



CHALMERS
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Impact of High Flow on Phosphorus Treatment Performance

A Comparative Study of Five Wastewater Treatment Plants in Sweden

Master's thesis in Infrastructure and Environmental Engineering

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

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ABSTRACT

This thesis assesses the impact of high flow conditions on the performance of five wastewater treatment plants (WWTPs) in Sweden in terms of phosphorus (P) removal, focusing specifically on effluent P mass flow. Predictive models were developed for each WWTP using actual flow and effluent P concentration data to estimate the effluent P mass flow outcomes under varying flow rates. These estimates provide stakeholders with valuable insights into current performance and potential opportunities for optimisation.

The research involved the collection and analysis of three years of flow, influent, and effluent P concentration data for each plant. Statistical analyses were conducted to identify flow rate patterns, and regression models were developed to predict effluent P concentration which is then used to estimate effluent P mass flow under different flow conditions.

Key findings indicate that as flow increases, effluent P mass flow also rises. When a WWTP's capacity is exceeded, bypass scenarios occur, resulting in a significant increase in effluent P mass flow. The effectiveness of P removal at each WWTP is closely related to the plant's overall treatment capacity and the inflow it receives.

The study also examined the performance of WWTPs under two scenarios: swapping of catchments and swapping of WWTPs within municipalities, revealing additional opportunities for optimisation. For most municipalities, improving catchment area management could help reduce inflow peaks, and for all of them, upgrading design capacities, techniques, or WWTP operations could significantly enhance P removal performance.

In conclusion, this thesis provides important insights for optimising WWTP performance in P treatment under high flow conditions, contributing to improved environmental protection and regulatory compliance in Sweden.

Keywords: High Flow, Wastewater Treatment Plant, Phosphorus removal, Predictive Models, Process optimisation.

Effekten av högt flöde på fosforbehandlingsprestanda: en jämförande studie av fem reningsverk

En jämförande studie av fem reningsverk in Sverige

Examensarbete inom masterprogrammet Master Infrastruktur och Miljöteknik

ABOBACKER SIDDIQUE MOHAMMED SHAREEF

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Avdelningen för vatten miljö teknik

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SAMMANFATTNING

Denna avhandling undersöker påverkan av höga flödesförhållanden på prestandan hos fem reningsverk i Sverige när det gäller att reducera den utsläppta mängden av fosfor. Prediktiva modeller utvecklades för varje reningsverk baserat på faktiska flödes- och fosfor-koncentrationsdata för att uppskatta P-massflödet i utgående vatten under varierande flödesförhållanden. Dessa uppskattningar ger intressanta värdefulla insikter i nuvarande prestanda och potentiella möjligheter till optimering.

Forskningen innefattade insamling och analys av tre års data för flödets och fosfor koncentrationer för varje reningsverk. Statistiska analyser genomfördes för att identifiera flödesmönster, och regressionsmodeller utvecklades för att förutsäga massflödet av fosfor i utgående vatten under olika flödesförhållanden.

Viktiga resultat är att när flödet ökar så, ökar även massflödet av fosfor i utgående vatten. När ett reningsverks kapacitet överskrids uppstår ofta förbiledning av vatten, vilket resulterar i en betydande ökning av massflödet av fosfor i utgående vatten. Effektiviteten i fosforavlägsnandet för varje reningsverk är nära relaterad till anläggningens totala behandlingskapacitet och det inflöde den tar emot.

Studien undersökte även prestandan hos reningsverk under två scenarier: utbyte av avrinningsområden och utbyte av reningsverk, vilket avslöjade ytterligare möjligheter till optimering. För de flesta kommuner skulle förbättrad hantering av avrinningsområden kunna bidra till att minska inflödestoppar, medan för alla kommuner skulle uppgradering av designkapacitet, tekniker eller reningsverksdrift kunna förbättra avlägsnandet av fosfor avsevärt.

Sammanfattningsvis ger denna avhandling viktiga insikter och praktiska rekommendationer för att optimera reningsverks prestanda i fosforbehandling under höga flödesförhållanden, vilket bidrar till förbättrat miljöskydd och efterlevnad av regler i Sverige.

Nyckelord: Högt flöde, Reningsverk, Fosforavskiljning, Förutsägande modeller, Processoptimering.

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Aboobacker Siddique Mohammed Shareef

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1 Introduction

1.1 Background

Rapid urbanisation and the world's growing population are significant factors shaping our future (Daigger, 2007). By the midpoint of this century, the global population is projected to increase by as much as 30% in the highest-case scenario (Daigger, 2007; United Nations, 2022). This surge will result in a higher demand for clean water. Additionally, greater water consumption will lead to a proportional increase in wastewater discharge. Therefore, the efficiency of wastewater treatment processes becomes increasingly crucial. Effective water treatment not only improves the quality of water bodies but also provides a vital source of clean water to meet the escalating demand.

Wastewater treatment plants (WWTPs) receive a combination of sewage water and water from infiltration and inflow (I/I), particularly in combined sewer systems (Ohlin Saletti et al., 2023; Ohlin Saletti et al., 2021). Even separate sewer systems may experience this influx due to pipe breaks or illicit connections. An increase in I/I flow can disrupt treatment processes, diminish WWTP efficiency and lead to elevated effluent levels, which can harm receiving water bodies and the environment (Giokas et al., 2002; Kowalik et al., 2015). Moreover, this can escalate operational costs and environmental fees if effluent levels exceed regulatory limits (Bugajski et al., 2021). Therefore, evaluating WWTP performance under varying flows is essential for optimising processes and infrastructure to minimise effluent levels, safeguard the environment, and reduce operational costs.

1.2 Aim

The aim of this project is to evaluate the effects of high flows on the performance of five WWTPs-Rya, Essvik, Henriksdal, Kalmar, and Käppala-in treating phosphorus (P), specifically in terms of effluent P mass flows. The project involves developing a predictive model for each WWTP to estimate effluent P concentrations based on flow rates. These predicted concentrations will be used to calculate effluent P mass flows, enabling stakeholders to better understand the current WWTP systems and identify opportunities for improvement by comparing predicted mass flows.

1.3 Research questions

To achieve the aim, the following research questions guide the study:

- What are the effects of high flows in treating P, in terms of effluent P mass flows among the five WWTPs?
- How do the effects of flows compare across the five WWTPs, and what factors contribute to differences in performance?
- How can the insights from the comparison of performance be used to identify opportunities for process optimisation in P treatment at the five WWTPs?

1.4 Limitations

The project uses only weekly flows and effluent P concentrations to develop the model. The influent concentrations are used solely to calculate the average influent P mass flows to determine the excess effluent P mass flows due to the excess flows beyond treatment capacity. This can be considered a limitation of the project. Temperature could also play a significant role in the effluent P concentrations. This project did not consider temperature, which is also a limitation.

Even though some of the WWTPs had high capacities, the models were only created up to the highest flow recorded in the data. This is one of the main limitations of using weekly data. Using daily data instead of weekly data could have helped to capture higher flows in the models, which, in turn, might have allowed the creation of more accurate models for higher capacities than those currently used.

2 Theory

This chapter provides a comprehensive overview of the key concepts and processes relevant to wastewater treatment, and also focuses on the challenges of high flow conditions. By establishing a theoretical foundation, this section helps readers with the understanding necessary to grasp the context and implications of the study. Additionally, this chapter introduces the predictive models that can be used to assess the performance of WWTPs.

2.1 Water reaching WWTPs

Wastewater from domestic and industrial sources carries numerous amounts of pollutants that can harm ecosystems and human health if released untreated (Metcalf & Eddy, AECOM., 2014). Nutrients like nitrogen (N) and P, when discharged in excess, can cause eutrophication, leading to algae blooms, fish kills, and further degradation of water quality. Organic compounds such as oils, grease, and detergents can deplete oxygen levels in water bodies, suffocating aquatic life. Additionally, inorganic substances such as heavy metals and toxic chemicals can accumulate in organisms, causing long-term damage to ecosystems and posing health risks to humans through bioaccumulation. Pathogens like bacteria, viruses, and parasites present in wastewater can spread diseases if discharged untreated, leading to outbreaks of waterborne illnesses among communities. Therefore, it is crucial to treat the wastewater before its release into the environment.

Wastewater collected from different sources is transported to WWTPs through a sewer system (Ohlin Saletti, 2022). The sewer system can be either separated or combined. Separated systems are designed to handle sanitary sewage and stormwater in separate networks. In these systems, there are two independent sets of pipelines: one dedicated to carrying sanitary sewage from homes and businesses to wastewater treatment facilities, and another specifically for diverting stormwater runoff directly to local water bodies or stormwater management systems. This separation ensures that the two types of water are managed appropriately. Combined systems, in comparison, use a single network of pipes to transport both sanitary sewage and stormwater.

Both combined and separate sewer systems experience high flow issues with the entry of additional water, which is commonly referred to as infiltration and inflow (I/I) (Ohlin Saletti, 2021; Chin, 2023). Infiltration water enters sewer systems gradually, through damaged pipe infrastructure. The most frequently observed infiltration phenomenon in sewer systems is the seepage of groundwater (Chin, 2023). However, there may also be seepage of rainwater or water that is a result of defects in another water supply system that is in close vicinity (Ohlin Saletti, 2021). Inflow, another concern in sewer systems, is the water that enters intentionally through various stormwater collection systems and unintentionally through illegal and unidentified connections (Ohlin Saletti et al., 2021; Sowby & Jones, 2022). This water can enter the system either instantly or gradually (Sowby & Jones, 2022).

Increased flow in sewer systems due to I/I can lead to various operational challenges. One significant issue occurs when high flow rates exceed the capacity of the sewer pipes, potentially resulting in the discharge of untreated water into nearby water bodies, known as sewer overflows (Yu et al., 2022; Tan et.al, 2019). These overflows often contain pollutants that contaminate water bodies and pose significant environmental

and human health risks (Hey et al., 2016). However, overflow events are also necessary because, during periods of high flow, they help reduce the risk of pipe infrastructure deterioration and vulnerability to flooding (Petrie, 2021).

2.2 Water at the WWTPs

The water in a WWTP undergoes various physical, chemical and biological processes in order to remove different pollutants of concern (Metcalf & Eddy, AECOM., 2014). The physical processes in wastewater treatment include screening, grit removal, sedimentation, and filtration. Screening can remove coarse, fine, and even micro-sized particles, depending on the type of screen used. Grit removal targets materials like sand and gravel. Sedimentation allows heavier particles to settle at the bottom of tanks by gravity, making them easier to remove. Filtration is then used to remove smaller suspended particles that did not settle during sedimentation, ensuring a clearer effluent. These separation processes, particularly sedimentation and filtration, are essential for the effectiveness of the subsequent biological and chemical treatment stages. The particles generated during these biological and chemical processes must be effectively removed to maintain the overall efficiency of the treatment system.

Chemical treatments are used to facilitate the removal of dissolved pollutants and to neutralise harmful substances (Metcalf & Eddy, AECOM., 2014). Examples of chemical treatment include chemical precipitation, oxidation, reduction, coagulation, and flocculation. Chemical disinfection methods such as chlorination are used to kill harmful pathogens present in the wastewater.

Biological treatment relies on microorganisms to break down organic matter and remove nutrients from the wastewater (Metcalf & Eddy, AECOM., 2014). Aerobic processes, such as activated sludge systems, use oxygen to support the growth of bacteria that consume organic pollutants. Anaerobic processes, such as anaerobic digestion, break down organic matter in the absence of oxygen.

An increase in flow to the WWTP can disrupt treatment processes (Giokas et al., 2002; Kowalik et al., 2015). As the flow rate increases, the concentration of pollutants decreases as a result of dilution effects. This was demonstrated in a study conducted by Mines Jr. et al. (2007) which investigated the performance of 24 WWTPs in the state of Georgia, USA. The study found that with an increase in flow, over 90% of the plants showed a decrease in the average monthly influent biochemical oxygen demand (BOD) concentrations, and more than 60% showed a decrease in the average monthly influent total suspended solids (TSS) concentrations. The analysis also revealed that in approximately 63% of the plants, the average monthly effluent BOD concentrations increased when the BOD mass flow rose with higher flow. Similarly, about half of the plants experienced an increase in average monthly effluent TSS concentrations as the TSS mass flow increased with the flow. This suggests that increased flow reduces the biological activity within the treatment systems, leading to higher effluent concentrations when mass flow rises due to increased flow.

An increase in flow can also lead to a decrease in influent temperature, which negatively affects biological activity (Metcalf & Eddy, AECOM., 2014). A study conducted at the Bekkelaget WWTP in Oslo, Norway by Plósz et al. (2009) demonstrated several impacts of increased flow rates on the plant's performance. As the flow rate to the plant increased, there was a noticeable decrease in the influent sewage temperature. This reduction in temperature was accompanied by a dilution effect, which lowered the

nitrogen concentrations in the influent. However, this dilution had a negative consequence: higher effluent nitrogen concentrations were observed, indicating that the biological treatment process was less effective at high flow rates. Additionally, the study found a negative correlation between temperature and nitrogen removal efficiency, suggesting that the lower temperatures associated with increased flows led to decreased biological activity and a reduced efficiency in nitrogen removal.

High flow also poses operational and disposal cost issues for WWTPs. A study conducted by Bugajski et al. (2021) at the sewage system and WWTP in Nowy Targ, Małopolska Province, Poland, for the years 2016-2019 found that the increase in flow due to additional precipitation water led to a 9.2% increase in operational costs, based on a normal operational cost of around €3,650,000 per year. Additionally, there was an 8.6% increase in environmental disposal costs, from a baseline of around €18,800 per year.

The European Union (EU) imposes strict regulations regarding discharge limits for treated wastewater (Council Directive 91/271/EEC). The Council Directive (91/271/EEC) sets specific standards for the treatment and discharge of urban wastewater within the European Union. Each country in EU may have its own set of rules and regulations that incorporate the EU directive (Naturvårdsverket, 2020). For example, in Sweden, Swedish EPA regulations (NFS 2016:6) governs discharge limit from WWTPs. The Council Directive (91/271/EEC) forms the base for it.

Key requirements according to the Council Directive (91/271/EEC) includes:

- **BOD₅ without nitrification:** Effluent BOD₅ levels must not exceed 25 mg/l O₂, with a minimum removal efficiency of 70-90%. For locations 1,500 meters above sea level, the removal efficiency limit is 40%.
- **Chemical Oxygen Demand (COD):** Effluent COD levels should be ≤ 125 mg/l O₂, with a minimum removal efficiency of 75%.
- **TSS:** Although optional, TSS should ideally not exceed 35 mg/l, with a 90% removal efficiency. In high-altitude areas serving 2,000-10,000 people, the optional TSS limit is 60 mg/l with a 70% removal efficiency.

In highly sensitive areas, following additional requirements apply for Total Phosphorus (P-tot) and Total Nitrogen (N) (Council Directive 91/271/EEC):

- **P-tot:** For WWTPs connected to 10,000-100,000 people, P-tot levels must be ≤ 2 mg/l P with at least 80% removal efficiency. For WWTPs serving more than 100,000 people, the limit is 1 mg/l P with the same efficiency requirement.
- **N:** WWTPs connected to 10,000-100,000 people should have N levels ≤ 15 mg/l N. For those serving over 100,000 people, the limit is 10 mg/l N, both with a removal efficiency of 70-80%.

Failure to comply with these limits could result legal actions and huge financial penalties for the non-compliant Member states (European Commission, 2010).

Ultimately, non-compliance with EU environmental directives can result in environmental harm, impacting ecosystems, water quality, public health, and biodiversity.

2.3 P in wastewater and its treatment

P in wastewater exists in various forms, including soluble forms such as orthophosphates, polyphosphates, and organic phosphates, as well as non-soluble forms. Effective removal of P can be achieved through both chemical and biological methods (Metcalf & Eddy, AECOM., 2014).

Chemical removal involves the use of metal salts, such as aluminium and iron salts, as well as calcium salts, to precipitate P (Metcalf & Eddy, AECOM., 2014). This chemical treatment can be applied during different stages of wastewater treatment, such as primary sedimentation, secondary biological treatment, or other secondary and tertiary treatments. Depending on the specific requirements, chemical treatment can be implemented at a single point or multiple points within the treatment processes. The choice of chemicals and the points of applications are determined based on the specific requirements of the treatment processes. Each approach offers distinct advantages and disadvantages.

P can also be removed from wastewater biologically through a process called Enhanced Biological Phosphorus Removal (EBPR) (Metcalf & Eddy, AECOM., 2014). This process uses microorganisms known as polyphosphate-accumulating organisms (PAOs), which have a unique ability to absorb and store polyphosphates. The EBPR process involves moving the wastewater through anaerobic and aerobic conditions, which aids in the P removal.

During the anaerobic phase, PAOs absorb volatile fatty acids, such as acetic and propionic acids, from the wastewater using the energy from the stored polyphosphates and store them as polyhydroxyalkanoates (PHAs) (Metcalf & Eddy, AECOM., 2014). During this process, PAOs release orthophosphates into the water. In the subsequent aerobic phase, the PAOs use the stored PHAs to fuel their metabolic needs in the presence of oxygen. Using the energy derived from this process, the PAOs uptake orthophosphates from the wastewater and store them as polyphosphates in their cells. The particulate P, present in the biomass, must be separated from the water. This is typically achieved through sedimentation and filtration processes. To optimise the process, some of the sludge is returned to the anaerobic tank from the sedimentation tank.

2.4 Predictive modelling in wastewater treatment

Predictive modelling is a crucial aspect of wastewater treatment analysis, enabling the prediction of treatment performance and optimisation of processes (Sharma et al., 2020; Bodaka et al., 2023). Among the various tools and techniques used for predictive modelling, regression analysis tools are some of the most commonly employed in different studies related to the wastewater treatment (Bodaka et al., 2023). One of the most common regression analysis tools used for predictive modelling is simple linear regression.

Simple linear regression is a statistical method used to model the relationship between a dependent variable (Y) and an independent variable (X) (Marill, 2004). The relationship is expressed as a straight line. The equation can be given as (Marill, 2004):

$$Y = a + bX$$

Where:

- Y is the dependent variable,
- X is the independent variable,
- a and b are the regression coefficients.

Accumulation is a concept used to understand how quantities build up over time. In wastewater modelling, it involves summing incremental values like flow rates or other parameters over a period to create a cumulative total. This cumulative total provides a comprehensive picture of the wastewater system's behaviour over time, with increasing flow, or other parameters.

By calculating accumulated values for specific limits, such as statistical limits like the median, 90th percentile, and maximum flows, we can segment the data into meaningful intervals.

For example, the median flow represents typical conditions, offering a baseline for understanding the system's normal behavior. The accumulated flow and mass flow at the median flow provide insights into the system's typical operating conditions. To determine the concentration at this limit, the accumulated mass flow is divided by the accumulated flow within the interval. The 90th percentile flow highlights higher flow conditions, which are critical for understanding the system's response during periods of increased flow, with its concentration calculated in a similar manner. The maximum flow represents the most extreme conditions, helping assess the system's resilience, with its concentration derived from the accumulated values up to the peak flow. This segmentation helps us understand typical, high, and extreme flow conditions and their impact on pollutant behaviour. By determining these concentrations, a model can be developed that states: for flow within the first limit, the concentration will be a specific amount; for flow above the first and within the second limit, the concentration will differ, and so on.

By analysing the accumulated flow and mass flow for these limits, we can also identify the total volume of water and pollutant load under various flow conditions. This analysis helps us understand the distribution of flows and pollutant loads, providing valuable information on their effects on the system.

In summary, accumulation in wastewater modelling provides a robust framework for analysing and predicting system behaviour under different scenarios, such as high flow conditions.

3 Methodology

In this chapter, the methodology used to evaluate the effects of high flows on the performance of five WWTPs in treating P is detailed. The primary focus is on developing predictive models for each WWTP to estimate effluent P concentrations under high flow conditions. These models will then be used to calculate effluent P mass flows, providing stakeholders with insights into current performance and identifying opportunities for optimisation.

3.1 Data collection

To conduct a thorough analysis of WWTPs, specific data were requested from the individuals in charge of each treatment facility through email communication. Additional data were sourced from publicly available reports on the internet. All the data were collected for the years 2021, 2022, and 2023. The Table 1 outlines the data requested and the reasons behind each request.

Table 1 Overview of data collected for analysis: Description and reasons for data collection.

Data Requested	Description	Reason
Flow into the WWTP	Measured in m ³ /s or similar units	To understand the volume of wastewater each plant handles. It helps to analyse the mass flows in and out of the WWTPs, which is crucial for understanding the overall efficiency and effectiveness of the treatment process. Additionally, this data allows for the comparison of flow rates between WWTPs.
Influent and effluent P concentration	Measured in mg/l or similar units	To observe the behaviour of influent and effluent concentrations for different WWTPs. This data allows for the calculation of both influent and effluent P mass flows, which is key for assessing the performance differences between WWTPs in removing P.

Population served	Number of individuals served by the WWTP	To know how many people are serviced by each WWTP and to standardise flow measurements to per capita (l/p, d). This data also helps to standardise mass flow calculations (g/p, d or per year).
Treatment steps	Details of each treatment step	Detailed information about the treatment steps provides insight into the operational processes of the WWTPs.
Treatment capacities	Capacities of biological, chemical, and physical treatment processes	The capacity of various treatment processes (biological, chemical, and physical) is necessary to create models based on different capacities of the WWTP.
Volume of each treatment basins	Volume of the physical space for each treatment process	It helps in understanding the physical footprint and space utilisation of the treatment processes.
Discharge limits of P	Concentration limits in mg/l and mass flow limits in tons/year	This data helps to analyse the regulatory compliance and performance of each WWTP in meeting P discharge standards.

3.2 Analysis

This section details the analytical methods and steps employed in this project. All analyses were conducted using Microsoft Excel, utilising its powerful data processing

and visualisation capabilities. Since, except for Rya WWTP, the data for the other WWTPs was in weekly average form, most of the analysis was done using weekly data.

3.2.1 Analysis of flow rates to each WWTP

Since this study examines the impact of high flow rates on the performance of each WWTP, it is essential to analyse the flow rates at these facilities. Understanding the flow behaviour at each plant will help us compare the flow rates across the WWTPs.

The WWTPs being studied are located in various areas of Sweden and differ in terms of flow rates, size, and treatment methods. To conduct an accurate analysis and comparison of the different plants, it is essential to standardise the flow rates (Bashide, 2015). Therefore, the flow data obtained from the WWTPs, originally measured in units such as cubic meters per second (m^3/s), cubic meters per hour (m^3/h), and cubic meters per day (m^3/d), were converted into litres per person per day (l/p, d). This conversion allows for the standardisation of flow measurements across each treatment plant.

When analysing flow data, it is important to consider the uncertainties related to the number of people using the sewer systems, especially the distinction between actual population and population equivalents (PE). The actual population is the number of people physically connected to and using the sewer system as recorded, while PE includes contributions from residential, industrial, commercial, and institutional sources (Bertanza & Boiocchi, 2022). These contributions are converted into an equivalent number of residential users based on their BOD₅ calculations. Using actual population data can be influenced by factors like seasonal variations and unregistered residents or visitors (Metcalf & Eddy, AECOM., 2014). Conversely, using population equivalents can complicate calculations due to varying wastewater outputs from non-residential sources.

For this thesis, actual population data for the year 2023 were collected. This approach, while straightforward, still faces challenges such as seasonal variations and data collection inaccuracies. However, it avoids the additional complexities associated with converting non-residential contributions into population equivalents.

The weekly flows to different treatment plants were then arranged in ascending order for three years separately to observe the trends and patterns between each WWTP. Statistical summaries, such as minimum, median, mean, percentile flows, and maximum flow were calculated to compare the flow data between different WWTPs for all three years combined.

3.2.2 Analysis of daily and weekly data

Considering that the effluent P concentration data for most WWTPs were available only as weekly averages, and only Rya WWTP had both daily and weekly data available for flow and effluent P concentrations, an analysis was conducted on both types of data for Rya WWTP by arranging it according to the dates for all three years combined. The purpose was to determine the impact of using different data types.

3.2.3 Analysis of influent and effluent concentrations across different WWTPs

This analysis examines the P concentrations in the influent and effluent of each WWTP. The weekly influent and effluent P concentrations were plotted against weekly flows, arranged in ascending order for all three years combined, with flows on the x-axis and concentrations on the y-axis. By analysing these concentrations, we can gain insights into how much P is entering and exiting each facility, allowing us to compare the performance of the WWTPs. This analysis also assesses how effectively each WWTP manages P levels to ensure they remain below specified regulatory limits, providing a clear picture of each plant's treatment efficiency. It is important to note that these limits are set for specific periods, such as quarterly or yearly, not individual days or weeks. Therefore, it can be acceptable for effluent concentrations to exceed limits for individual weeks as long as the overall period averages meet the regulatory standards.

3.2.4 Development and selection of best model for Rya WWTP

To analyse the effects of high flows on the performance of five WWTPs in treating P, specifically in terms of effluent P mass flows, the first step was to develop a predictive model for each WWTP to estimate effluent P concentrations based on actual flow rates and actual effluent P concentrations. These predicted concentrations were used to calculate effluent P mass flows. To select the optimal model, three methods were chosen to create models and evaluated using the data from Rya WWTP. The best of the three models was selected to develop models for the other WWTPs as well. This section will explain the three methods used to create the models for Rya WWTP.

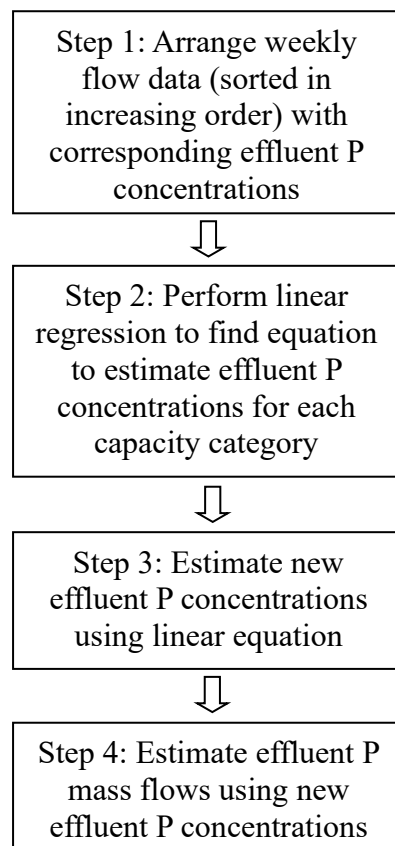


Figure 1 Methodology overview for model 1: Linear Regression Model.

In the first model, the linear regression model, weekly flows were arranged in increasing order for all three years combined, along with their corresponding effluent P concentrations and effluent P mass flows. For each capacity category, a linear equation was estimated to describe the relationship between effluent P concentrations and flows. The linear equation for each capacity category is given by:

$$P_i = a + b \times F_i \quad (1)$$

where:

- P_i is the effluent P concentration for flow F_i ,
- F_i is the flow in week i ,
- a and b are the coefficients determined through linear regression for each capacity category.

Using this linear equation, the new effluent P concentration (P_i) was found for each flow. The linear equation coefficients (a and b) changed based on which capacity interval the flow fell into.

Next, the effluent P mass flow was calculated for each weekly flow using the new effluent P concentration:

$$M_i = F_i \times P_i \quad (2)$$

where:

- M_i is the estimated effluent P mass for flow F_i ,
- P_i is the estimated effluent P concentration for flow F_i ,
- F_i is the flow in week i .

Finally, the estimated effluent P mass flows were compared to the actual effluent P mass flows using Coefficient of Determination (R^2) and Root Mean Square Error (RMSE) to determine the model's effectiveness.

An overview of the methodology for developing Model 1 is illustrated in Figure 1, providing a visual summary of the steps involved.

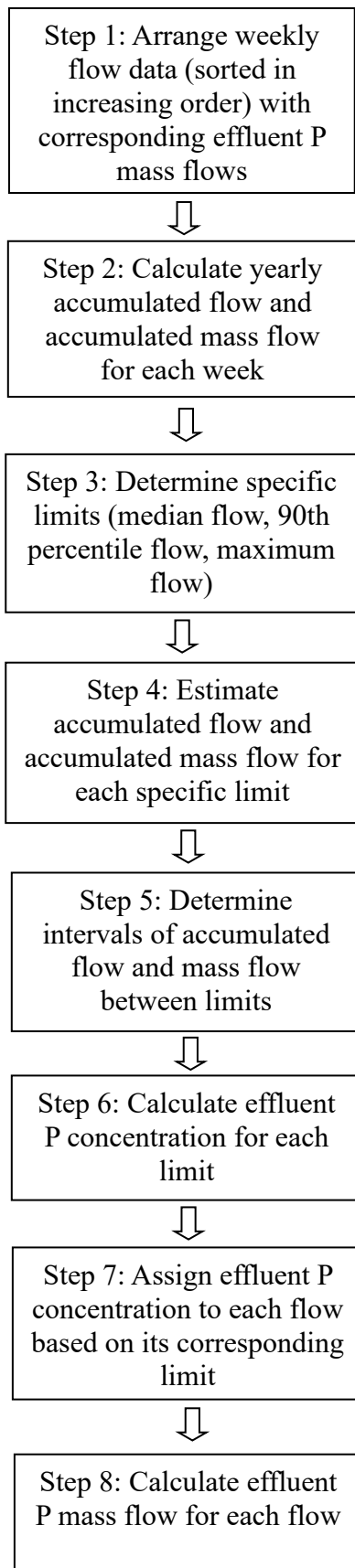


Figure 2 Methodology overview for model 2: Limit-based Accumulation Model.

In the second model, the limit-based accumulation model, weekly flows were arranged in increasing order for all three years combined, along with their corresponding effluent P concentrations and effluent P mass flows. The yearly accumulated flow and accumulated effluent P mass flow were calculated for each week:

$$F_{A,i} = \sum_{k=1}^i \text{Weekly Flow}_k \quad (3)$$

where:

- $F_{A,i}$ is the total flow accumulated up to week i . It is calculated by summing the weekly flow values from the beginning up to week i .
- Weekly Flow_k is the flow in week k .

$$M_{A,i} = \sum_{k=1}^i \text{Weekly Effluent P Mass Flow}_k \quad (4)$$

where:

- $M_{A,i}$ is the total effluent P mass flow accumulated up to week i . It is calculated by summing the weekly effluent P mass flow values from the beginning up to week i .
- $\text{Weekly Effluent P Mass Flow}_k$ is the effluent P mass flow in week k .

For three specific flow limits—median flow, 90th percentile flow, and maximum flow, the accumulated flow and accumulated mass flow were determined:

$$F_{A,L} = \text{Accumulated Flow up to Limit } L_i \quad (5)$$

where:

- $F_{A,L}$ is the total flow accumulated up to a specific flow limit L_i . This value is determined from the previously calculated accumulated flow data.

$$M_{A,L} = \text{Accumulated Mass Flow up to Limit } L_i \quad (6)$$

where:

- $M_{A,L}$ is the total effluent P mass flow accumulated up to a specific flow limit L_i . This value is determined from the previously calculated accumulated mass flow data.

Next, the interval of accumulated flow between each limit was calculated, and similarly, the interval of accumulated effluent P mass flow between each limit was also calculated. The effluent P concentration for each limit was then calculated:

$$P_i = \Delta M_{A,L} / \Delta F_{A,L} \quad (7)$$

where:

- P_i is the effluent P concentration for the interval between two consecutive flow limits L_{i-1} and L_i .
- $\Delta M_{A,L}$ is the change in accumulated effluent P mass flow between flow limits L_{i-1} and L_i .
- $\Delta F_{A,L}$ is the change in accumulated flow between limits L_{i-1} and L_i .

Based on these concentrations, the effluent P concentration was assigned to each flow depending on which limit interval it fell into:

- For flows $F_i \leq F_{Median}$, use P_{median}
- For flows $F_{Median} < F_i \leq F_{90\%}$, use $P_{90\%}$
- For flows $F_{90\%} < F_i \leq F_{Max}$, use P_{Max}

Then, the effluent P mass flow was calculated for each weekly flow using the assigned effluent P concentrations:

$$M_i = P_i \times F_i \quad (8)$$

where:

- M_i is the estimated effluent P mass flow for flow F_i ,
- P_i is the assigned effluent P concentration for flow F_i ,
- F_i is the flow in week i .

Finally, the estimated effluent P mass flow for each flow was compared to the actual effluent P mass flow using R^2 and RMSE to determine the model's effectiveness.

An overview of the methodology for developing Model 2 is illustrated in Figure 2, providing a visual summary of the steps involved.

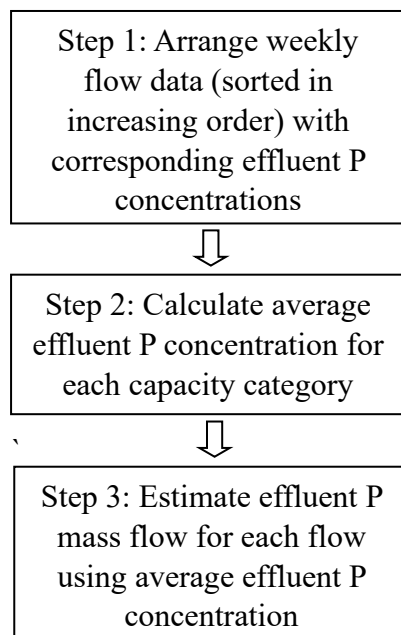


Figure 3 Methodology overview for model 3: Average Concentration Model.

In the third model, the average concentration model, the weekly flows were arranged in increasing order for all three years combined, with corresponding effluent P concentrations and effluent P mass flows, categorised according to Rya WWTP's hydraulic capacity. The average effluent P concentration for each capacity was then calculated:

$$P_{avg} = \sum P_{eff} / n \quad (9)$$

where:

- P_{avg} is the average effluent concentration,
- P_{eff} is the effluent P concentration for flow within the capacity category for each week i ,
- n is the number of flows.

The effluent P mass flow for each weekly flow was then estimated using the average effluent P concentration for each capacity, and the average concentration changed based on which capacity interval the flow fell into:

$$M_i = F_i \times P_{avg} \quad (10)$$

where:

- M_i is the estimated effluent P mass flow for flow F_i ,
- F_i is the flow in week i ,
- P_{avg} is the assigned effluent P concentration for each capacity.

Finally, this estimated effluent P mass flows was compared to the actual effluent P mass flows using R^2 and RMSE to determine the model's effectiveness.

An overview of the methodology for developing Model 3 is illustrated in Figure 3, providing a visual summary of the steps involved.

3.2.5 Application of the chosen model to other WWTPs.

Using the methodology for the chosen best model for Rya WWTP, models for the other treatment plants were developed in the same manner.

3.2.6 Analysis of weekly influent P mass flows and calculation of the average weekly influent P mass flow for different WWTPs.

To compare the effects of high flows on P treatment among the five WWTPs, the next step was to use the flow data from all the municipalities, arranged in increasing order for all three years combined, and apply it to the developed model for each WWTP.

When the flow limit of each model was exceeded, any excess flow was assumed to bypass the treatment steps. For this bypassed flow, the effluent concentration was assumed to be equal to the influent concentration. While it is generally assumed that the influent P mass flows remain the same across all flow rates, this may not be correct in reality. Therefore, the first step was to analyse the influent P mass flows and

determine the average influent P mass flow for each WWTP, so that it can be used to estimate the effluent P mass flows for excess flows bypassing the capacity of the WWTP.

The weekly influent P mass flow for each weekly flow was then arranged in increasing flow order for all three years combined for each WWTP. Then, a linear equation was derived to represent the relationship between influent P mass flows and flows. The linear equation was given by:

$$M_{inf} = a + b \times F_i \quad (11)$$

where:

- M_{inf} is the influent P mass flow for flow F_i ,
- F_i is the flow for week i ,
- a and b are the coefficients determined through linear regression.

Using this linear equation, new effluent P mass flows were calculated and the absolute differences between the actual and predicted influent P mass flows were calculated. The absolute difference is the difference between the actual and predicted values, indicating how far off the predictions are from the actual values without considering the direction of the error.

Descriptive statistics were then calculated in excel for these absolute differences, including the median, and standard deviation. Given that the mean averages out all the points including the outliers, one standard deviation from the median was used to determine the threshold for marking “Close” and “Far” values. Combining the median with the standard deviation allows us to establish a threshold that reflects both the central tendency and the variability of the absolute differences. Rows where the absolute difference was within this threshold were marked as “Close,” while rows where the difference exceeded this threshold were marked as “Far”.

The actual effluent P mass flow data were then sorted by the absolute differences to easily identify the “Close” and “Far” values. For the “Close” range, the average influent P mass flow was calculated:

$$M_{inf,avg} = \sum M_{inf,close} / n_{close} \quad (12)$$

where:

- $M_{inf,avg}$ is the calculated average influent P mass flow,
- $M_{inf,close}$ is the sum of the actual influent P mass flows marked as “Close”,
- n_{close} is the number of influent P mass flows marked as “Close”.

3.2.7 Utilisation of flow data from each WWTP into the developed model for each WWTP.

As mentioned in Section 3.2.6, the flow data from all the municipalities, arranged in increasing order for the combined three-year period, was applied to the developed

method for each WWTP. The effluent P mass flow was then calculated for each weekly flow for each WWTP.

When the flow limit of each model is exceeded, the influent P concentration is calculated by dividing the previously calculated average influent P mass flow for each WWTP by the corresponding total flow:

$$P_{inf} = M_{inf,avg}/F \quad (13)$$

where:

- P_{inf} is the calculated influent P concentration for each total flow F (flow up to limit + excess flow),
- $M_{inf,avg}$ is the previously calculated average influent P mass flow for each WWTP,
- F is the total flow.

Then, the extra effluent P mass flow is calculated by multiplying the excess flow by the calculated influent P concentration:

$$M_{eff,extra} = F_{excess} \times P_{inf} \quad (14)$$

where:

- $M_{eff,extra}$ is the calculated extra effluent P mass flow,
- F_{excess} is the excess flow,
- P_{inf} is the influent P concentration for each total flow F

3.2.8 Analysis of effluent P mass flow changes when catchments and WWTPs are swapped across municipalities.

In order to identify opportunities for process optimisation in P treatment at the five WWTPs, the difference in total effluent P mass flow for each WWTP was analysed under two different scenarios.

In the first scenario, the effects of swapping catchments between municipalities were examined. The effluent P mass flow per person per year was calculated for each WWTP when the catchment was swapped between municipalities. By comparing the actual effluent P mass flow per person per year with the values calculated when catchments were swapped, the impact on each WWTP's performance was evaluated.

In the second scenario, the effects of swapping WWTPs across municipalities while keeping their own catchments were analysed. The effluent P mass flow per person per year was calculated for each WWTP when it was relocated to different municipalities. By comparing the actual effluent P mass flow per person per year with the values calculated when WWTPs were swapped, the impact on each WWTP's performance was evaluated.

4 Description of WWTPs

In this section, a detailed description of each WWTP will be provided. This includes an overview of the treatment processes used, the methods employed to remove P from the wastewater, the number of people connected, the average sewage flow to each WWTP, the volume of treatment basins, the capacity of treatment steps, and any unique features or challenges specific to each plant. Additionally, this section will cover the regulatory limits for P discharge that each plant must adhere to.

Figure 4 shows the locations of five WWTPs in Google Maps.

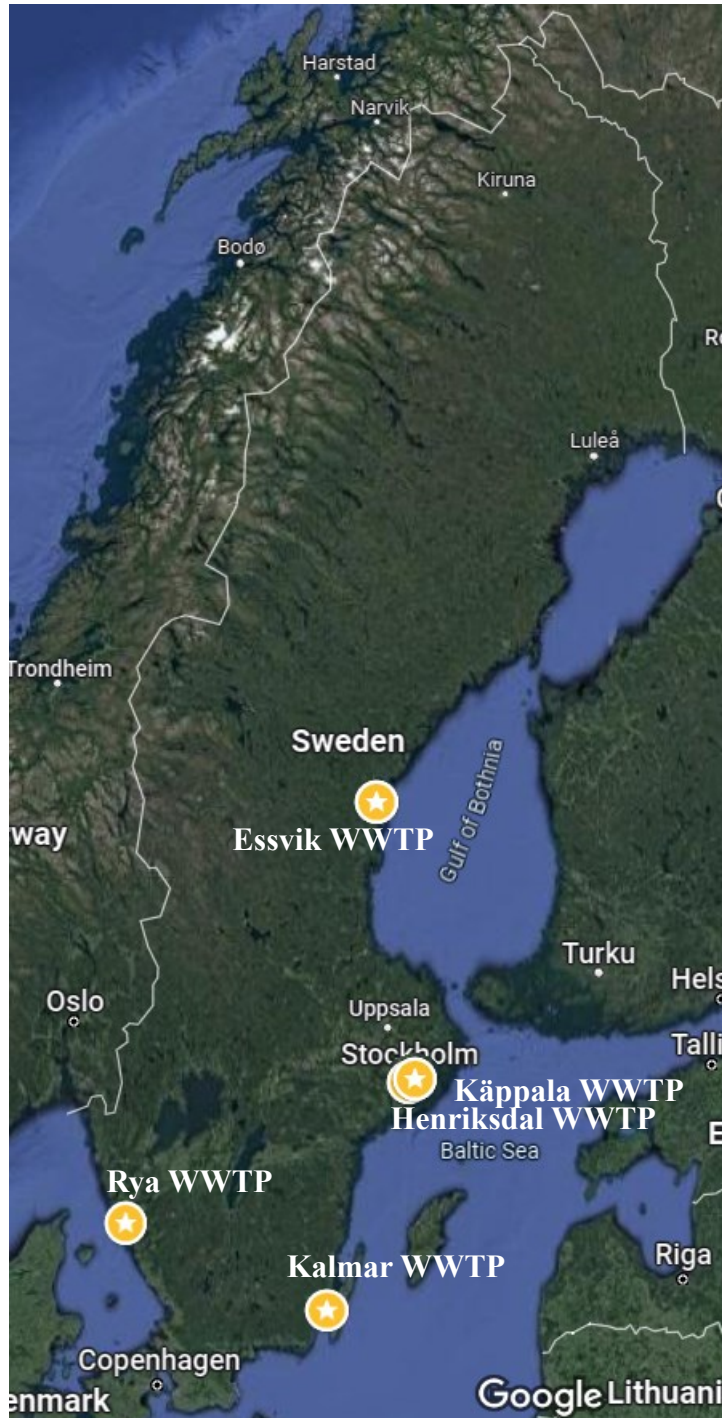


Figure 4 Map view highlighting the WWTPs under study (Google Maps, n.d.).

4.1 Rya WWTP, Gryaab AB

Rya WWTP is located in Gothenburg, Västra Götaland and is responsible for treating wastewater for over 820,000 residents in the Gothenburg Metropolitan Area (Videbris, 2024). Wastewater is delivered to the plant through a gravity-fed tunnel system (Molander, 2015).

The mechanical treatment at Rya WWTP involves several stages: coarse screening, sand trap, fine screening, and pre-sedimentation basins, also referred to as primary settlers (Videbris, 2024). P is removed chemically after pre-sedimentation, precipitating as phosphate, which is then captured along with the sludge in the activated sludge basin. When flow rates are high and the biological treatment capacity is exceeded, P is removed through direct precipitation using additional chemicals in the pre-sedimentation tank, with the excess water bypassing the biological treatment stages and released into the Göta älv after the direct precipitation process.

For biological treatment, the Rya WWTP employs activated sludge basins, nitrifying trickling filters, and moving bed biofilm reactors (MBBR) for both post-nitrification and denitrification (Videbris, 2024). Post-sedimentation basins are also an integral part of the process. During this stage, water from the primary settlers is mixed with water from the trickling filter and led to the activated sludge basins, which feature both anoxic and aerobic zones.

After treatment in the activated sludge basins, the water moves to the post-sedimentation basins, where the sludge is separated from the treated water (Videbris, 2024). This step is essential for removing particulate P from the water. Most of the sludge is recirculated back to the activated sludge tank. Some of the water from the post-sedimentation basins is directed to the nitrifying trickling filters, some to the nitrifying MBBRs, and some directly to the disc filters. The flow split varies mainly depending on the inflow to the WWTP.

Water from the trickling filters is recirculated to the activated sludge system, whereas water from the nitrifying MBBRs usually proceeds to the post-denitrification MBBRs and then to the disc filters to remove suspended particles (Videbris, 2024). Passing through the disc filters is a crucial step for ensuring that particulate P and other fine particles are effectively removed, enhancing the quality of the discharged water. The sludge collected during the treatment process undergoes further treatment.

Table 2 presents the specific volumes of each basins involved in the wastewater treatment process at Rya WWTP, detailing the capacity of each treatment step within the facility.

Table 2 Volumes of treatment basins at the Rya WWTP

Treatment steps/basins	Volume
	m ³
Primary settlers	22 670
Activate sludge basins	50 990
Nitrifying trickling filters	33 000
Post-nitrification MBBRs	10 800
Post-denitrification MBBRs	11 000
Post-sedimentation basins	72 200

4.2 Essvik WWTP, MittSverige Vatten och Avfall AB

Essvik WWTP is located in the Essvik area in Sundsvall Municipality, Västernorrland County. The WWTP treats wastewater from around 11,200 people in the Njurunda, Fläsian, Stångom, Åmon, and Juniskär areas of Sundsvall. It also treats water from some nearby industries connected to it (M. Tuveesson, personal communication, August 8, 2024).

The mechanical treatment consists of drum screens (M. Tuveesson, personal communication, August 8, 2024). After the mechanical treatment, chemicals are added to the water, which is then channelled into flocculation chambers. From there, it flows into pre-sedimentation basins, where solids are allowed to settle out. This step is crucial for ensuring that particulate P are effectively removed from the water. Following this, the water moves to the activated sludge basins for biological treatment. The Essvik WWTP is designed to remove only P-tot and BOD from the wastewater, and it does not remove N.

After biological treatment, the water is directed to a post-sedimentation tank where sludge separation occurs (M. Tuveesson, personal communication, August 8, 2024). This step is crucial for ensuring that particulate P and other fine particles are effectively removed from the water. To sustain the continuity of the biological treatment process, a considerable portion of the separated sludge is recirculated back to the activated sludge basins. The treated water is then discharged into the Ljungan River.

In certain situations, the water can bypass the main mechanical and biological treatment stages (M. Tuveesson, personal communication, August 8, 2024). The water can be diverted directly through bar screens at the beginning of the process. The water can also be bypassed after undergoing mechanical treatment. Additionally, sludge treatment processes are also conducted at the Essvik WWTP.

Table 3 presents the specific volumes of each basin involved in the wastewater treatment process at Essvik WWTP, detailing the capacity of each treatment step within the facility.

Table 3 Volumes of treatment basins at the Essvik WWTP

Treatment steps/basins	Volume
	m ³
Pre-sedimentation basins	1340
Activated sludge basins/Aeration basins	950
Post-sedimentation basins/bio-sedimentation basins	1500

4.3 Henriksdal WWTP, Stockholm Vatten och Avfall AB

Henriksdal WWTP is located in Stockholm Municipality, near Nacka Municipality in Stockholm County (D. Fujii, personal communication, May 27, 2024). The plant is responsible for treating wastewater from over 884,000 residents in Stockholm and several surrounding municipalities (Eriksson, 2023).

Wastewater enters Henriksdal WWTP through the Sickla and Henriksdal facilities, where it first undergoes mechanical treatment involving screens and sand traps (D. Fujii, personal communication, May 27, 2024). Following this, a precipitation chemical is added at both facilities to remove P from the water. At the Sickla facility, the water also undergoes pre-aeration before being combined with water from both facilities and directed to the pre-sedimentation tanks, where primary sludge, including P, is removed.

The water then flows into activated sludge basins for biological treatment, where additional P is removed, although in smaller amounts (D. Fujii, personal communication, May 27, 2024). The water is then directed to post-sedimentation basins to separate sludge from the water, with a portion of the sludge recirculated back to the activated sludge basins. Afterward, another dose of precipitation chemical is added, and the water passes through a sand filter to remove any remaining small particles, a crucial step in eliminating the remaining particulate P.

Some of the water from the activated sludge basins is also directed to membrane filters immediately after adding the precipitation chemical, where the sludge is separated from the water (D. Fujii, personal communication, May 27, 2024). Finally, the treated, clean water is released into the Saltsjön. Additionally, sludge treatment processes are also conducted at the Henriksdal WWTP.

Table 4 presents the specific volumes of each basin involved in the wastewater treatment process at Henriksdal WWTP, detailing the capacity of each treatment step within the facility.

Table 4 Volumes of treatment basins at the Henriksdal WWTP

Treatment steps/basins	Volume
	m ³
Pre-sediment basins	33 000
Activate sludge basins	204 000
Post-sedimentation basins	58 000

4.4 Kalmar WWTP, Kalmar Vatten AB

Kalmar WWTP is located in Vesholmarna, Kalmar Municipality, Kalmar County, and treats wastewater from approximately 64,600 people (Q. Zhao personal communication, April 18, 2024).

The wastewater first undergoes mechanical treatment, which includes passing through screens, sand traps, and a grease separator (Q. Zhao personal communication, August 14, 2024). The water is then directed to aeration basins, where chemicals are added to remove phosphate P. Following this, 70% of the water is directed to pre-sedimentation basins, while the remaining portion goes to sequential bioreactors for biological treatment. Additional chemicals are added before the water enters the pre-sedimentation basins to facilitate sludge separation.

Next, the water is sent to activated sludge basins for further biological treatment, where some P is also removed (Q. Zhao personal communication, August 14, 2024). The water then flows into bio-sedimentation basins, where sludge is separated, and most of it is recirculated back to the activated sludge basins. After this, the water from both the bio-sedimentation basins and sequential bioreactors is directed to post-sedimentation basins, where chemicals are added to ensure complete sludge separation before the water is released into Kalmarsund. These separation processes are crucial for removing particulate P from the water. Additionally, sludge treatment processes are also conducted at the Kalmar WWTP.

Kalmar WWTP has an overall treatment capacity of only 340 l/p, d (Q. Zhao personal communication, August 14, 2024). Beyond this capacity, the extra flow bypasses the biological treatment steps but still go through all other treatment processes, leading to a decline in overall treatment efficiency.

Table 5 presents the specific volumes of each basin involved in the wastewater treatment process at Kalmar WWTP, detailing the capacity of each treatment step within the facility.

Table 5 Volumes of treatment basins at the Kalmar WWTP

Treatment steps/basins	Volume
	m ³
Pre-sedimentation basins	3000
Activate sludge basins	3960
Bio-sedimentation basins	3460
Sequential bioreactors	7100
Post-sedimentation basins	5310

4.5 Käppala WWTP, Käppalaförbundet

Käppala WWTP, located in Lidingö Municipality, Stockholm County, treats wastewater from approximately 728,000 people (J. Grundestam, personal communication, April 19, 2024).

The treatment process begins with mechanical treatment, which includes sieve grates, a pre-aeration tank, and sand traps (J. Grundestam, personal communication, April 19, 2024). After this, the water is directed to the pre-sedimentation tanks for primary sludge extraction. The water then flows into activated sludge basins for biological treatment, where P is removed biologically. Additional P removal is achieved in the aeration basins through the use of chemicals.

Next, the water is directed to post-sedimentation basins to separate sludge from the water (J. Grundestam, personal communication, April 19, 2024). After this, the water passes through sand filters before being released into the Saltsjön. The post-sedimentation and sand filtration processes are crucial for removing particulate P left in the water. Additionally, sludge treatment processes are also conducted at Käppala WWTP.

During periods of high flow, when the flow exceeds 5 m³/s, excess water is bypassed before reaching the sand traps and undergoes a process known as Actiflo[®] (J. Grundestam, personal communication, April 19, 2024). Actiflo[®] is a chemical treatment process combined with sedimentation, consisting of a coagulation basin, injection tank, maturation basin, and sedimentation basin. This process is particularly effective in removing P during high flow scenarios, and it also helps to remove organic pollutants and suspended solids (SS). The treated water is then released into the Saltsjön.

Table 6 presents the specific volumes of each basin involved in the wastewater treatment process at Käppala WWTP, detailing the capacity of each treatment step within the facility.

Table 6 Volumes of treatment basins at the Käppala WWTP

Treatment steps/basins	Volume
	m ³
Pre-sedimentation basins	24 450
Activate sludge basins	143 100
Post-sedimentation basins	65 120

4.6 Key data for analysis and model development for five WWTPs

This section provides an overview of the treatment processes employed, the number of people served, the average sewage flow to the WWTPs, the capacity of treatment steps at each WWTP, and the regulatory limits for P discharge that each plant must adhere to. This information, collected from each company, is essential for the analysis and offers a comprehensive overview of the WWTPs. Additionally, the process schematic for each WWTP is shown in Appendix A.

Table 7 The specific processes involved in each WWTP's treatment operations

WWTP	Process involved
Rya	Mechanical treatment (coarse bar screen, sand trap, fine bar screen), pre-sedimentation/primary settlers (direct precipitation), activate sludge process with denitrification and chemical treatment, nitrification (trickling filter), post-sedimentation, post-nitrification (MBBR), post-denitrification (MBBR) and disc filtering.
Essvik	Mechanical treatment (drum screens, flocculation basin), pre-sedimentation with chemical treatment, activated sludge process (BOD-removal), and post-sedimentation.

Henriksdal	Mechanical treatment (screens, sand traps, pre-aeration), pre-sedimentation with chemical precipitation, activated sludge process, post-sedimentation, membrane filtering and sand filtering.
Kalmar	Mechanical treatment (screens, sand trap, grease separator, pre-aeration), pre-sedimentation, activated sludge process with pre-denitrification, bio-sedimentation and post-sedimentation with chemical precipitation.
Käppala	Mechanical treatment (sieve grates, pre-aeration, sand trap), pre-sedimentation, activated sludge process with chemical treatment, post-sedimentation, sand filtering, and Actiflo (chemical treatment with sedimentation).

Table 7 provides an overview of the treatment steps involved in the five WWTPs.

Table 8 Summary of data collected from WWTPs required for model development.

WWTP	Number of people	Average sewage flow	First hydraulic capacity	Second hydraulic capacity	Third hydraulic capacity
		l/p, d	l/p, d	l/p, d	l/p, d
Rya	824 490	175	891 (Biological treatment)	1257 (Chemical)	1677 (Mechanical)
Essvik	11 179	200*	1847 (Pre-sedimentation with chemical precipitation + biological treatment)	4294 (Mechanical treatment-Sieves)	-
Henriksdal	883 613	198**	783 (Biological treatment)	978 (Tertiary treatment)	-
Kalmar	64 650	186	340 (Biological treatment)	-	-
Käppala	728 405	137	593 (Biological treatment+ sand filters) ***	712 (Primary clarifiers + Sand trappers)	1186 (Mechanical treatment-Sieves)

* - The average sewage flow was assumed to be 200 l/p, d due to the lack of available data (Hey et al., 2016) .

** - The average sewage flow value was taken from Molander (2015).

*** - When the flow exceeded 593 l/p, d, Käppala WWTP implemented an additional chemical treatment step known as Actiflo[®], which has a capacity of 356 l/p, d.

Table 8 presents the data collected from the WWTP representatives, which is fundamental for analysis and model development. The table includes the number of people connected to each WWTP, and the flow capacities of the WWTPs, providing essential information that forms the basis for developing the model. The table also includes the average sewage flow to each WWTP.

Rya, Henriksdal, and Käppala WWTPs had a high number of people connected to their WWTPs in 2023, with Henriksdal WWTP having the highest number. Meanwhile, Kalmar WWTP had significantly fewer people connected to its WWTP compared to these three, and Essvik WWTP had the fewest connections among all the WWTPs.

When considering capacity per person per day, Essvik WWTP has the highest capacity, followed by Rya WWTP with the second highest, then Henriksdal WWTP. Käppala WWTP also has a good capacity. As mentioned in Section 4.4, Käppala WWTP included an additional chemical treatment step for extra flow, known as Actiflo®. Kalmar WWTP has a very low capacity and was the lowest among all the WWTPs.

Table 9 Discharge limits for WWTPs: Concentration in mg/l.

WWTP	P-tot	BOD	N tot	COD
	mg/l	mg/l	mg/l	mg/l
Rya	0.3* (Yearly average)	10* (Yearly average)	8* (Yearly average)	-
Essvik	0.5 (Quarterly average)	12 (Quarterly average)	-	70 (Quarterly average)
Henriksdal	0.3 (Until 2029) 0.2 (From 2029) (Yearly average)	8 (Until 2029) 5 (From 2029) (Yearly average)	10 (Until 2029) 6 (From 2029) (Yearly average)	-
Kalmar	0.3 (Yearly average)	10 (Yearly average)	15 (Yearly average)	-
Käppala	0.3 (Yearly average)	8 (Yearly average)	10 (Yearly average)	-

*- Rya WWTP has an additional regulatory limit for the months of May to August, known as the Tertiary 2 limit, which is the same as the annual average limit.

Table 10 Discharge limits for WWTPs: Mass Flow in tons/year.

WWTP	P-tot	BOD	N tot
	Tons/year	Tons/year	Tons/year
Rya	40	1300	1000
Essvik	1.5	46	-
Henriksdal	35 (Until 2029) 27 (From 2029)	850	1550
Kalmar	-	-	-
Käppala	-	-	-

Table 9 shows the regulatory limits for effluent concentration, and Table 10 shows the regulatory limits for mass flow for the specified time periods, specific to each WWTP. These tables are key to understanding the compliance requirements that each WWTP must adhere to.

For effluent concentrations, Rya WWTP has a yearly average regulatory limit and a tertiary limit for the months of May to August, which is the same as the yearly average. Essvik WWTP has a quarterly average regulatory limit but does not have a limit for N-tot; instead, it has a limit for COD. All other WWTPs have a yearly average regulatory limit. Starting in 2029, Henriksdal WWTP will have a more stringent limit than its current value.

Only Rya, Essvik, and Henriksdal WWTPs have regulatory limits for effluent mass flows as of 2024, and Essvik WWTP does not have a limit for N-tot.

5 Results and discussion

This chapter presents the results of the analyses conducted and provides an in-depth discussion of the findings.

5.1 Analysis of flow rate to each WWTP

This section presents the statistical data for the weekly flows for all three years combined, as well as the flow patterns for each of the three years for each WWTP observed over the study period.

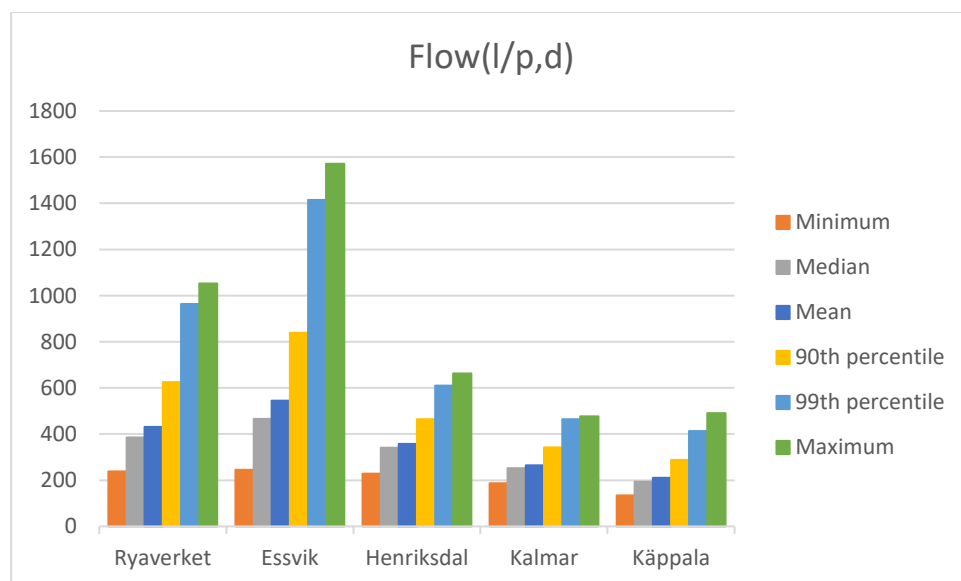


Figure 5 Weekly average flow statistics for WWTPs combined over all three years.

Table 11 Weekly average flow statistics for WWTPs combined over all three years.

Flow to WWTPs					
Statistic	Rya	Essvik	Henriksdal	Kalmar	Käppala
	l/p, d	l/p, d	l/p, d	l/p, d	l/p, d
Minimum	238	246	228	187	134
Median	385	466	340	252	194
Mean	431	545	358	265	211
90 th percentile	626	839	464	343	288
99 th percentile	964	1414	610	465	413
Maximum	1053	1572	663	477	491

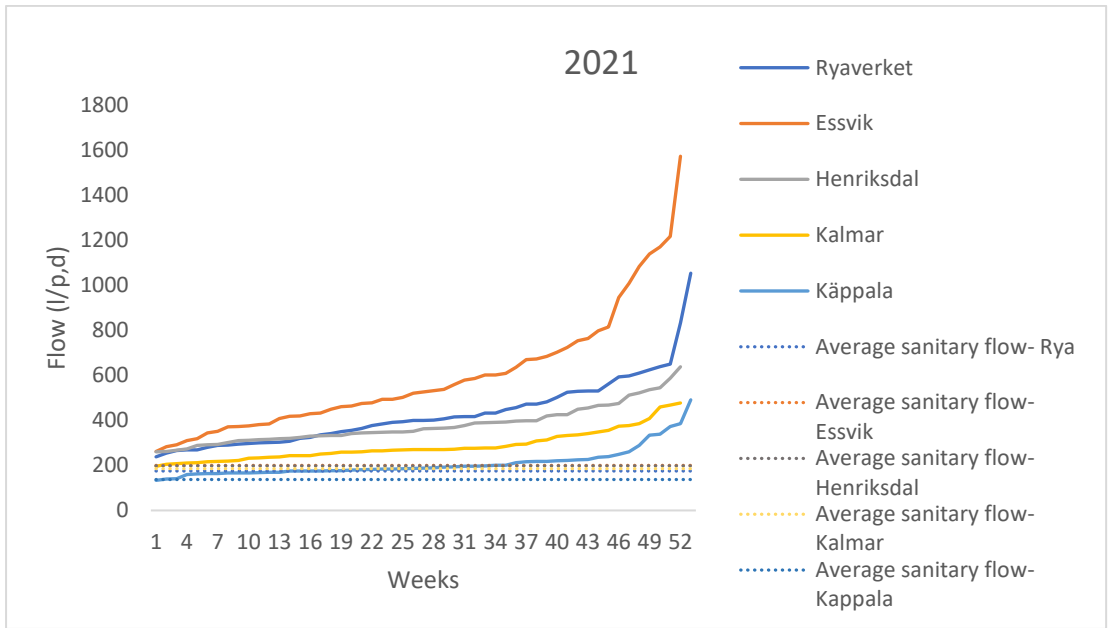


Figure 6 Weekly flow to five WWTPs in increasing order for the year 2021.

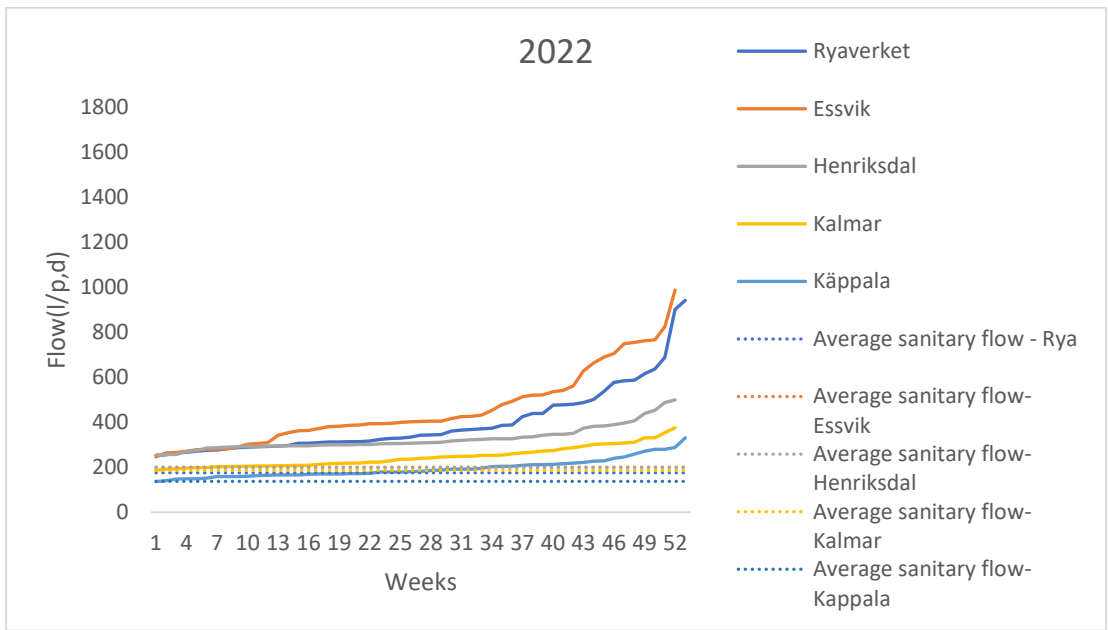


Figure 7 Weekly flow to five WWTPs in increasing order for the year 2022.

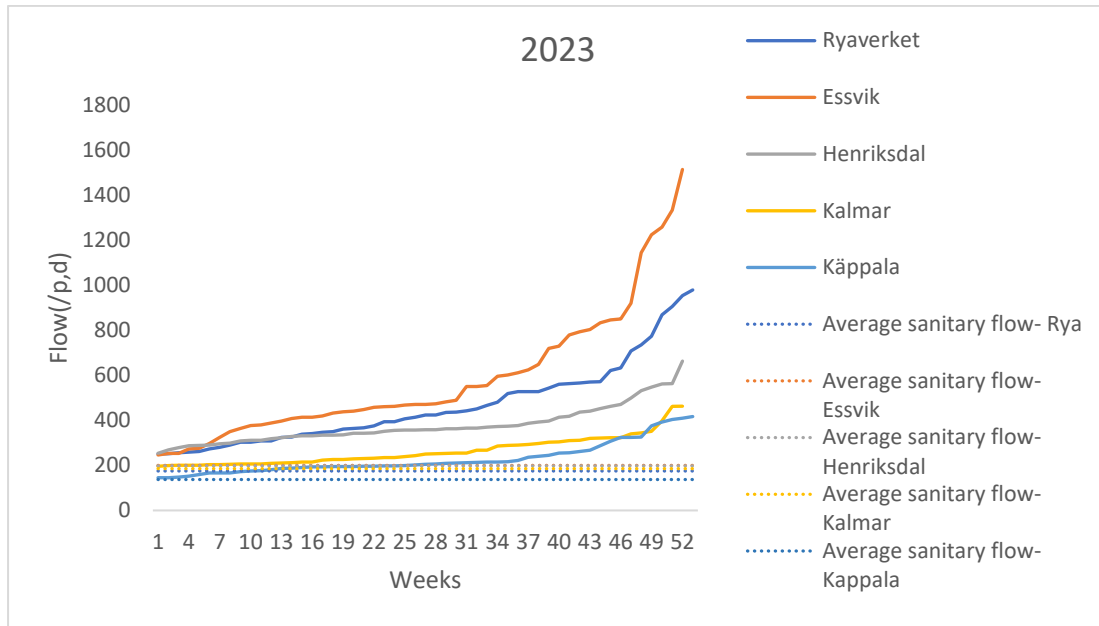


Figure 8 Weekly flow to five WWTPs in increasing order for the year 2023.

Figures 6, 7 and 8 show that the Essvik WWTP consistently had the highest inflow among all the treatment plants over the three-year period, with Rya WWTP following. The years 2021 and 2023 had the most weeks with high flow, and 2021 had the week with the highest flow. These observations are further supported by the statistical data in Figure 5 and Table 11, which shows that Essvik WWTP exhibited the highest minimum, mean, median, 90th percentile, 99th percentile, and maximum values. This indicates not only high overall flow but also significant variability in flow rates throughout the study period, as evidenced by the wide range between the minimum and maximum values.

For Rya WWTP, Figures 6, 7 and 8 show that 2023 had the most weeks with high flow, followed by 2021, and then 2022. Notably, 2021 had the week with the highest flow. Rya WWTP had the second-highest values for minimum, mean, median, 90th percentile, 99th percentile value and maximum flow (Figure 5, Table 11).

Henriksdal WWTP had the third-highest inflow, with its minimum, mean, median, 90th percentile, 99th percentile, and maximum values followed by Kalmar WWTP (Figure 5, Table 11). In 2023, Henriksdal WWTP had the most weeks with high flow, but 2021 had the week with the highest flow (Figure 6, 7 and 8).

Kalmar WWTP experienced the most weeks with high flow in 2021, followed by 2023 and 2022, with 2021 also having the highest weekly flow (Figure 6, 7 and 8).

Käppala WWTP had the lowest inflow among the five WWTPs. In 2023, Käppala WWTP had the most weeks with high flow, yet 2021 saw the week with the highest flow (Figure 6, 7 and 8). Käppala WWTP also had the lowest minimum, mean, median, 90th percentile, and 99th percentile values among the five WWTPs (Figure 5, Table 11), indicating lower overall flow rates with minimal variability compared to the other treatment plants.

Additionally, Figures 6, 7, and 8 show that all five treatment plants experienced some degree of infiltration and inflow each week throughout the three-year period.

In summary, the statistical data from Figure 5 and Table 11 highlights the distinct flow characteristics of each WWTP, with Essvik WWTP showing the highest flow and greatest variability, followed by Rya and Henriksdal WWTPs with high and consistent flows. In contrast, Kalmar and Käppala WWTPs exhibit low flows with less variability.

5.2 Analysis of daily and weekly flows and effluent P concentrations.

This section presents the results of the analysis conducted on both daily and weekly flow and effluent P concentration data from Rya WWTP.

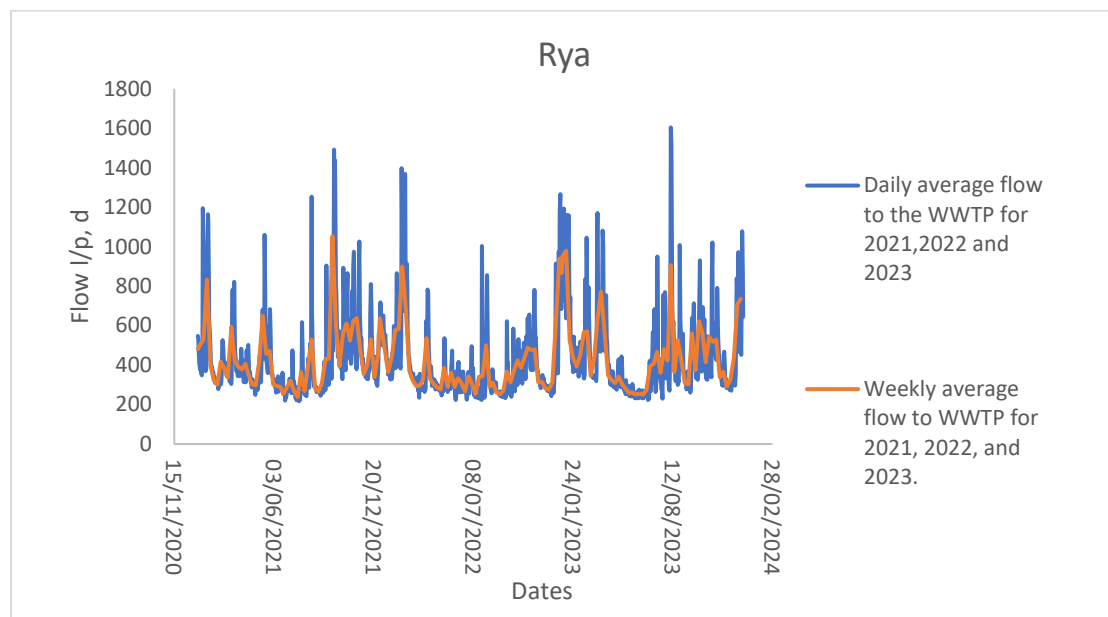


Figure 9 Daily and weekly flows to Rya WWTP arranged in the date order for the years 2021, 2022, and 2023.

Table 12 Median, 90th percentile and 99th percentile for daily and weekly flow to Rya WWTP for years 2021, 2022, and 2023.

Flow to Rya WWTP			
l/p, d			
	Median	90 th percentile	99 th percentile
Daily	345	667	1160
Weekly	385	626	964

The daily data shows variations in flow to the WWTP on a daily basis, whereas the weekly data averages these variations, smoothing them out to provide weekly averages. As shown in Figure 9 and Table 12, the weekly flow data exhibits higher median value than the daily flow data, indicating that it is smoothing out the lower flow values than high flow values. The 90th percentile and 99th percentile are both greater for daily data,

indicating that higher flows are more noticeable in daily data compared to weekly data, where they are averaged out. Averaging out leads to the underestimation of real peak flows.

From this, we can conclude that analysing data on a weekly basis can lead to the averaging out of important high flow rates and the reduction of daily fluctuations. This may lead to the model being underestimated.

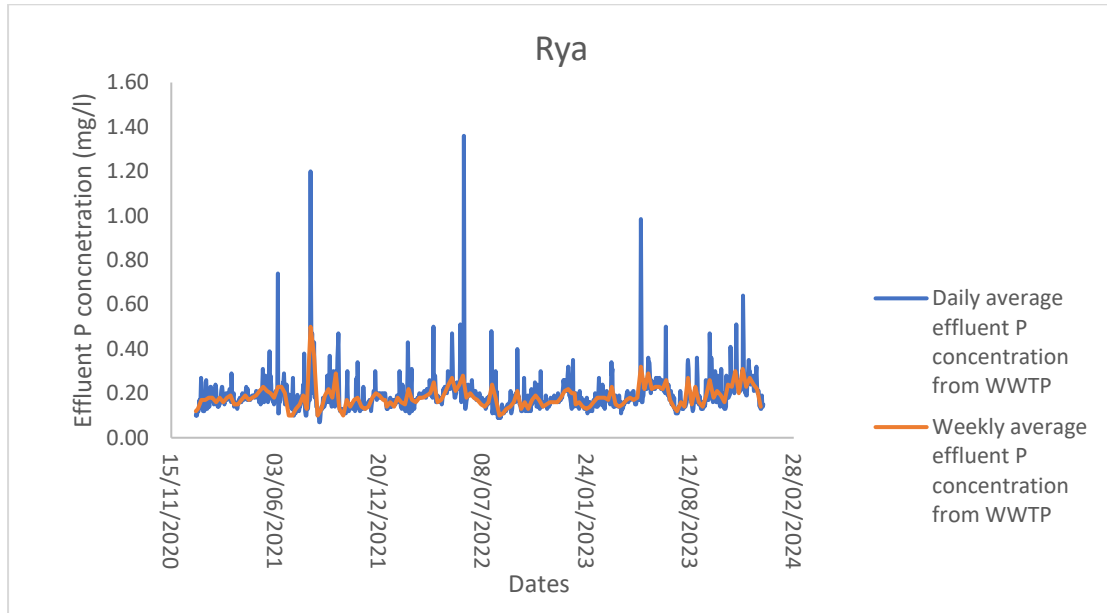


Figure 10 Daily and weekly average effluent P concentrations from Rya WWTP arranged in the date order for the years 2021, 2022, and 2023.

Table 13 Median, 90th percentile and 99th percentile for daily and weekly effluent P concentration from Rya WWTP for years 2021, 2022, and 2023.

Effluent P concentration from Rya WWTP			
l/p, d	Median	90 th percentile	99 th percentile
Daily	0.17	0.26	0.47
Weekly	0.18	0.24	0.34

From Figure 10 and Table 13, we can observe that the median effluent P concentration values are nearly identical for both the daily and weekly datasets, indicating consistent central tendency across both types of data. However, the 90th percentile reveals that higher concentrations are more pronounced in the daily data. Additionally, the 99th percentile is significantly higher in the daily data, suggesting that extreme high values are averaged out in the weekly data.

5.3 Analysis of influent and effluent P concentrations across different WWTPs

This section presents the results of analysis of influent and effluent P concentrations for each WWTP. The results provide insights into the WWTPs' performance in managing P levels, specifically in relation to the specified regulatory limits

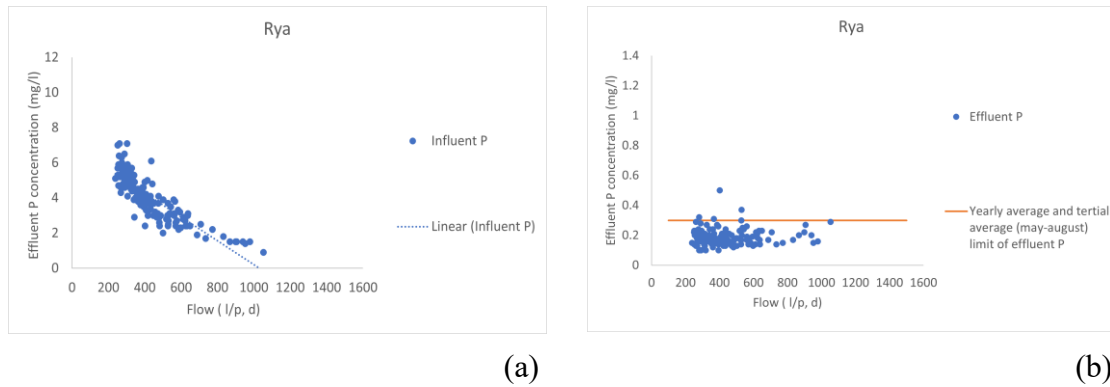


Figure 11a-b. (a) Relationship between flow and influent P concentration for Rya WWTP; (b) Relationship between flow and effluent P concentration for Rya WWTP.

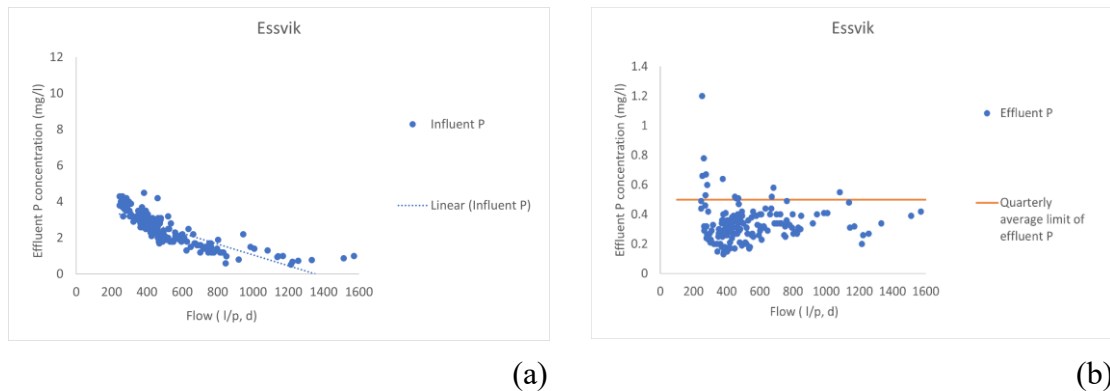


Figure 12a-b. (a) Relationship between flow and influent P concentration for Essvik WWTP; (b) Relationship between flow and effluent P concentration for Essvik WWTP.

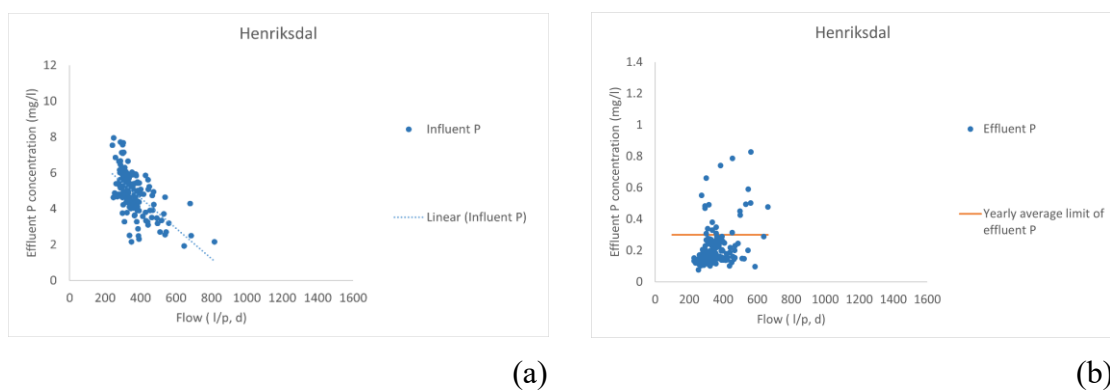
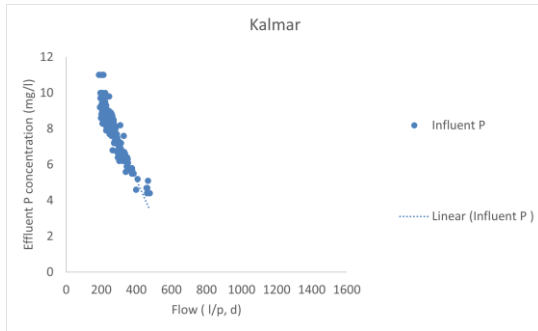
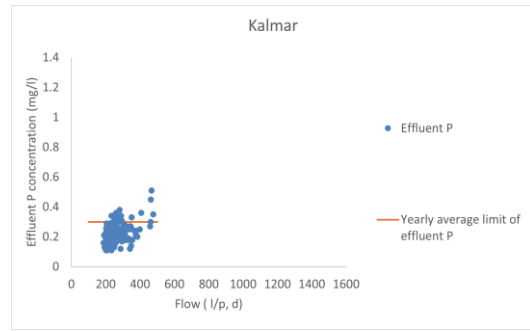


Figure 13a-b. (a) Relationship between flow and influent P concentration for Henriksdal WWTP; (b) Relationship between flow and effluent P concentration for Henriksdal WWTP.

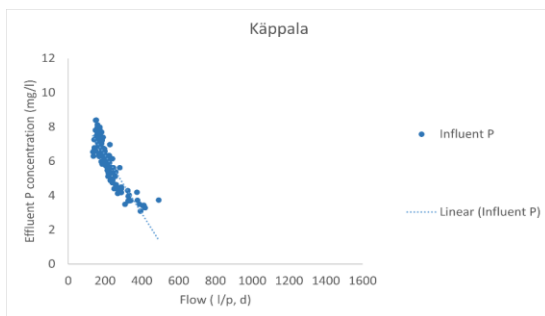


(a)

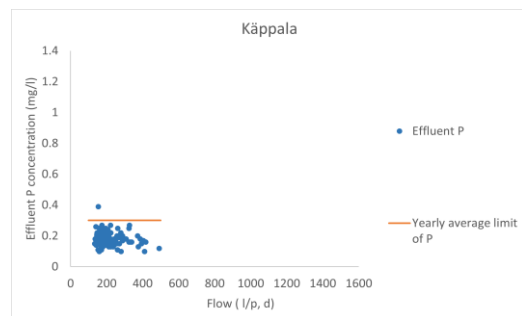


(b)

Figure 14a-b (a) Relationship between flow and influent P concentration for Kalmar WWTP; (b) Relationship between flow and effluent P concentration for Kalmar WWTP.



(a)



(b)

Figure 15a-b (a) Relationship between flow and influent P concentration for Käppala WWTP; (b) Relationship between flow and effluent P concentration for Käppala WWTP.

Table 14 Effluent P concentration compliance of Rya, Henriksdal, Kalmar, and Käppala WWTPs for the years 2021, 2022, and 2023 (Videbris, 2022; Videbris 2023; Videbris 2024; Eriksson, 2023; Kalmar Vatten, 2021; Kalmar Vatten, 2022; Kalmar Vatten, 2023; Käppalaförbundet, 2023; Käppalaförbundet, 2024).

WWTP	Annual Limit	Additional Limit (May-Aug)	Result 2021	Result 2022	Result 2023	Result 2021 (May-Aug)	Result 2022 (May-Aug)	Result 2023 (May-Aug)
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Rya	0.3	0.3	0.19	0.18	0.20	0.21	0.19	0.21
Henriksdal	0.3	-	0.21	0.21	0.25	-	-	-
Kalmar	0.3	-	0.22	0.23	0.24	-	-	-
Käppala	0.3	-	0.20	0.20	0.20	-	-	-

Table 15 Quarterly effluent P concentration compliance of Essvik WWTP for the years 2021, 2022, and 2023 (M. Tuveesson, personal communication, August 8, 2024).

Essvik	Quarterly Limit	Q1	Q2	Q3	Q4
	mg/l	mg/l	mg/l	mg/l	mg/l
Result 2021	0.5	0.34	0.36	0.35	0.38
Result 2022		0.39	0.34	0.32	0.32
Result 2023		0.30	0.40	0.40	0.40

Table 14 and Table 15 present the specific limits for P concentration for each WWTP and the actual result values collected from the environmental reports of each facility.

From Figures 11-15, we can see that for all the WWTPs, the concentration of influent P decreased with increasing flow, clearly demonstrating the phenomenon of dilution. The highest influent P concentrations were observed at Kalmar WWTP, followed by Käppala WWTP. Henriksdal WWTP had the third highest influent P concentration levels, followed by Rya WWTP. Essvik WWTP had the lowest influent P concentration levels.

For Rya WWTP, the effluent P concentrations were generally below the annual limit of 0.3 mg/l for most flow rates, with only a few exceptions where the concentration exceeded 0.3 mg/l. This indicates that Rya WWTP was effective in removing P from the water across various flow rates.

For Essvik WWTP, the effluent P concentration was higher than the quarterly limit of 0.5 mg/l for some lower flows, but as the flow increased, the P removal efficiency improved. For Henriksdal WWTP, the effluent P concentration exceeded 0.3 mg/l for only a few flow rates.

At Kalmar WWTP, the effluent P concentration level slightly exceeded 0.3 mg/l for some flows, but for higher flows, the effluent P concentration increased significantly up to 0.5 mg/l, indicating a decrease in P removal efficiency for higher flows. Käppala WWTP maintained an effluent P concentration below 0.3 mg/l for all flows, except for one instance, which might have been due to measurement error or a treatment issue during that particular week.

Although some treatment plants had effluent P concentrations exceeding 0.3 mg/l for individual weeks, this limit was an annual average limit for all except Essvik WWTP, which had a quarterly average limit of 0.5 mg/l. The yearly average effluent P concentration was below 0.3 mg/l for all treatment plants for all the three years, and for Essvik WWTP, the quarterly average was also below 0.5 mg/l for all the three years. Furthermore, Rya WWTP had an additional discharge limit known as average tertiary 2 limit for the months of May to August, which was same as the annual limit of 0.3 mg/l. The average tertiary discharge for Rya WWTP also remained below this limit across all three years.

5.4 Development and selection of best model for Rya WWTP

This section presents the findings from the evaluation of three different methods used to develop the optimal model for the Rya WWTP's data. The results detail the performance of each method, highlighting the parameters and criteria used to determine the most effective approach.

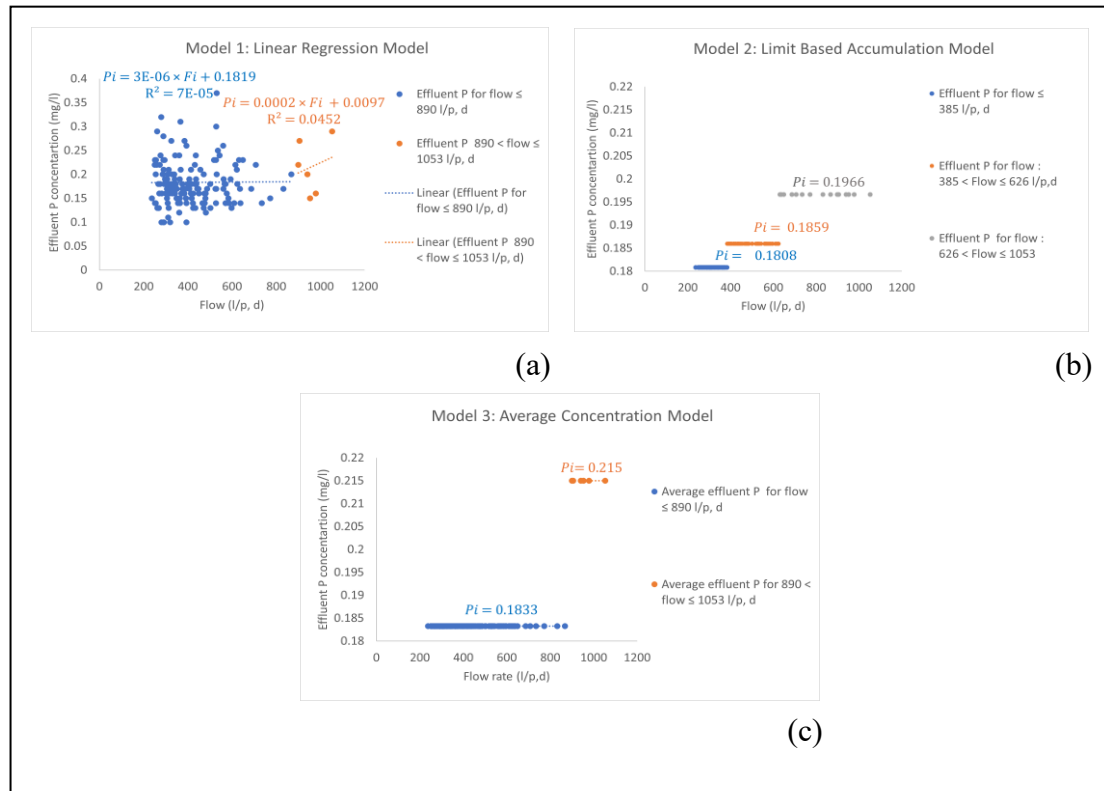


Figure 16a-c. (a) Linear regression model for Rya WWTP; (b) Limit-based accumulation model for Rya WWTP; (c) Average concentration model for Rya WWTP.

In Model 1, a linear regression equation was used to describe the relationship between effluent P concentrations and flows for each capacity category. For flows less than or equal to the first capacity limit (biological treatment capacity), the linear regression equation was $P_i = 3 \times 10^{-6} \times F_i + 0.1819$, represented by the blue line in Figure 16a. For the Rya WWTP, the second capacity limit was 1257 l/p, d, but the highest weekly flow was 1053 l/p, d. Therefore, it was only possible to create a model up to that flow rate. For flows greater than the first capacity limit but less than or equal to the second capacity limit of 1053 l/p, d in this case, the linear regression equation was $P_i = 0.0002 \times F_i + 0.0097$, indicated by the orange line in Figure 16a. These equations were used to calculate the effluent P concentration for each flow rate, and subsequently, the effluent P mass flow.

In Model 2, the accumulated effluent P concentration was calculated for three specific flow limits: median flow, 90th percentile flow, and maximum flow. For flows less than or equal to the median flow (F_{Median}), the effluent P concentration was 0.1808 mg/l, as indicated by the blue dots in Figure 16b. For flows greater than the median flow but

less than or equal to the 90th percentile flow ($F_{90\%}$), the effluent P concentration was 0.1859 mg/l, shown by the orange dots in Figure 16b. For flows greater than the 90th percentile flow but less than or equal to the maximum flow (F_{Max}), the effluent P concentration was 0.1966 mg/l, represented by the grey dots in Figure 16b. These concentrations were used to estimate the effluent P mass flow for each flow rate.

In the Model 3, the effluent P concentrations were determined based on two capacity limits. For flows less than or equal to the first capacity limit (biological treatment capacity), the average effluent P concentration was 0.1833 mg/l, as indicated by the blue dots in Figure 16c. For flows greater than the first capacity limit but less than or equal to the second capacity limit (biological + chemical treatment capacity), the average effluent P concentration was 0.215 mg/l, shown by the orange dots in Figure 16c. These average concentrations were used to estimate the effluent P mass flow for each flow rate.

For Model 1 and Model 3, which are based on capacity limits, Rya WWTP could only develop the model up to the highest weekly flow of 1053 l/p, d, which was below the second hydraulic limit.

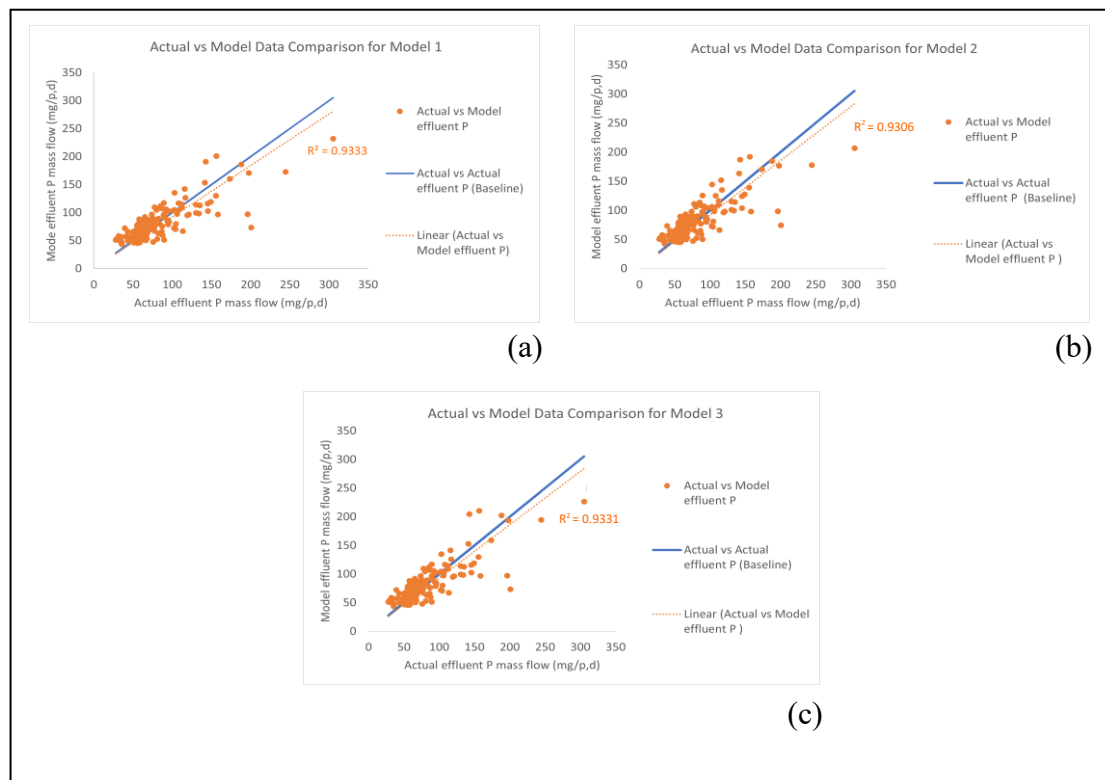


Figure 17a-c. Comparison between actual mass flows and estimated (model) mass flows predicted for Rya WWTP using (a) Linear regression model; (b) Limit-based accumulation model; (c) Average concentration model.

The figure 17a-c present the comparison between the estimated effluent P mass flows (based on the models) and the actual effluent P mass flows. Each graph includes:

- Orange dots: Representing the actual versus model effluent P mass flows.
- Solid blue line: The reference line, which is the actual data vs. actual data, helping to visualise how closely the model data is related to the actual data.

- Orange dotted line: The linear fit of the actual versus model effluent P mass flows.

The R^2 values, which were close to 1 for all three models, indicate a strong relationship between the estimated and actual effluent P mass flows (Figure 17a-c). The RMSE values were 23.35 for Model 1, 23.8 for Model 2, and 23.36 for Model 3. Given that the actual effluent P mass flow ranged from 30 to 200, these RMSE values represent moderate errors relative to the total range. While not extremely low, they suggest that all the three models have a reasonable level of accuracy, with some deviation between the predicted and actual effluent P mass flows. This indicates that the models fit the data well and provide reliable estimates.

However, a common observation is that for higher flow rates, the models tend to underestimate the effluent P mass flows, as evidenced by the scattering of points below the baseline in the higher flow range. This deviation suggests that while the models are accurate at lower flow rates, their predictions become less reliable as the flow increases. This underestimation at higher flow rates points to a potential limitation in the models.

Given the importance of accurately modelling effluent P mass flow, especially for higher flows, it is crucial to select a model that considers key operational parameters of WWTPs. Since capacity is a major distinguishing factor between different WWTPs, using a capacity-based model is particularly beneficial for comparative purposes. Therefore, it was chosen to proceed with the capacity-based model.

In Model 3, the average concentration method, effluent P concentrations are averaged for each capacity category. This approach, which is straightforward and easy to implement, actually resulted in a high degree of data smoothing within each capacity category, as shown in the figure 16c. Consequently, it may not capture the finer details and fluctuations in effluent P concentrations at different flow rates within the same capacity category.

Similarly, Model 1, the linear regression method, significantly smooths the data, as it represents the relationship between effluent P concentration and flow with a straight line for each capacity category. However, as shown in Figure 16a, Model 1 captures trends better than Model 3, at least for the second capacity category, providing a more accurate representation of how effluent P concentrations change with flow. Despite both models' limitations in capturing detailed fluctuations, Model 1 was ultimately chosen for its better performance and was subsequently used to develop models for other WWTPs.

5.5 Application of the chosen model to other WWTPs

After determining that the first model was the most effective, models were created for all other WWTPs following the same approach as used for Rya WWTP. This section presents the results obtained from applying the chosen model to each WWTP.

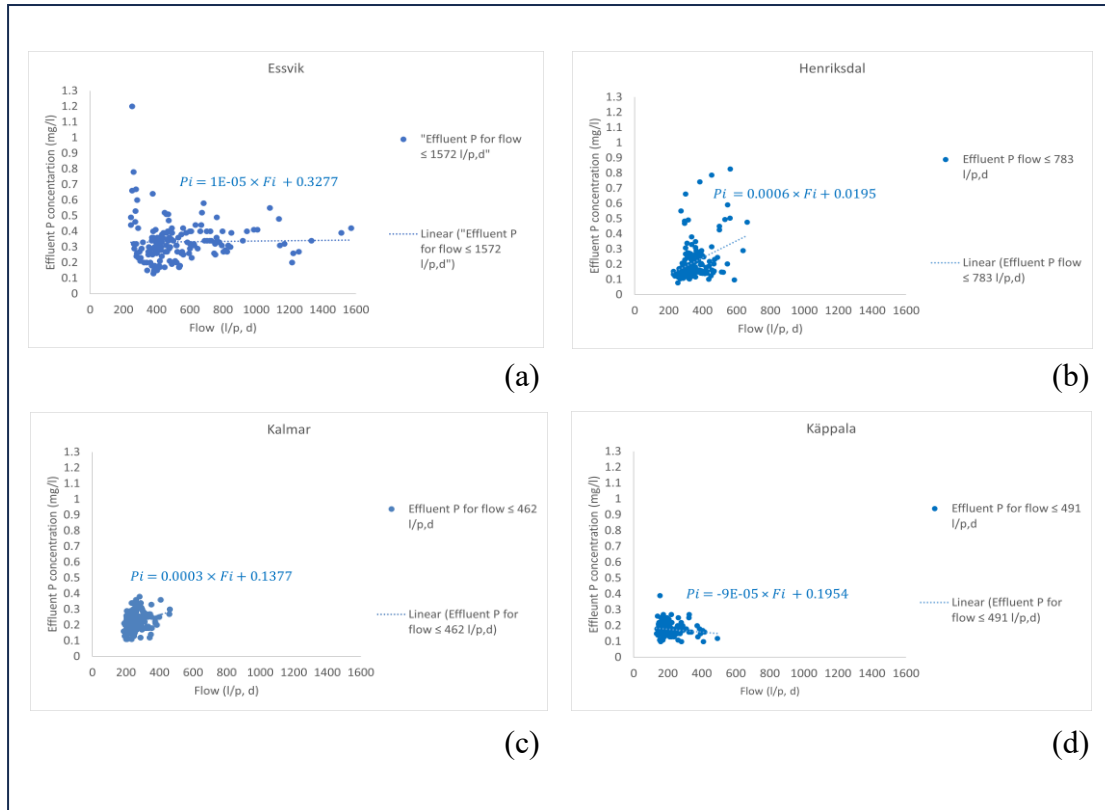


Figure 18a-d. Linear regression model for (a) Essvik WWTP; (b) Henriksdal WWTP; (c) Kalmar WWTP; (d) Käppala WWTP.

Table 16 Capacity limits and effluent P concentration equations for Essvik, Henriksdal, Kalmar and Käppala WWTPs.

WWTP	First Capacity	Second Capacity	Linear Equation for Effluent P Concentration (First Capacity)	Linear Equation for Effluent P Concentration (Second Capacity)
	l/p, d	l/p, d	mg/l	mg/l
Rya	890	1053	$P_i = 3 \times 10^{-6} \times F_i + 0.1819$	$P_i = 0.0002 \times F_i + 0.0097$
Essvik	1572	-	$P_i = 1 \times 10^{-5} \times F_i + 0.3277$	-
Henriksdal	663	-	$P_i = 0.0006 \times F_i + 0.0195$	-
Kalmar	340*	-	$P_i = 0.0003 \times F_i + 0.1377$	
Käppala	491	-	$P_i = -9 \times 10^{-5} \times F_i + 0.1954$	-

*- Created a linear equation for the flow rate up to 462 l/p, d.

Table 16 shows the capacity limits and effluent P concentration equations for each capacity limit for all WWTPs. For Essvik WWTP, despite having two hydraulic limits, the maximum weekly flow to the plant was below the first limit. Consequently, the model was only developed up to a maximum flow of 1572 l/p, d. At Henriksdal WWTP, although there are two hydraulic limits, the maximum weekly flow was below the first limit, so the model was created only up to a maximum flow of 663 l/p, d.

For Kalmar WWTP, the highest recorded weekly flow was 476 l/p, d, but the plant has an overall treatment capacity of only 340 l/p, d. Beyond this capacity, the extra flow bypasses the biological treatment steps, though it still passes through all other treatment steps, resulting in reduced treatment efficiency. From the analysis of effluent P concentration explained in Section 5.3, it was observed that up to 462 l/p, d, the effluent P concentration level was below 0.3 mg/l for most flows and below 0.4 mg/l for all flows (Figure 14b). Beyond this flow rate, the effluent P concentration increased significantly, reaching up to 0.5 mg/l. Therefore, it was assumed that Kalmar WWTP effectively treats P up to a limit of 462 l/p, d, and the model was developed up to this flow rate.

In the case of Käppala WWTP, although there were more than two hydraulic limits, the maximum flow remained below the first limit. Thus, the model was developed only up to the highest flow of 491 l/p, d.

5.6 Analysis of weekly influent P mass flows and calculation of average weekly influent P mass flow for different WWTPs

This section presents the findings from the analysis of influent P mass flows to each WWTP, as well as the results derived from the calculations used to determine the average influent P mass flow.

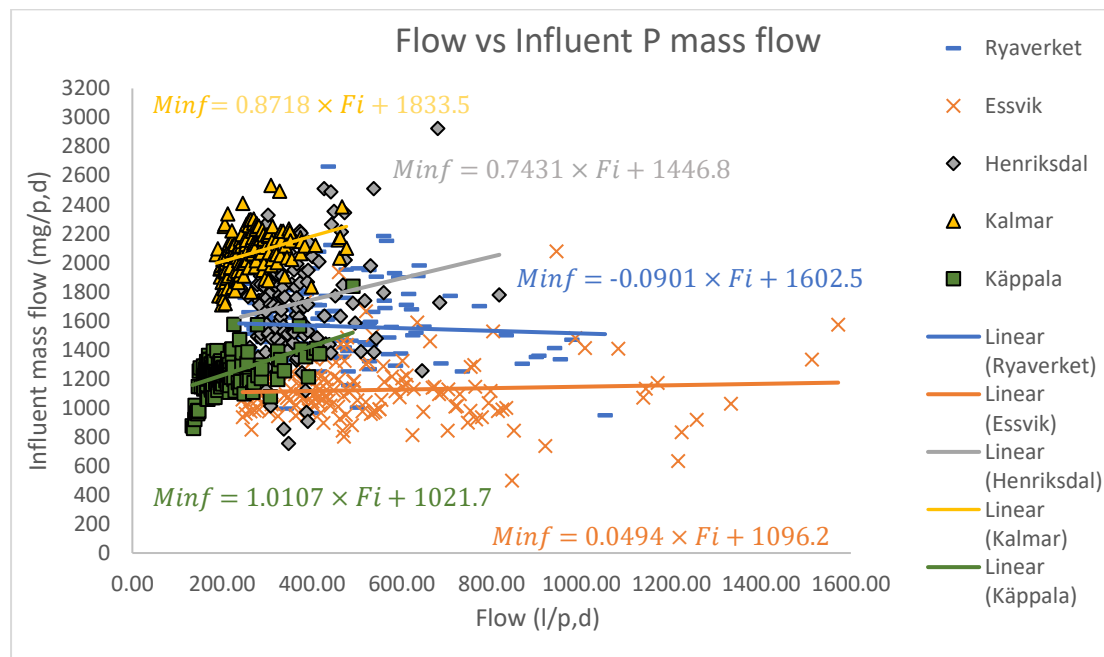


Figure 19 Relationship between weekly flow and weekly influent P mass flow for different WWTPs

Figure 19 presents the relationship between flow and influent P mass flow for five WWTPs. Kalmar WWTP shows the highest influent P mass flows, often exceeding 2000 mg/p, d, with a strong positive correlation between flow and mass flow. Henriksdal WWTP, although not having the highest overall mass flows, records the highest individual influent P mass flow among all WWTPs and also demonstrates a strong positive correlation with flow. Käppala WWTP shows moderate influent P mass flows, typically around 1200-1600 mg/p,d, with a positive correlation. These three WWTPs-Kalmar, Henriksdal, and Käppala-exhibit lower flow variations but have a strong positive correlation between flow and influent P mass flow.

In contrast, Rya and Essvik WWTPs display different patterns. Rya WWTP shows a slight negative correlation, where the influent P mass flow decreases slightly as the flow increases. Essvik, with the lowest influent P mass flows, generally below 1200 mg/p,d, also exhibits a weak positive correlation, indicating minimal increases in mass flow with increasing flow. Notably, both Rya and Essvik WWTPs, which experience higher flow variations compared to the other WWTPs, show nearly horizontal lines in their flow versus influent P mass flow relationships. This horizontal trend suggests that, under high-flow conditions, the mass flow does not increase significantly with flow, indicating a different behaviour compared to the other WWTPs.

These observations imply that WWTPs with lower flow variation are more likely to exhibit a strong positive correlation between flow and influent P mass flow, while those with higher flow situations (Rya and Essvik WWTPs), tend to show a more horizontal trend. This difference indicates a limitation in extrapolating mass flow trends to high-flow situations, where data is scarce, as the relationship may not hold true under such conditions.

Table 17 Summary of linear equations, thresholds, and average influent P mass flow for five WWTPs

Treatment Plant	Linear Equation for Influent P Mass Flow	Threshold Value (Median + Standard Deviation for the Absolute Difference Between the Actual vs Predicted Influent P Mass Flow)	Average Influent P Mass Flow
	mg/p, d		mg/p, d
Rya	$Minf = -0.0901 \times F_i + 1602.5$	305.6	1547
Essvik	$Minf = 0.0494 \times F_i + 1096.2$	255.7	1089
Henriksdal	$Minf = 0.7431 \times F_i + 1446.8$	434.3	1705
Kalmar	$Minf = 0.8718 \times F_i + 1833.5$	173.9	2067
Käppala	$Minf = 1.0107 \times F_i + 1021.7$	130.0	1242

The Table 17 summarises the derived linear equations for influent P mass flows, the thresholds calculated as the median plus one standard deviation, and the calculated average influent P mass flows for the “Close” range for five WWTPs. This calculated average influent P mass flow is used to determine the effluent P mass flow for excess flows for each WWTP, as detailed in section 3.2.6.

5.7 Utilisation of flow data from each WWTP into the developed model for each WWTP.

This section presents the results obtained from the estimation of the effluent P mass flow for each flow by utilisation of flow data from each municipality into the developed model for each WWTP. When the capacity of each model is exceeded, any excess flow is assumed to bypass treatment. Then the extra effluent P mass flow for the extra flow is calculated as explained in Section 3.2.7.

Rya WWTP has a first capacity limit of 890 l/p, d, which is for biological treatment capacity, and a second capacity limit of 1257 l/p, d, which is for chemical treatment capacity. Therefore, it was assumed that the Rya WWTP could handle flows up to 1257 l/p, d for P treatment. When flows from other municipalities are incorporated into Rya WWTP’s model, it was assumed that there would be no bypass of the P treatment steps

for flows up to 1257 l/p, d. A linear equation for the effluent P concentration, applicable for flows greater than 890 l/p, d and up to 1053 l/p, d (the flow rate up to which the model was developed), was used to estimate the effluent P concentration for flows up to 1257 l/p, d.

Rya WWTP also has a third hydraulic capacity of 1677 l/p, d, which represents its mechanical treatment capacity. Although the mechanical treatment includes disc filters that play a significant role in removing particulate P from the water, only the water that has undergone biological treatment is subjected to disc filter treatment. Consequently, the capacity of the disc filters is considered to be the same as that of the biological treatment. Thus, the mechanical capacity was not considered for the capacity of P treatment.

Henriksdal WWTP has a first capacity limit of 783 l/p, d, which is for biological treatment, and a second capacity limit of 978 l/p, d, which is for tertiary treatment. Since tertiary treatment also includes sand filters, which play a significant role in removing particulate P from the water, it was assumed that Henriksdal WWTP could manage flows up to 978 l/p, d for P treatment. When flows from other municipalities are included in Henriksdal WWTP's model, it was assumed that there would be no bypass of the P treatment steps up to 978 l/p, d. A linear equation for the effluent P concentration, applicable for flows less than or equal to 663 l/p, d (the flow rate up to which the model was developed), was used to estimate the effluent P concentration for flows up to 978 l/p, d.

Käppala WWTP has a first capacity limit of 593 l/p, d for biological treatment combined with sand filters, a second capacity limit of 712 l/p, d for primary clarifiers and sand trappers, and a third capacity limit of 1186 l/p, d for treatment in sieves. As explained in Section 4.5, when the flow exceeds 5 m³/s or 593 l/p, d, Käppala WWTP uses a treatment step called Actiflo[®] for the additional flow, which is an important step for P removal and has a capacity of 356 l/p, d. Therefore, it was assumed that Käppala WWTP could handle flows up to 949 l/p, d (593 + 356 l/p, d) for P treatment. When flows from other municipalities are included in Käppala WWTP's model, it was assumed that there would be no bypass of the P treatment steps up to 949 l/p, d. A linear equation for the effluent P concentration, applicable for flows less than or equal to 491 l/p, d (the flow rate up to which the model was developed), was used to estimate the effluent P concentration for flows up to 949 l/p, d.

Figure 20 shows the graphical results of using flow data from all the municipalities combined in each WWTP's model.

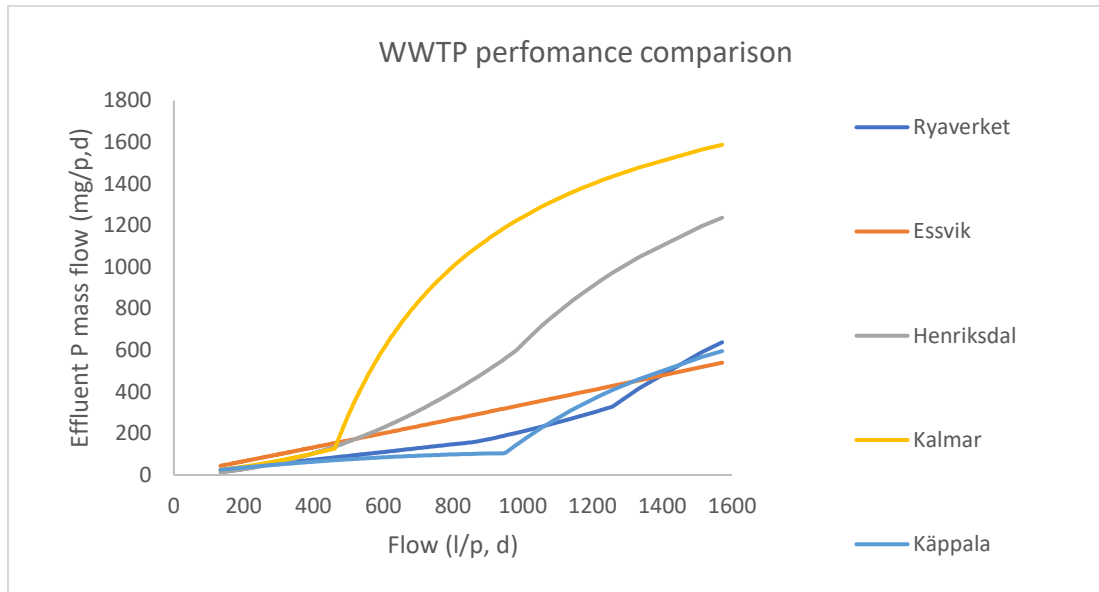


Figure 20 WWTP performance comparison.

From Figure 20, it can be observed that the Rya WWTP showed a steady increase in effluent P mass flow with increasing flow rates, with a minor spike at 890 l/p, d, indicating the exceedance of the first hydraulic capacity. After reaching 890 l/p, d, the Rya WWTP showed a slight increase in effluent P mass flow but maintained steady performance without any major bypass events. At 1,257 l/p, d, however, the capacity limit was exceeded, leading to a significant increase in effluent P mass flow due to the bypassing of excess flow. Overall, the Rya WWTP performed well, maintaining relatively low effluent P mass flow and demonstrating good treatment efficiency up to 1,257 l/p, d. For most flow rates, the Rya WWTP showed the second-lowest effluent P mass flow. For flows above approximately 1,100 l/p, d, it had the lowest effluent P mass flow among all WWTPs until around 1,400 l/p, d, where the Essvik WWTP showed better performance. At around 1,500 l/p, d, the Käppala WWTP outperformed the Rya WWTP.

For low flows up to around 500 l/p, d, the Essvik WWTP showed a slightly higher effluent P mass flow compared to other WWTPs. However, the Essvik WWTP exhibited no spikes in effluent P mass flow, suggesting effective treatment without any major bypass events. It maintained relatively low effluent P mass flows, indicating good treatment efficiency, which was attributed to its very high flow capacity. For higher flows above around 1,400 l/p, d, the Essvik WWTP showed the lowest effluent P mass flow among all WWTPs.

The Henriksdal WWTP showed the lowest effluent P mass flow at the lowest flow rates and exhibited a steady increase in effluent P mass flow up to 978 l/p, d. Beyond this point, it showed a sudden spike, indicating that the capacity limit had been exceeded and bypass events were occurring. After approximately 500 l/p, d, the Henriksdal WWTP had the second-highest effluent P mass flow among all WWTPs. Up to around 500 l/p, d, the Henriksdal WWTP performed better than the Essvik WWTP, but beyond this point, its performance declined compared to the Essvik WWTP. This suggested

that as flow rates increased, the Henriksdal WWTP's performance deteriorated compared to other WWTPs, except the Kalmar WWTP.

The Kalmar WWTP exhibited the highest increase in effluent P mass flow among all WWTPs. Initially, it followed a low, steady increase in effluent P mass flow but showed a substantial spike at 462 l/p, d. This spike indicated the exceedance of capacity for P treatment and significant bypass of treatment steps at higher flow rates, leading to an increase in effluent P mass flow. Consequently, the Kalmar WWTP performed poorly compared to the others, with high effluent P mass flow and less effective treatment at high flows. This was because it has the lowest flow capacity among all WWTPs.

The Käppala WWTP showed the lowest effluent P mass flow for most flows up to 978 l/p, d, after which its capacity to treat P was exceeded, resulting in a significant spike. At around 1,100 l/p, d, the Rya WWTP performed better than the Käppala WWTP, and at around 1,400 l/p, d, the Essvik WWTP performed better than the Käppala WWTP, indicating that the Käppala WWTP's treatment efficiency declined at higher flow rates due to the exceedance of its capacity. However, around 1,400 l/p, d, the Käppala WWTP again performed better than the Rya WWTP due to a significant deterioration in the Rya WWTP's treatment efficiency.

In summary, the Essvik WWTP maintained a low effluent P mass flow across most flow rates and effectively managed increasing flows without any significant bypass events. The Käppala WWTP showed the lowest effluent P mass flow for most flows up to 978 l/p, d, but its treatment efficiency declined significantly for flows higher than that, particularly after exceeding its capacity. The Rya WWTP maintained relatively low effluent P mass flow and showed good treatment efficiency up to 1,257 l/p, d, after which it experienced a significant increase in effluent P mass flow when its capacity was exceeded. The Henriksdal WWTP performed well at lower flow rates but showed high but steady increase in effluent P mass flow and showed a sudden spike in effluent P mass flow after its capacity was exceeded, leading to poor performance at higher flows. The Kalmar WWTP performed the poorest among all WWTPs, with high effluent P mass flow and less effective treatment, particularly at high flows, due to its low flow capacity.

Overall, each WWTP's performance was influenced by its design capacity for typical flow rates, the flow rates and corresponding effluent P concentrations used to create the model, and the average influent P mass flow used to find the effluent P mass flows for excess flows. For instance, the Kalmar WWTP is designed for the flow rates it usually receives, which also explains its poor performance at higher flows, as it has a low capacity. Additionally, Kalmar and Henriksdal WWTPs have high average influent P mass flows, which results in very high effluent P mass flows when capacity is exceeded. As mentioned in Section 5.6, extrapolating mass flow trends to high-flow situations, especially for plants with low flows, is a limitation, as the relationship may not hold true under such conditions. This can be considered as one of the limitations of the study.

5.8 Analysis of effluent P mass flow changes when catchments and WWTPs are swapped across municipalities.

This section presents the results from the analysis of effluent P mass flow per person per year for each WWTP under two different scenarios: swapping catchments between municipalities and swapping WWTPs across municipalities while maintaining their own catchments. The detailed results for each WWTP under these scenarios are discussed in the following subsections. For clarity in the figures, the WWTPs are labelled as follows: Rya as A, Essvik as B, Henriksdal as C, Kalmar as D, and Käppala as E.

5.8.1 Rya WWTP

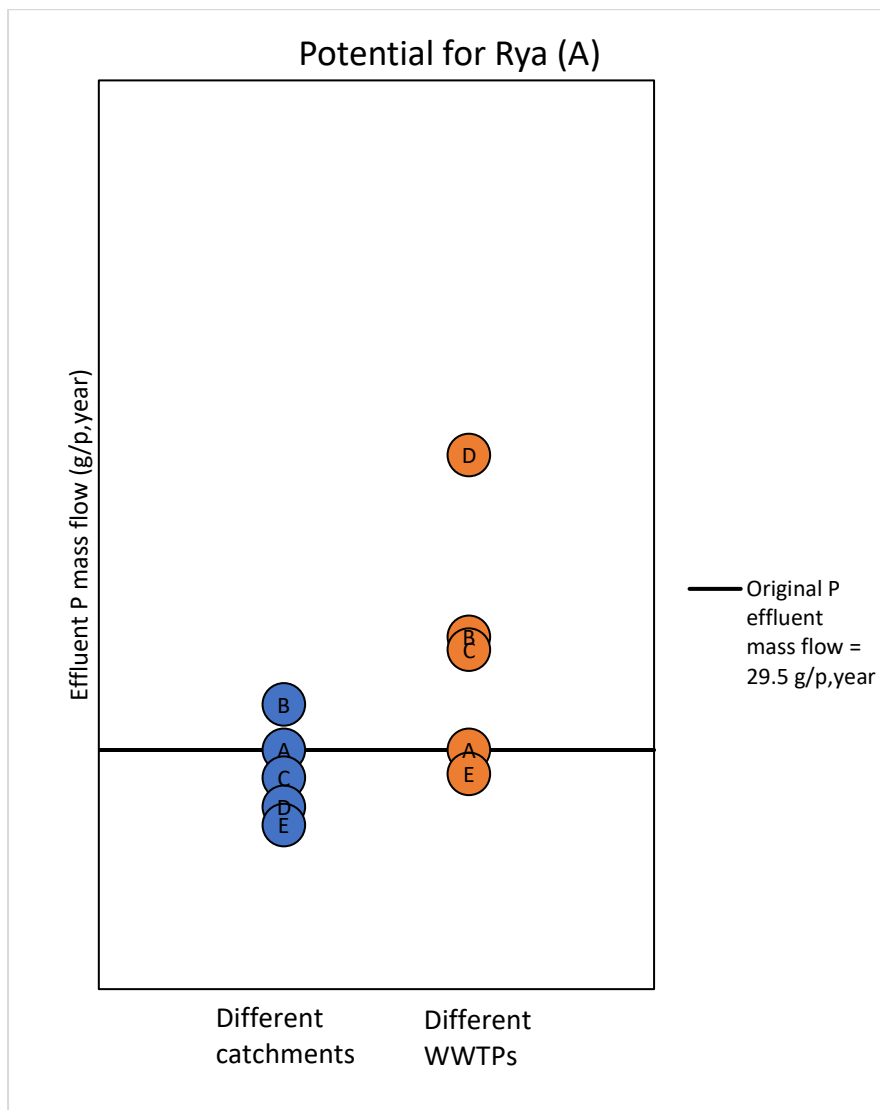


Figure 21 Potential effluent P mass flow for Rya WWTP under two scenarios.

From Figure 21, it can be observed that in the first scenario, where catchments between municipalities were swapped, the effluent P mass flow per person per year was higher than its own value of 29.5 g/p, year when the flow intended for Essvik WWTP was

treated by Rya WWTP. This indicates that Rya WWTP is not well-suited to handle the flows designated for Essvik WWTP, which are the highest among the five WWTPs, compared to its own. When flows intended for other WWTPs, excluding Essvik WWTP, were treated by Rya WWTP, the effluent P mass flow was lower than its actual value. Specifically, the flow from Käppala WWTP resulted in the lowest effluent P mass flow. These results suggest that Rya WWTP is well-suited for handling flows from all the WWTPs except Essvik WWTP, compared to its own flows.

In the second scenario, where WWTPs were swapped across municipalities while keeping their own catchments, it was observed that when the flow intended for Rya WWTP was treated by other plants, all WWTPs except Käppala WWTP performed poorly compared to Rya WWTP's own performance, with Kalmar WWTP being the least effective. Käppala WWTP performed the best, with an effluent P mass flow lower than Rya WWTP's actual value of 29.5 g/p, year, demonstrating its capability in handling the high flow volumes from Rya WWTP.

5.8.2 Essvik WWTP

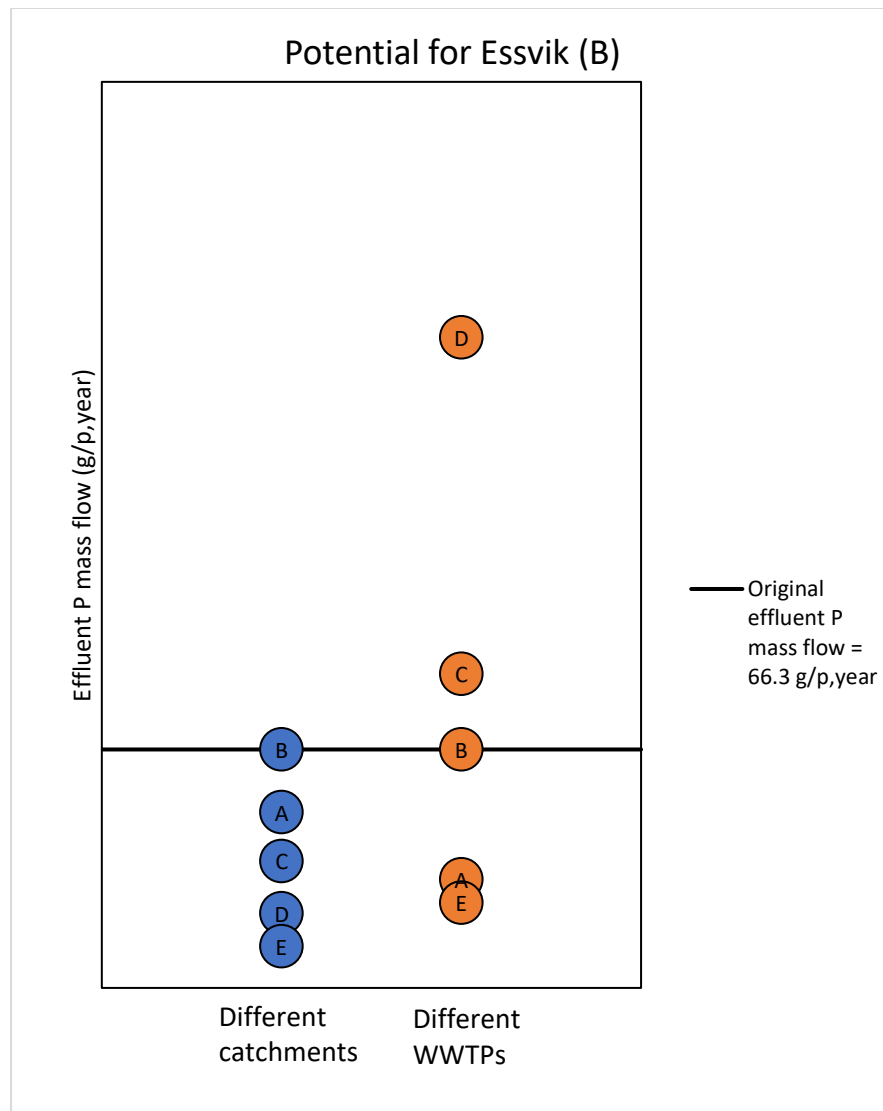


Figure 22 Potential effluent P mass flow for Essvik WWTP under two different scenarios.

From Figure 22, it can be observed that in the first scenario, where Essvik WWTP treated flows intended for other WWTPs, the effluent P mass flow was lower than its actual P mass flow value of 66.3 g/p, year. This indicates that Essvik WWTP is highly effective at treating flows from other WWTPs compared to its own flows. Specifically, the flow from Käppala WWTP resulted in the lowest effluent P mass flow, followed by flows from Kalmar and Henriksdal WWTPs. In contrast, the flow from Rya WWTP resulted in the highest effluent P mass flow among these WWTPs.

In the second scenario, where the flows intended for Essvik WWTP were treated by other plants, Henriksdal and Kalmar WWTPs performed worse than Essvik itself. Käppala and Rya WWTPs excelled, with an effluent P mass flow lower than Essvik WWTP's actual value of 66.3 g/p, year, demonstrating their capability in handling the high flow volumes from Essvik WWTP compared to Essvik WWTP itself. Among the two WWTPs, Käppala WWTP performed the best in maintaining an effluent P mass flow lower than Essvik WWTP's actual value. Of the remaining WWTPs, Kalmar WWTP performed the worst, followed by Henriksdal WWTP, compared to Essvik WWTP itself.

5.8.3 Henriksdal WWTP

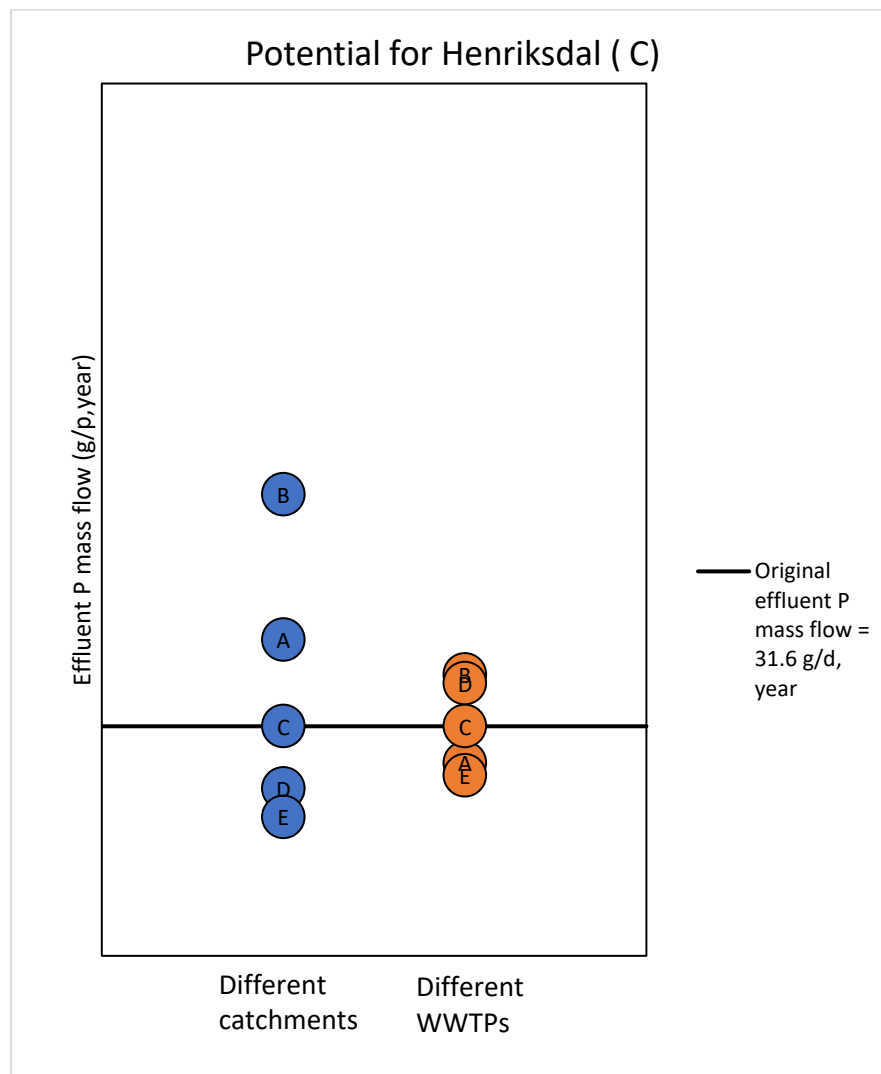


Figure 23 Potential effluent P mass flow for Henriksdal WWTP under two scenarios.

From Figure 23, it can be observed that in the first scenario, Henriksdal WWTP struggled to manage the flows designated for Rya and Essvik WWTPs. The effluent P mass flow was greater than the actual value of 31.6 g/p, year, indicating that Henriksdal WWTP is not well-suited to handle the flows designated for Rya and Essvik WWTPs compared to its own flow. Conversely, when Henriksdal WWTP treated flows intended for Kalmar and Käppala WWTPs, the effluent P mass flow was lower than the actual value. The flow intended for Käppala WWTP resulted in the lowest effluent P mass flow, highlighting Henriksdal WWTP's effectiveness in managing flows from Käppala WWTP compared to its own flow.

In the second scenario, when other plants treated the flow intended for Henriksdal WWTP, Rya and Käppala WWTPs stood out with an effluent P mass flow lower than the actual value of 31.6 g/p, year, with Käppala WWTP performing the best of the two. Among the other WWTPs, Essvik and Kalmar WWTPs showed slightly higher values than the actual value.

5.8.4 Kalmar WWTP

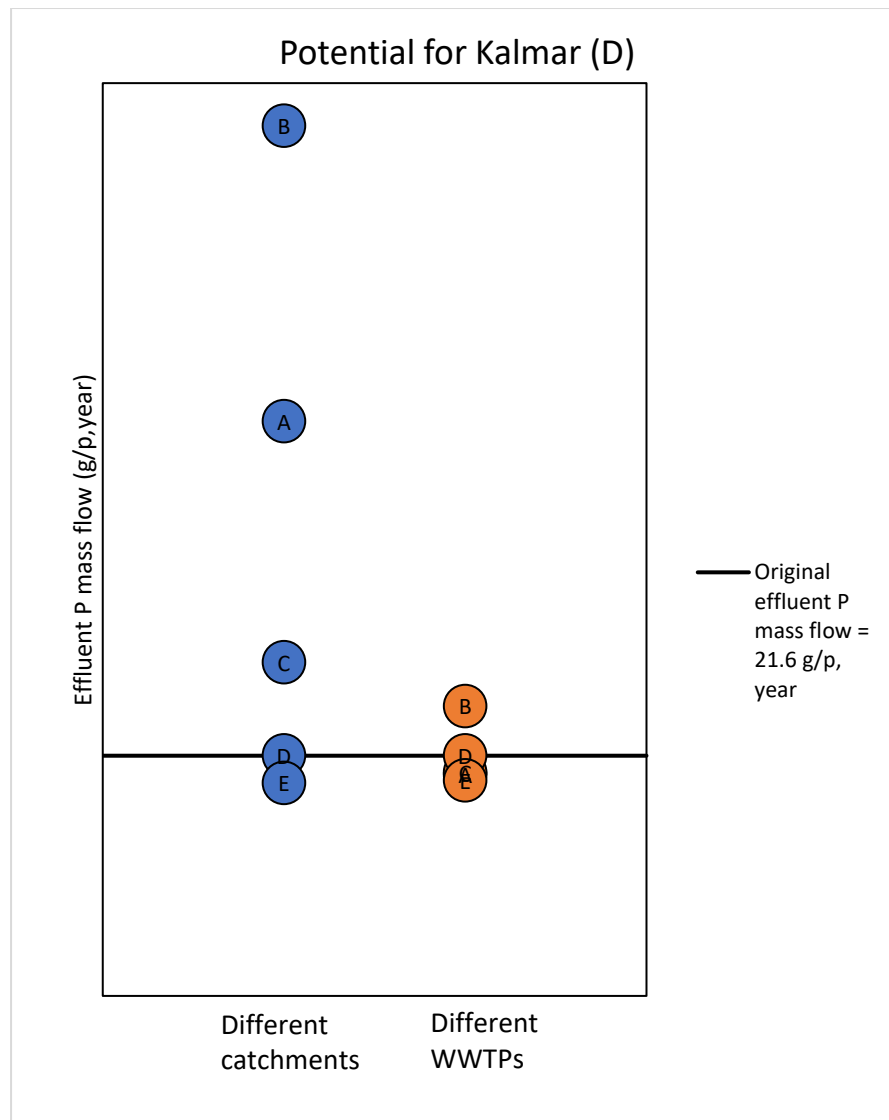


Figure 24 Potential effluent P mass flow for Kalmar WWTP under two scenarios.

From Figure 24, it can be observed that in the first scenario, for Kalmar WWTP, the effluent P mass flow exceeds the actual value of 22.9 g/p, year for flows intended for all other WWTPs except Käppala WWTP. The highest effluent P mass flow was observed for flows from Essvik WWTP, followed by Rya WWTP, and then Henriksdal WWTP. This suggests that Kalmar WWTP is less effective in treating flows from Essvik, Rya, and Henriksdal WWTPs compared to its own flow. Conversely, when Kalmar WWTP treated flows intended for Käppala WWTP, the effluent P mass flow was lower than the actual value, indicating that Kalmar WWTP performs better in treating flows from Käppala WWTP compared to its own flows.

In the second scenario, when other plants were used to treat the flow intended for Kalmar WWTP, all plants except Essvik WWTP showed a lower effluent P mass flow than the actual value of 22.9 g/p, year. This suggests that these WWTPs are more effective at treating flows from Kalmar WWTP compared to Kalmar WWTP itself. Essvik WWTP showed a slightly higher value than the actual, indicating it is less suitable for treating the flow from Kalmar WWTP compared to Kalmer WWTP itself.

5.8.5 Käppala WWTP

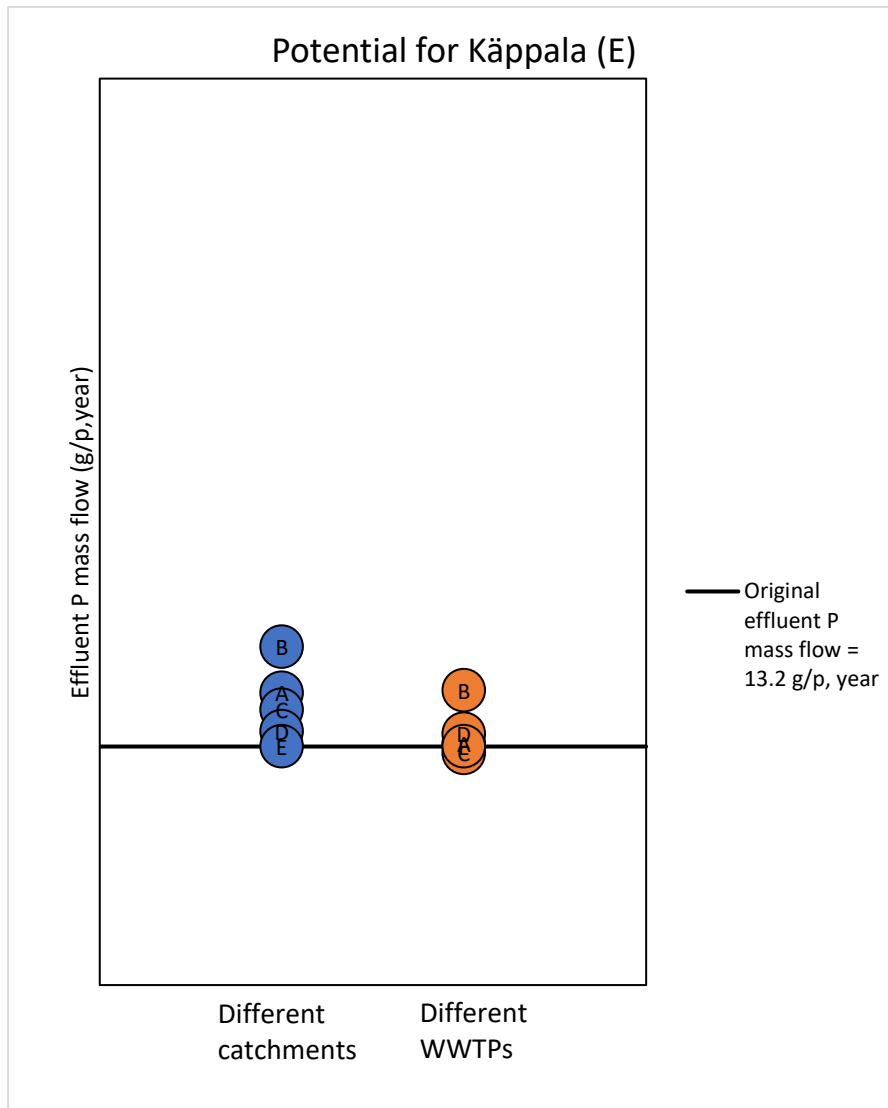


Figure 25 Potential effluent P mass flow for Käppala WWTP under two scenarios.

From Figure 25, it can be observed that for Käppala WWTP, in the first scenario, the effluent P mass flow exceeds the actual value of 13.2 g/p, year for flows intended for all other WWTPs. The highest effluent P mass flow was observed for flows from Essvik WWTP, followed by Rya WWTP, Henriksdal WWTP, and then Kalmar WWTP. This suggests that Käppala WWTP is less effective in treating flows from other WWTPs compared to its own flows.

In the second scenario, when other WWTPs were used to treat the flow intended for Käppala WWTP, Kalmar and Essvik WWTPs showed slightly higher effluent P mass flow values than the actual value of 13.2 g/p, year, indicating that these plants are not as suitable for treating the flows from Käppala WWTP compared to Käppala WWTP itself. Henriksdal WWTP showed a slightly lower value than the actual value, while Rya WWTP showed an effluent P mass flow almost equal to the actual value.

5.8.6 More discussion on scenario analysis.

Table 18 Effluent P mass flow per person per year for each WWTP when catchments are swapped across municipalities.

WWTPs	Catchments				
	Rya	Essvik	Henriksdal	Kalmar	Käppala
	(g/p, year)				
Rya	29.5	39.0	23.7	17.6	13.8
Essvik	53.1	66.3	42.9	31.9	25.0
Henriksdal	50.5	82.2	31.6	18.1	11.9
Kalmar	91.2	152.7	41.0	21.6	15.9
Käppala	24.5	34.1	20.9	16.4	13.2

Table 19 Effluent P mass flow per person per year for each WWTP when WWTPs are swapped across municipalities.

Catchments	WWTPs				
	Rya	Essvik	Henriksdal	Kalmar	Käppala
	(g/p, year)				
Rya	29.5	53.1	50.5	91.2	24.5
Essvik	39.0	66.3	82.2	152.7	34.1
Henriksdal	23.7	42.9	31.6	41.0	20.9
Kalmar	17.6	31.9	18.1	21.6	16.4
Käppala	13.8	25.0	11.9	15.9	13.2

From the data in Table 18, we can see that all WWTPs demonstrated better performance when treating Käppala WWTP's flows compared to their own, based on the yearly effluent P mass flow per person. This suggests that Käppala WWTP's flows is less challenging for other WWTPs to treat, as Käppala WWTP has the lowest flows among all municipalities.

All the WWTPs showed the second-lowest yearly effluent P mass flow per person for Kalmar's flows and the third-highest mass flows for Henriksdal WWTP's flows. The second-highest mass flows were observed for Rya WWTP's flows. All WWTPs showed the highest mass flow for Essvik WWTP's flows. The results of the yearly effluent P

mass flow for each WWTP followed the flow hierarchy explained in the section 5.1, where Essvik WWTP had the highest flows, followed by Rya WWTP, then Henriksdal WWTP. Käppala WWTP had the lowest flows, followed by Kalmar WWTP.

From this, we can conclude that the mass flow is lowest when the flow is less and increases with increasing flows. Therefore, improving the catchment, particularly for Rya, Essvik, Henriksdal, and Kalmar WWTPs, would help reduce their yearly effluent P mass flow per person from the current value.

The data presented in Table 19 indicate that Käppala WWTP is the most effective in treating flows from Rya, Essvik, Henriksdal, and Kalmar WWTPs, which have the first, second, third, and fourth largest inflows among all the WWTPs, when comparing the yearly effluent P mass flow per person. This effectiveness is likely due to Käppala WWTP's enhanced treatment capacity, which includes an additional method for handling higher flows known as Actiflo[®]. Its high performance in treating P can be confirmed from the results presented in Section 5.3 and Figure 15b from the results section, which show low effluent P concentration levels.

For flows from Käppala WWTP, Henriksdal WWTP shows the lowest effluent P mass flow per year. This is because Käppala WWTP had the lowest inflow among all the WWTPs, and both the results in Section 5.7 and Figure 20 from the results section show that Henriksdal WWTP performs the best for the initial lower flows. Therefore, when the flow reaches the Kalmar's level, Henriksdal WWTP is the most effective.

For flows from Käppala WWTP, Käppala WWTP itself shows the second-lowest effluent P mass flow per year, followed by Rya WWTP. Among the remaining WWTPs, Rya WWTP performs the second best. Its high flow capacity and strong performance in treating P, as confirmed by the results in Section 5.3 and Figures 11b from the results section, contribute to its effectiveness. This suggests that, for flows ranging from the level of Essvik WWTP down to the level of Kalmar WWTP, Rya WWTP is the second-best option.

For flow levels from Rya, Henriksdal, and Kalmar WWTPs, Henriksdal WWTP shows the third-best performance due to its good treatment capacity. For flows from Essvik, Essvik itself performs third best, indicating that Henriksdal WWTP's performance deteriorates as it reaches the flow level of Essvik WWTP.

For flow levels from Essvik to Rya WWTPs, Kalmar WWTP shows the highest yearly effluent P mass flow value, followed by Essvik WWTP. This is because Kalmar WWTP has the lowest capacity among all the WWTPs, making it the WWTP with the highest effluent P mass flow when flow rates are high. Meanwhile, for flow levels from Henriksdal to Käppala WWTP, Essvik WWTP shows the highest effluent P mass flow, followed by Kalmar. The poor performance of Essvik WWTP is evident from the results presented in Sections 5.3 and 5.7, as well as Figures 12b and 20 from the results section, which show that Essvik WWTP has poor performance at lower flows compared to other WWTPs in terms of both effluent P concentration levels and effluent P mass flows. Essvik WWTP's poor performance at lower flows, and Kalmar WWTP's very low treatment capacity both results in a high yearly effluent P mass flow.

In conclusion, improving the operational capacity and techniques for all WWTPs could help reduce the effluent P mass flow from the current yearly levels.

It is worth noting that each WWTP's performance in this project is influenced by its design capacity, the typical flow rates it receives, the corresponding effluent P concentrations used to create the model, and the influent P mass flow used to estimate the effluent P mass flow for bypassing flows.

6 Conclusion

- From the analysis, we can conclude that with an increase in flow, the effluent P mass flow also increases. When the capacity of a WWTP is exceeded, it often leads to bypass scenarios, where untreated water is discharged. This bypass results in a significant rise in effluent P mass flow emphasising the critical need to either maintain flow within the plant's designed capacity or to improve the plant's capacity and operational design to effectively control P levels.
- The performance of each WWTP in P removal is closely related to the flow it receives and the plant's overall treatment capacity. Differences in the increase in daily influent P mass flow per capita with rising flow among the WWTPs are primarily due to the varying treatment capacities each plant has. Some WWTPs are better equipped to manage higher flows without compromising P removal efficiency, while others struggle, especially when flow exceeds their design capacity, leading to higher effluent P mass flows due to bypass of treatment steps.
- For four of the five municipalities, improving the management of catchment areas could help reduce inflow peaks, thereby enhancing the efficiency of P removal in terms of yearly mass flow per capita. On the other hand, for all municipalities, improving WWTP operations or upgrading treatment techniques and capacities would help to significantly increase the efficiency of P removal in terms of yearly mass flow per capita. By focusing on these operational improvements and design enhancements, these WWTPs can better manage flow variations, ensuring more consistent and effective P removal even under high-flow conditions.
- The simple models developed and used for the analyses in this study provide valuable insights and can serve as effective tools for benchmarking WWTPs and catchments. To enhance the model's accuracy, using daily average flows instead of weekly flows is recommended for further improvement.

7 References

- Bashide, M. M. (2015). *Modeling of Kåppala Waste Water Treatment Plant- Evaluation of the Influence of Storm Water to the Treatment Process*. [Master thesis, Lund University]. LUP-SP.
<https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8046524&fileOId=8046525>
- Bertanza, G., & Boiocchi, R. (2022). Interpreting per capita loads of organic matter and nutrients in municipal wastewater: A study on 168 Italian agglomerations. *Science of The Total Environment*, 819, Article 153236.
<https://doi.org/10.1016/j.scitotenv.2022.153236>
- Bodaka, H., Farhoud, N., & Hlali, E. (2023). Modeling of wastewater treatment plant in Hama city using regression and regression trees. *Environmental Health Engineering and Management Journal*, 10(3), 293-300.
<https://doi.org/10.34172/EHEM.2023.33>
- Bugajski, P., Nowobilska-Majewska, E., & Majewski, M. (2021). The Impact of Atmospheric Precipitation on Wastewater Volume Flowing into the Wastewater Treatment Plant in Nowy Targ (Poland) in Terms of Treatment Costs. *Energies*, 14(13), 3806. <https://doi.org/10.3390/en14133806>
- Chin, D. A. (2023). Separation of Infiltration and Inflow in Sanitary Sewers. *Journal of Environmental Engineering*, 149(11), 8.
<https://doi.org/10.1061/JOEEDU.EEENG-7359>
- Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. Official Journal, L 135, 40-52. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01991L0271-20140101&qid=1485957216288&from=EN#page=12>
- Daigger, G. T. (2007). Wastewater Management in the 21st Century. *Journal of Environmental Engineering*, 133(7), 665-785.
[https://doi.org/10.1061/\(ASCE\)0733-9372\(2007\)133:7\(671\)](https://doi.org/10.1061/(ASCE)0733-9372(2007)133:7(671))
- Eriksson, M. (2023). *Miljörapport 2023. Avloppsverksamheten Stockholm Vatten och Avfall*. [Environmental Report 2023. Wastewater operations Stockholm Vatten och Avfall].
https://www.stockholmvattenochavfall.se/globalassets/pdfer/rapporter/miljorapporter-avlopp/miljorapport-2023_bilagor.pdf
- European Commission. (2010, June 24). *Waste water treatment: Commission seeks substantial fines for Belgium; sends fresh warning to Luxembourg*. European commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_10_835
- Giokas, D., Vlessidis, A., Angelidis, M., Tsimarakis, G., & Karayannis, M. (2002). Systematic analysis of the operational response of activated sludge process to variable wastewater flows. A case Study. *Clean Technologies and Environmental Policy*, 4, 183-190. <https://doi.org/10.1007/s10098-002-0145-z>

- Google. (n.d.). [Map view highlighting the WWTPs under study] Retrieved August 2024.
<https://www.google.com/maps/@63.350433,12.7859482,1599981m/data=!3m1!1e3!4m2!1m1!3e4?entry=ttu>
- Hey, G., Jönsson, K., & Mattsson, A. (2016). *The impact of infiltration and inflow on wastewater treatment plants. A case study in Sweden*. VA-tekniksödra.
https://va-tekniksodra.se/wp-content/uploads/2016/12/06-2016-Report-on-Infiltration-Inflow_Hey-et-al-2016.pdf
- Kalmar Vatten. (2022). *MILJÖRAPPORT 2021. Kalmar avloppsreningsverk [ENVIRONMENTAL REPORT 2021. Kalmar wastewater treatment plant]*.
<https://kalmarvatten.se/download/18.46a40a5417fab13602513da/1649232994074/Milj%C3%B6rapport%20Kalmar%20ARV%202021%20inkl%20Emissionnsdeklaration.pdf>
- Kalmar Vatten. (2023). *MILJÖRAPPORT 2022. Kalmar avloppsreningsverk [ENVIRONMENTAL REPORT 2022. Kalmar wastewater treatment plant]*.
<https://kalmarvatten.se/download/18.406d0a5d186e2b4f94383d/1679344972177/Milj%C3%B6rapport%20Kalmar%20ARV%202022%20Textdel%20och%20bilagor.pdf>
- Käppalaförbundet. (2023). *Miljörapport 2022. Käppalaförbundet [Environmental Report 2022. Käppalaförbundet]*.
<https://www.kappala.se/globalassets/dokument/vad-vi-gor/miljorapport-2022.pdf>
- Käppalaförbundet. (2024). *Miljörapport 2023. Käppalaförbundet [Environmental Report 2023. Käppalaförbundet]*.
<https://www.kappala.se/globalassets/dokument/vad-vi-gor/miljorapport-2023-pdf-08-mb.pdf>
- Kowalik, T., Bogdał, A., Borek, Ł., & Kogut, A. (2015). THE EFFECT OF TREATED SEWAGE OUTFLOW FROM A MODERNIZED SEWAGE TREATMENT PLANT ON WATER QUALITY OF THE BREŃ RIVER. *Journal of Ecological Engineering*, 16(4), 96-102.
<https://doi.org/10.12911/22998993/59355>
- Marill, K. A. (2004). Advanced statistics: linear regression, part I: simple linear regression. *Academic Emergency Medicine*, 11(1), 87 - 93.
<https://doi.org/10.1197/j.aem.2003.09.005>
- Metcalf & Eddy, AECOM. (2014). *Wastewater Engineering Treatment and Resource Recovery* (5th ed.). New York : McGraw-Hill Education.
- Mines Jr., R. O., Lackey, L. W., & Behrend, G. H. (2007). The Impact of Rainfall on Flows and Loadings at Georgia's Wastewater Treatment Plants. *Water, Air, and Soil Pollution*, 179, 135–157. <https://doi.org/10.1007/s11270-006-9220-0>

- Molander, C. (2015). *Influence of Excessive Water on Wastewater Treatment Performance: An Analysis Using Key Performance Indicators*. [Master thesis, Chalmers University of Technology]. Chalmers ODR.
<https://publications.lib.chalmers.se/records/fulltext/223718/223718.pdf>
- Naturvårdsverket. (2020). *Wastewater treatment in Sweden 2020*.
<https://www.naturvardsverket.se/4acbd4/globalassets/media/publikationer-pdf/8800/978-91-620-8896-5.pdf>
- Ohlin Saletti, A. (2021). *Infiltration and inflow to wastewater sewer systems - A literature review on risk management and decision support*. Chalmers University of Technology.
https://research.chalmers.se/publication/522159/file/522159_Fulltext.pdf
- Ohlin Saletti, A. (2022). *Risk-based management of the cost to society from infiltration and inflow to wastewater systems*. [Licentiate thesis, Chalmers University of Technology]. Chalmers Research.
<https://research.chalmers.se/en/publication/530358>
- Ohlin Saletti, A., Lindhe, A., Söderqvist, T., & Rosén, L. (2023). Cost to Society from infiltration and inflow to wastewater systems. *Water Research*, 229. Article 119505. <https://doi.org/10.1016/j.watres.2022.119505>
- Ohlin Saletti, A., Rosén, L., & Lindhe, A. (2021). Framework for Risk-Based Decision Support on Infiltration and Inflow to Wastewater Systems. *Water*, 13(17), 2320. <https://doi.org/10.3390/w13172320>
- Petrie, B. (2021). A review of combined sewer overflows as a source of wastewater-derived emerging contaminants in the environment and their management. *Environmental Science and Pollution Research*, 28, 32095–32110.
<https://doi.org/10.1007/s11356-021-14103-1>
- Plósz, B. G., Liltved, H., & Ratnaweera, H. (2009). Climate change impacts on activated sludge wastewater treatment: a case study from Norway. *Water Science and Technology*, 60(2), 533–541. <https://doi.org/10.2166/wst.2009.386>
- Sharma, P., Sood, S., & Mishra, S. K. (2020). Development of multiple linear regression model for biochemical oxygen demand (BOD) removal efficiency of different sewage treatment technologies in Delhi, India. *Sustainable Water Resources Management*, 6. Article 29. <https://doi.org/10.1007/s40899-020-00377-9>
- Sowby, R. B., & Jones, D. R. (2022). A Practical Statistical Method to Differentiate Inflow and Infiltration in Sanitary Sewer Systems. *Journal of Environmental Engineering*, 148(1). [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001962](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001962)
- Tan, P., Zhou, Y., Zhanga, Y., Zhu, D. Z., & Zhanga, T. (2019). Assessment and pathway determination for rainfall-derived inflow and infiltration in sanitary systems: a case study. *Urban Water Journal*, 16(8), 600-607.
<https://doi.org/10.1080/1573062X.2019.1700289>

- United Nations. (2022). *World Population Prospects 2022: Summary of Results*. Department of Economic and Social Affairs. Retrieved from <https://desapublications.un.org/file/989/download>
- Videbris, K.-E. (2022). *Miljörapport. Gryaab, Ryaverket 2021 [Environmental Report. Rya wastewater treatment plant 2021]*. <https://www.gryaab.se/wp-content/uploads/2022/04/Miljorapport-Ryaverket-2021.pdf>
- Videbris, K.-E. (2023). *Miljörapport. Gryaab, Ryaverket 2022 [Environment Report. Gryaab, Rya wastewater treatment plant 2022]*. <https://www.gryaab.se/wp-content/uploads/2023/04/Miljorapport-Ryaverket-2022-med-bilagor.pdf>
- Videbris, K.-E. (2024). *Miljörapport. Gryaab, Ryaverket 2023 [Environment Report. Gryaab, Rya wastewater treatment plant 2023]*. <https://www.gryaab.se/wp-content/uploads/2024/04/Miljorapport-2023-Ryaverket-tillganglighetsanpassad-final.pdf>
- Yu, D., Dian, L., Hai, Y., Randall, M. T., Liu, L., Liu, J., Wei, Y. (2022). Effect of rainfall characteristics on the sewer sediment, hydrograph, and pollutant discharge of combined sewer overflow. *Journal of Environmental Management*, 303. Article 114268. <https://doi.org/10.1016/j.jenvman.2021.114268>.

Appendix A

Process charts of the WWTPs

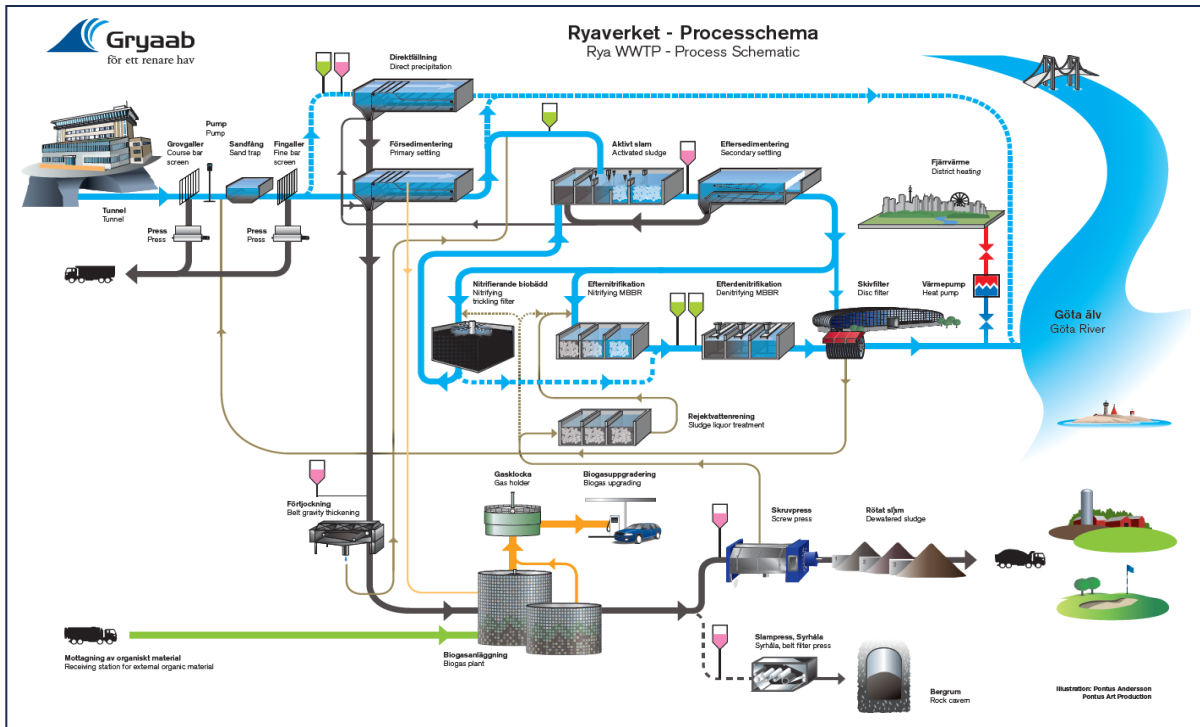


Figure A1 Process schematic for Rya WWTP (V. Tanskanen, personal communication, August 28, 2024).

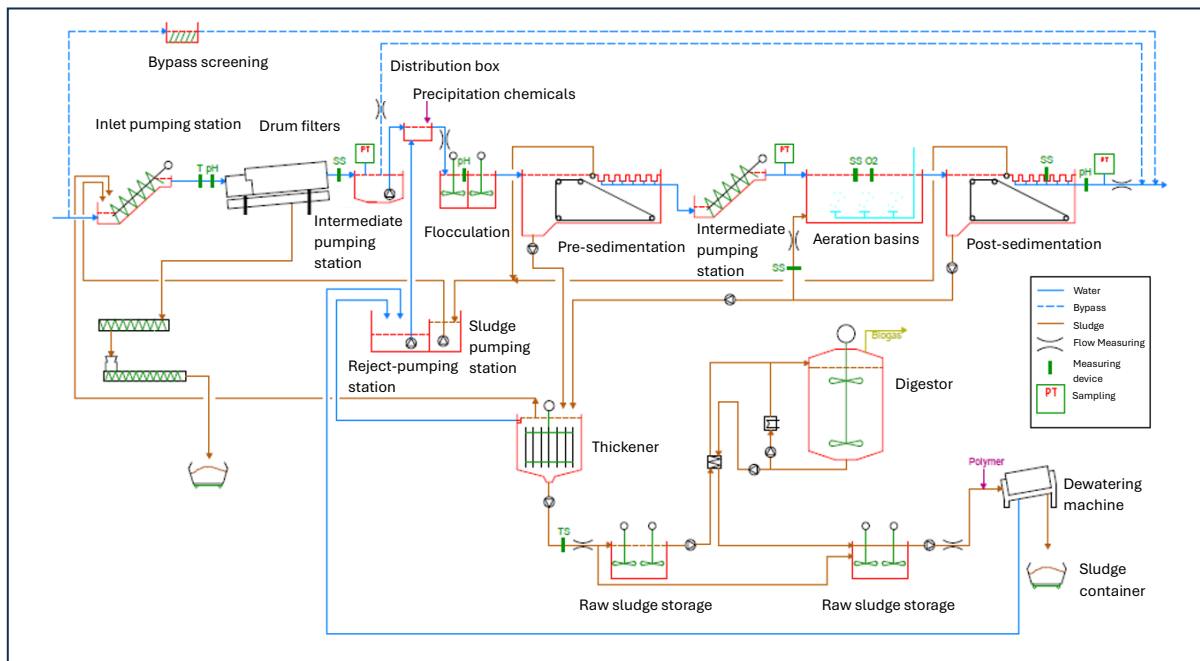


Figure A2 Process schematic for Essvik WWTP (M. Tuveesson, personal communication, August 8, 2024).

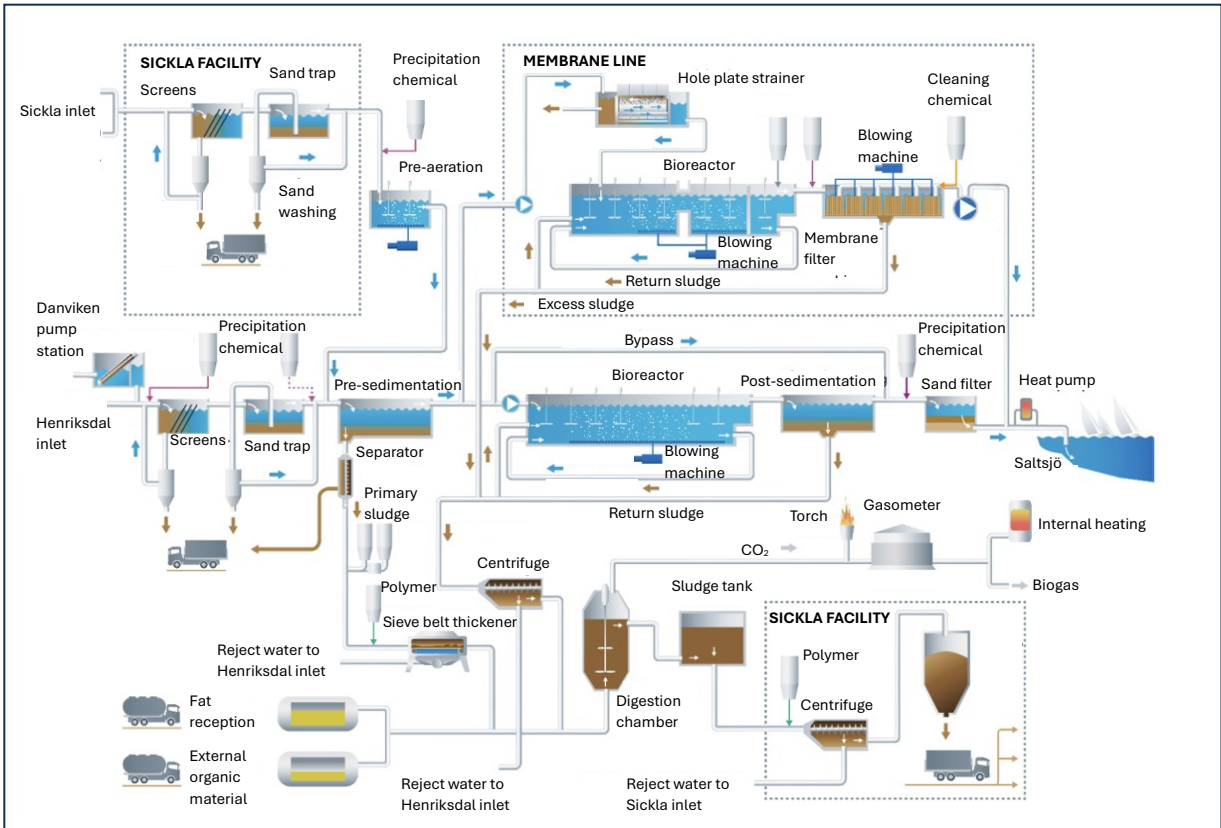


Figure A3 Process schematic for Henriksdal WWTP (D. Fujii, personal communication, April 24, 2024).

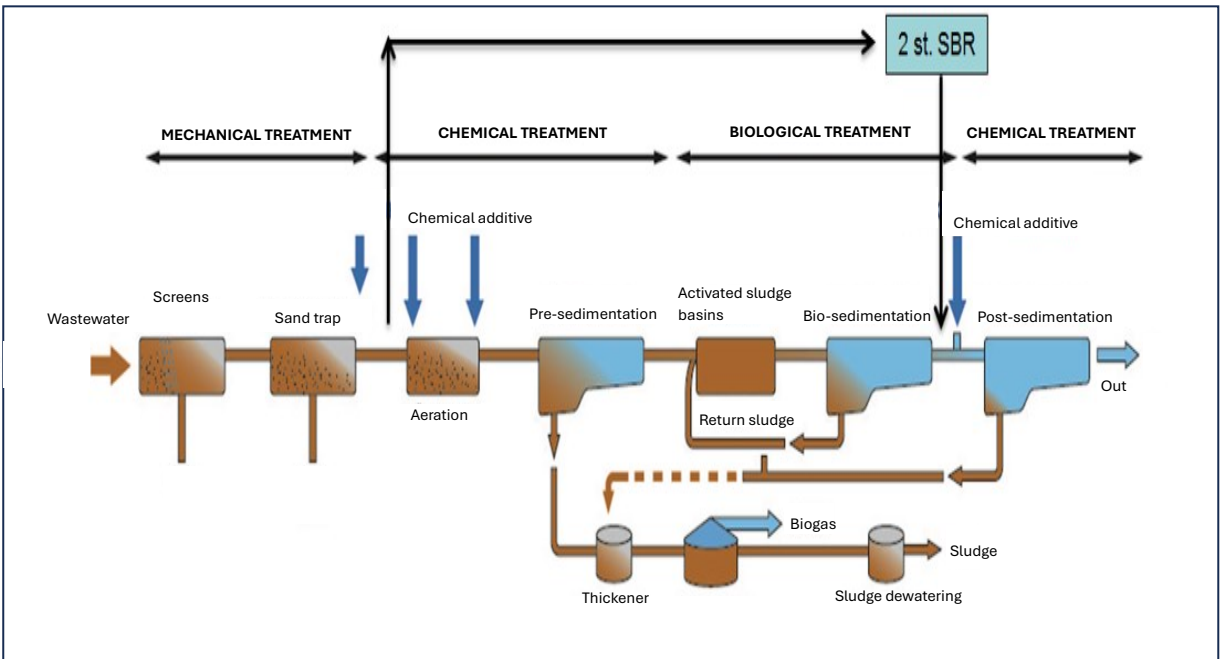


Figure A4 Process schematic for Kalmar WWTP (Q. Zhao, personal communication, August 14, 2024).

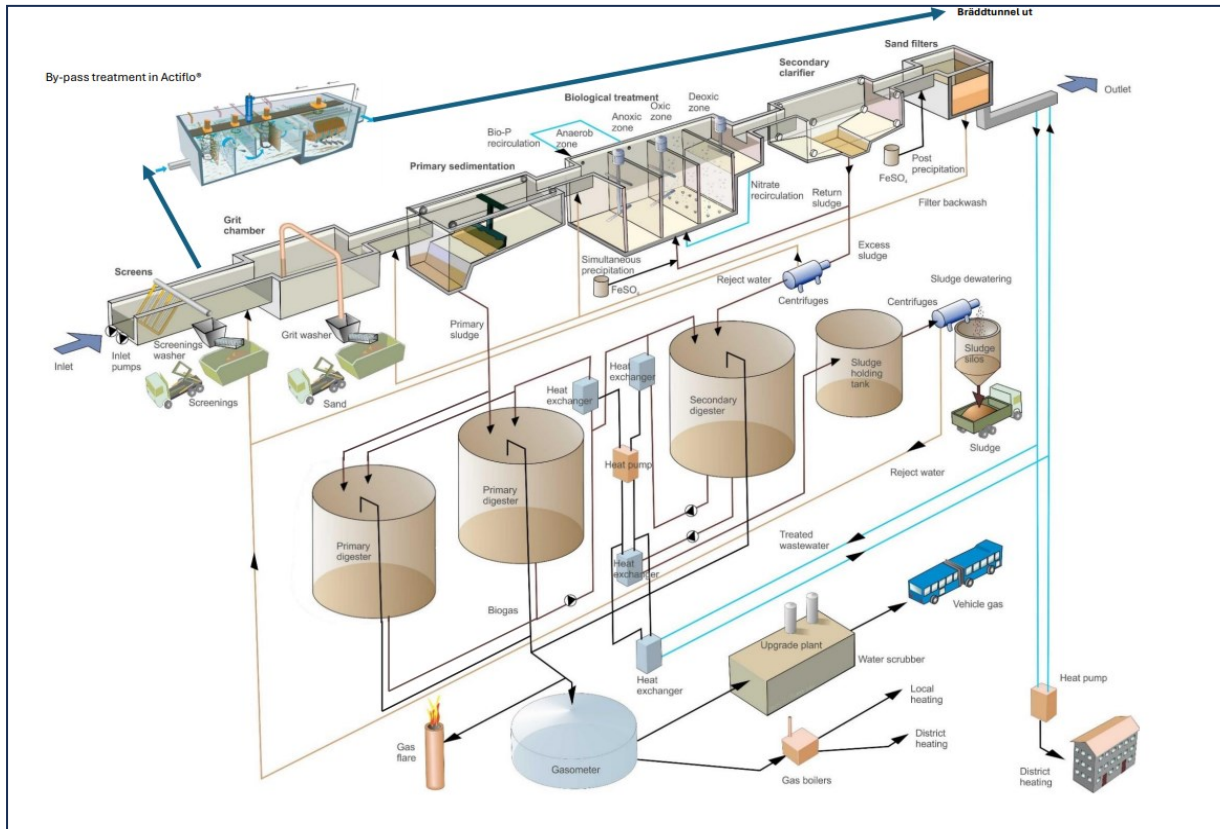


Figure A5 Process schematic for Käppala WWTP (C. Vendel, personal communication, August 28, 2024).

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