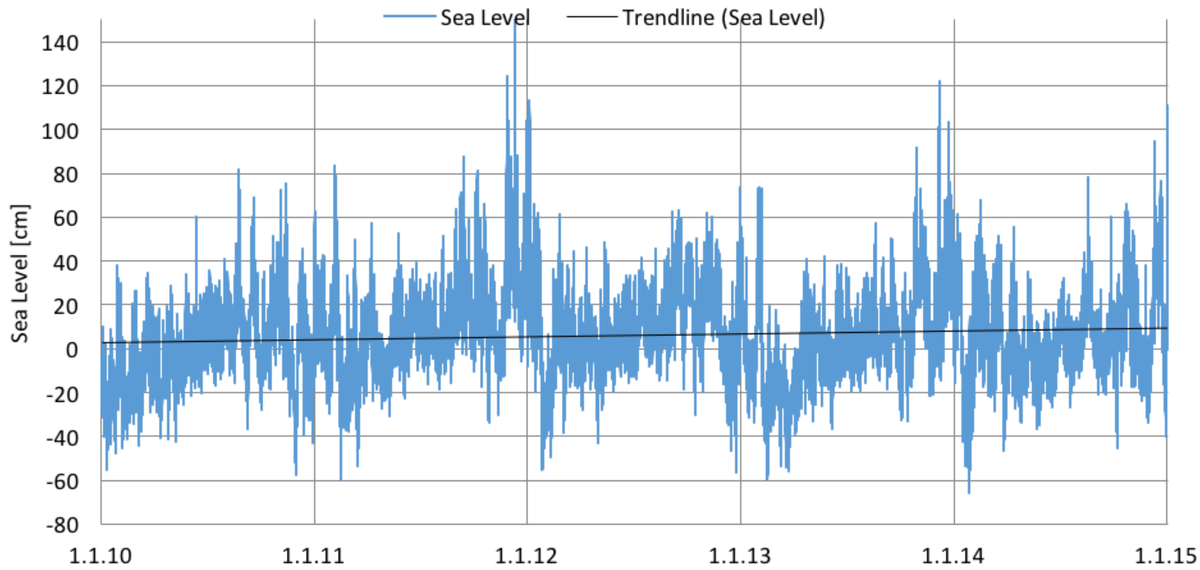

Figure A- 1 Sea level measurements 01.01.10 – 01.01.15

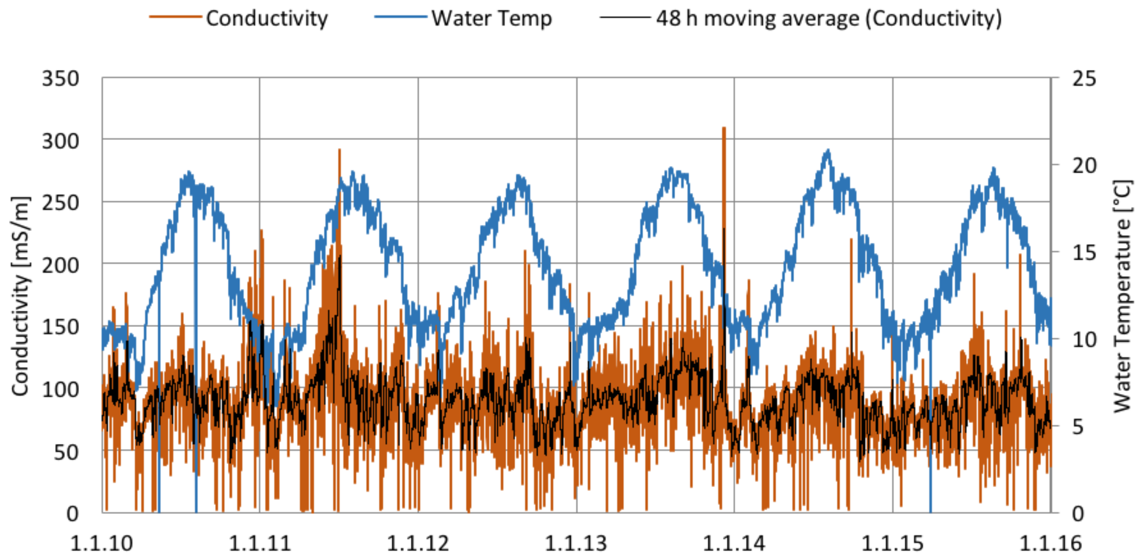

Figure A- 2 Conductivity and Water temperature 01.01.10 – 01.01.16

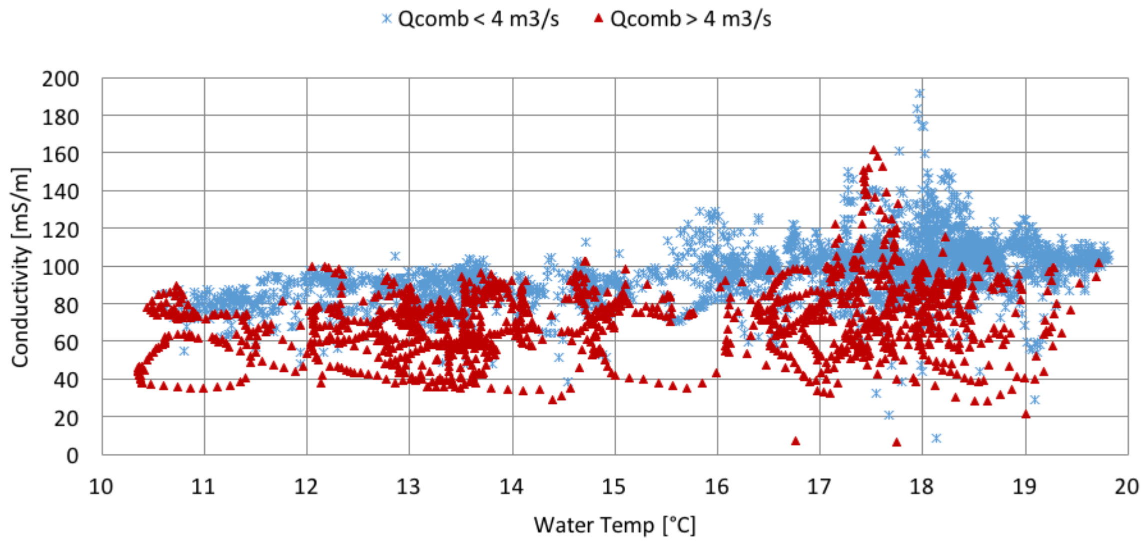

Figure A- 3 Water temperature vs. conductivity summer 2015

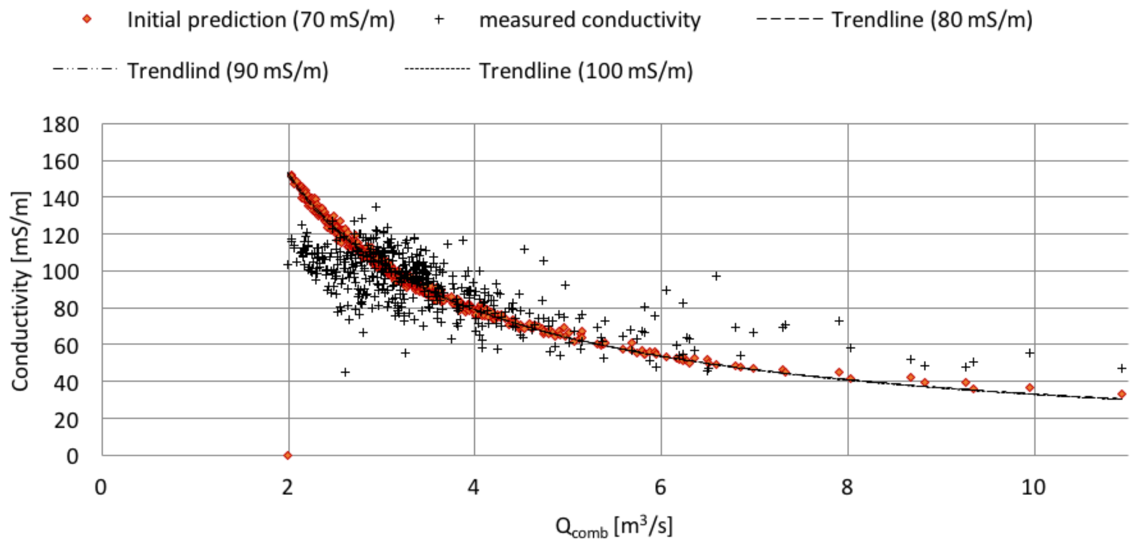

Figure A- 4 Sensitivity analysis for changes in σ_{ww}

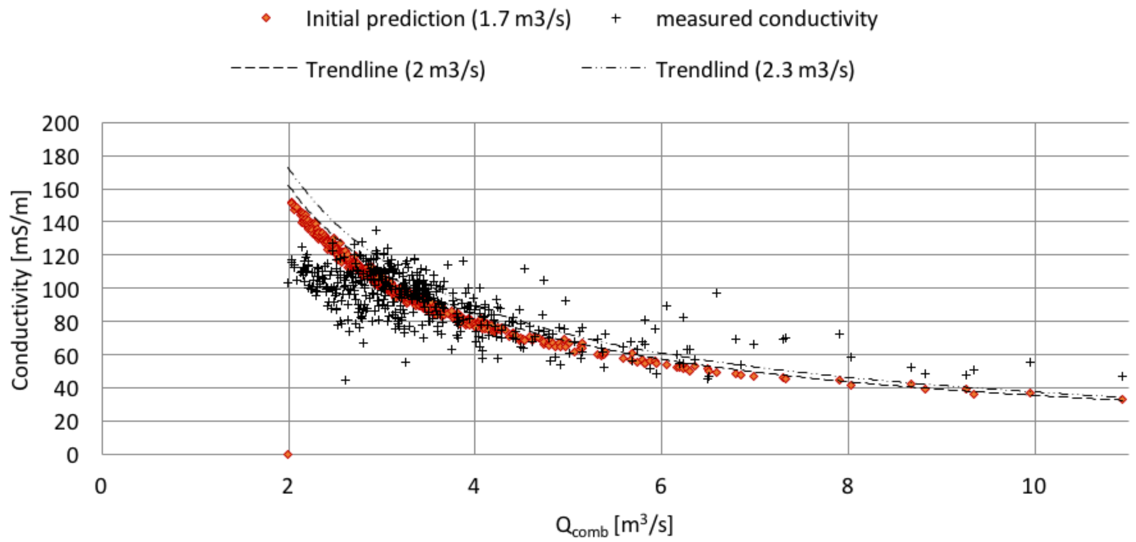

Figure A- 5 Sensitivity analysis for changes in Q_{ww}