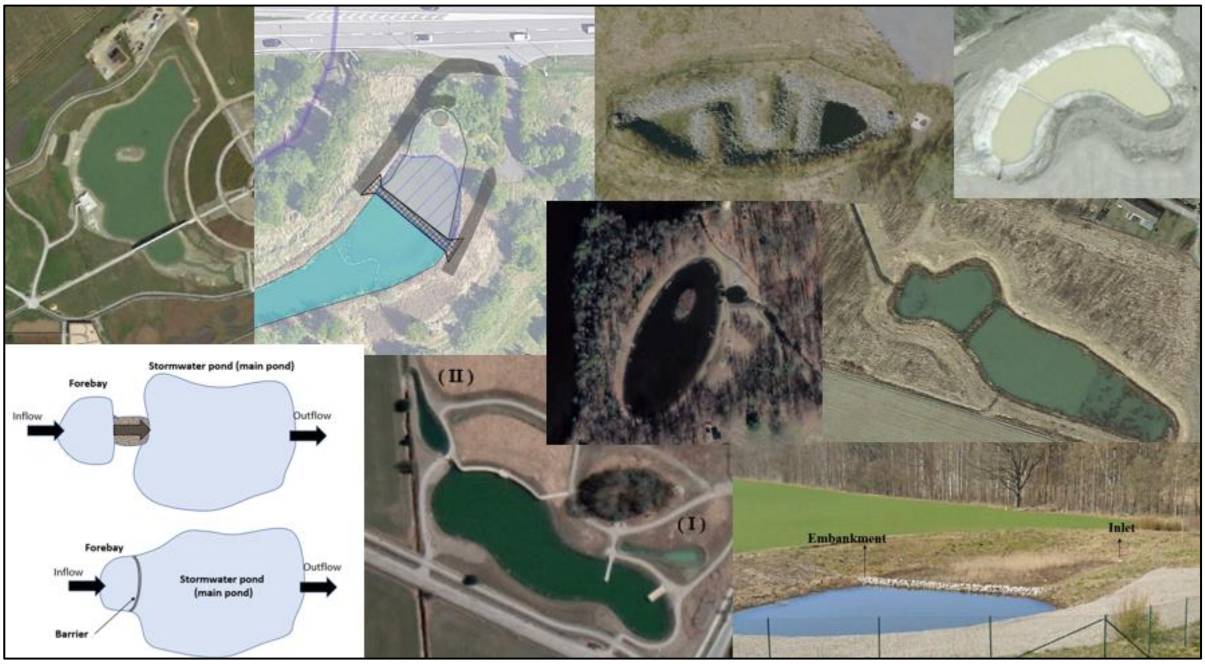
Design criteria for forebays in wet stormwater ponds



Study cases of stormwater pond's forebays in Sweden and international state-of-art

Nordic master thesis in Environmental Engineering – Urban Water & Water Resources Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Stormwater pollution is one main contributor to stormwater degradation. For this reason, many countries integrate best management practices (BMPs) to manage stormwater and reduce its pollution. Wet ponds are one possible BMPs to implement, widely applied internationally and in Sweden. A study made in Sweden concluded that the costs of construction are as significant as the cost of operating and maintaining these facilities. Therefore, there is a need of having more efficient designs, thus, some Swedish municipalities are interested in knowing more about the use of forebay. Some guidelines from different regions and countries and previous works are investigated during the literature review part of this thesis. Furthermore, an interview study has been made to investigate the existing design criteria in Sweden and an analysis of the design in existing cases of pond with forebay. Lastly, an example of the application of the design criteria in a case study is presented. Most of the local guidelines from different regions purpose design criteria based on the area or volume of the pond or based on a rain event. Few of them mentioned specifications about the shape of the forebay, even though the relationship between length and width is an important parameter when it comes to hydraulic efficiency in wet ponds. The results of the interview study made in Sweden shows that most of the design criteria applied in other countries are being applied in the country, however, there is a lack on unification. Furthermore, based on the analysis carried out in the studied cases in Sweden it is possible to notice that most of them do not follow the local guidelines from different regions. Some of the cases are clear examples of the importance of considering how is the system upstream and the importance to do maintenance of the forebays. To apply the design criteria important factors to consider are available space and the system upstream.

The conclusions of this work are the lack of theory when it comes to forebay design and that a methodology that takes into account more parameters is missing. Additionally, Sweden's design criteria consider most of the local design criteria from different counties, however, most of the studied facilities are not following these criteria. Furthermore, there is a lack of maintenance in the existing forebays in Sweden.

Keywords: BMP; forebay; maintenance; pre-treatment, stormwater management; wet ponds.

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Lucía Arce Rama, Gothenburg, June 2023

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LIST OF ACRONYMS

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ADT	Annual daily traffic
AU	Australia
BMPs	Best Management Practices
CAB	County Administrative Board
CIRIA	Construction Industry Research and Information Association
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Levy
EC	European Commission
EPA	Environmental Protection Agency
EQSs	Environmental Quality Standards
IDF	Intensity-Duration-Frequency
NZ	New Zeland
PoMs	Program of Measures
RANS	Reynolds averaged Navier Stokes
RBMPs	River Basin Management Plans
SVOA	Stockholm vatten och avfall
STA	Swedish Transport Administration (Trafikverket)
SWP	Stormwater Wet Pond
UK	United Kingdom
US	United States of America
WFD	Water Framework Directive

1. INTRODUCTION

1.1.BACKGROUND

The human influence on the planet has increased significantly in the past century: industries, roads and constructions are necessary to improve life quality, but are also sources of pollution and other environmental challenges. At the end of the past century, many countries started to worry about the water quality, introducing policies and implementing action to reduce stormwater pollution (Erickson et al., 2013). Urban runoff has been identified as a significant contributor to receiving water degradation, for this reason, it is crucial to take stormwater management into account when developing a city. In 2000, the European Union established the Water Framework Directive (European Commission, n.d.), which has been Europe's primary water protection regulation. The Directive´s aim is to ensure an integrated approach to water management, respecting the integrity of entire ecosystems by controlling specific contaminants and establishing matching regulatory requirements in rivers, lakes, groundwater, and bathing waters, being necessary to implement practices to improve water quality.

Throughout the years, several best management practices (BMPs) have been developed to reduce sediment and pollution loads in receiving waters. Stormwater ponds, including wet ponds, are one of the structural BMPs utilized extensively for stormwater management (Gu et al., 2017). Wet ponds are built basins with a permanent pool of water that help to control flood downstream, mitigate pollution and reduce channel erosion downstream (Hobart City Council, n.d.). Sediment settling and pollutant uptake, particularly of nutrients through biological activity, are the primary pollutant removal mechanisms in the pond. However, stormwater ponds are not just valuable for their water treatment and flood control uses, but they also provide ecological, social, and aesthetics services (Persson, 1999). Therefore, wet ponds have traditionally been a popular stormwater control method (Environmental Protection Agency, 2021).

One study made in Sweden investigated the costs associated with building, operation, and maintenance of stormwater ponds, concluding that the cost of operation and maintenance is as significant as the cost of construction, emphasizing the necessity of a good and efficient design (Berglund et al., 2022). The implementation of forebay in wet ponds will help to increase the efficiency of these facilities (EPA US, 2009). Forebays are small settling basins separated from the permanent wet pond, whose main goal is to encourage sedimentation to consolidate and capture coarse particles (McNett & Hunt, 2011). It is recommended that pre-treatment measures be built directly upstream of the main pond to decrease maintenance requirements and extend the lifetime of a stormwater treatment pond (Minnesota Pollution

Control Agency, n.d.). The use of a forebay will allow catching a significant amount of the entire sediment load in a small area, which makes easier the tasks related to cleaning and maintenance.

1.2. AIM

The aim of this thesis is to provide a state-of-the-art analysis of stormwater pond forebays by researching existing information and previous applications in Sweden. Additionally, the objective is to suggest how to design a forebay in Järnbrott pond, which has been chosen as the case study in this project.

1.3. SPECIFIC AIMS

A1) To research international guidelines in English and previous studies.
A2) To investigate the design criteria for forebays used in Sweden.
A3) To examine the recommendations and available information regarding maintenance frequency for forebays and ponds.
A4) To analyse how forebays have been implemented in Sweden.
A5) To suggest design criteria for implementing a forebay in Järnbrott pond.

1.4.LIMITATIONS

This section presents the general limitations of this thesis. To begin with, the language was one limiting factor during this work. Most of the documents describing ponds in in Sweden are in Swedish, and they were translated to English using Google Translate during this project. The quality of the translated documents was not precise as the original documents in Swedish. Another limitation related to language is that some of the interviewees answered in English despite they were not comfortable in this language. Even this was not an impediment for having an answer, the extension and amount of information could have changed if the interviews were carried in Swedish. A second limiting factor was the previous experience with MIKE 3, every steep was a challenge and not reliable results were obtained while trying to model some scenarios. Another limitation was the fact that no ponds with forebay are located in Gothenburg, which is the reason why no pond in the Gothenburg area is in this research. Lastly, the information of Järnbrott pond regarding bathymetry and levels was limited by the information available in previous studies.

2. THEORY

This chapter provides the theory related to stormwater and stormwater wet ponds (SWPs). Firstly, an introduction to stormwater is presented, including a brief introduction to stormwater quantity and quality and a description on how stormwater is managed in Sweden. Secondly, this chapter covers the design criteria and main mechanisms of wet stormwater ponds. Lastly, an overview of SWPs modeling is presented.

2.1.STORMWATER

Stormwater is the water that is generated through an environmental process that involves precipitation (rain and snow), land use, soil, vegetation, water bodies and landscapes. Precipitation infiltrates in the soil, comes back to the atmosphere by evapotranspiration processes, accumulates on the surfaces and in water bodies; the excess water that remains on the land surface is defined as stormwater (B. K. Ferguson, 1998). Urban catchments are characterised by impervious areas, thus, infiltration in permeable soils and evapotranspiration carried by plants are considerably reduced, resulting in higher stormwater volumes and flow peaks (Erickson et al., 2013). Higher pollutant concentrations are also expected as a reduction of infiltration areas, and increment of urbanization, since pollutants accumulate in the surfaces. It is widely known that population growth and urbanization result in the need for new roads, industries, and edifications that affect the quantity and quality of the stormwater of a watershed. Therefore, it is fundamental to include stormwater management when urbanizations are planned, since it includes important areas such as drainage, flooding control, water bodies, urban runoff, and water supply. Thus, stormwater management is essential for minimising the risk of floods and erosion, as well as for protecting water quality by reducing the amount of pollutants carried into streams, rivers, and lakes (Ferguson, 1998; Johnson, 2006). Stormwater composition depends on duration of the rain event and its intensity (Erickson et al., 2013). For this reason, pollutant concentration is usually represented as median concentrations.

2.1.1. STORMWATER ADMINISTRATION IN SWEDEN

This section describes the main organisations and legislation related to the stormwater management and water bodies in Sweden.

<u>European Water Framework Directive</u>

The Water Framework Directive (WFD), which was established in 2000, aims to protect and restore surface and ground water across the European Union, being the most important law for water protection in Europe (European Commission, n.d.). The WFD focuses on achieving good ecological and chemical status of water bodies, through an integrated approach to water management.

The WFD regulates specific contaminants and establishes regulatory standards. For surface waters, the WFD identifies 33 priority pollutants and establishes concentration limits for these contaminants in sources that discharge into water bodies and in water bodies themselves. The directive is based on the idea of a river basin district to ensure that neighbouring nations manage the shared rivers and other bodies of water.

Swedish Administration

Swedish legislation has adopted the WFD, therefore water management in Sweden is governed by the following three statutes: Swedish Environmental Code[1], Swedish Water Quality Management Ordinance[2] (also known as the Water Management Ordinance), and Swedish Ordinance[3] containing Instructions to the County Administrative Boards (Swedish Environmental Protection Agency, 2010). National Environmental Quality Standards (EQS) have been implemented in Sweden using the Swedish Environmental Code.

On a regional level, Sweden is divided into five water districts, which are established based on the water borders and catchment areas. The implementation of the Water Framework Directive and determination of the EQS is the responsibility of each district individually. They manage water delegation, coordinate the regional country administrative boards, and cooperate in a national and international level (European Committee of the Regions, n.d.).

On a local level, Sweden is divided into 290 municipalities. The local authorities are responsible for providing water, sewers, and wastewater treatment, either directly or through water companies that are owned by the municipalities (European Committee of the Regions, n.d.). In addition, they are in charge of planning the use of land and water, applying some PoM’s measures, and following WFD-related permits and enforcement. Municipalities have to coordinate local collaboration.

Swedish Transport Administration

When it comes to road runoff management, the Swedish Transport Administration (STA) (Trafikverket in Swedish) is responsible for implementing the Swedish Environmental Codein roads (Andersson et al., 2018). STA has written handbooks that guide how to deal with stormwater, but without establishing which treatment facility has to be implemented. The treatment design for each case depends on

[1] Miljöbalk (1998:808)
[2] Vattenförvaltningsförordning (2004:660)
[3] Förordning (2002:864) med länsstyrelseinstruktion

environmental, hydraulic, economic, and aesthetic aspects based on the requirements of local authorities.

2.1.2. STORMWATER QUANTITY

Determining the amount of runoff in a drainage design is one of the first steps to solve in hydrological design projects. Runoff, also known as effective rainfall, is the surface water generated from a rainfall event after considering the losses generated in the catchment and the routing effect at the surface (Butler et al., 2018). Rainfall events are commonly approached by defining a relationship between frequency, intensity and duration based on the catchment characteristics and location (Chow, 1988). The relationship is usually presented by the IDF (Intensity-Duration-Frequency) curves graph. The temporal distribution of a rainfall event and its intensity depends on the location, and in some areas the intensity of rain events is increasing as a consequence of climate change (NASA, n.d.; Tamm et al., 2023)

The frequency of the rainfall event is established with the return period, T_r (Chow, 1988). Considering that the largest event in one year is statistically independent of the largest event in any other year, annual maximum storm events are typically used to calculate return period (Butler et al., 2018). Therefore, the return period is the average time between precipitation events with a magnitude equal to or greater than the design one (Chow, 1988). The return period indicates the probability of exceeding a certain magnitude by the relationship stated in Equation (2-1).

$$T_r = \frac{1}{Pr_{ex}} \tag{2-1}$$

Where T_r is the return period in years, and Pr_{ex} is the probability of exceeding a certain magnitude during the rain event (a specific volume of water in the duration of the rain event).

The intensity, i, refers to the time rate precipitation, usually in mm/h. It can be an instantaneous value, or an average in time. It can be written as presented in Equation (2-2) (Chow, 1988).

$$i = \frac{P}{d} \tag{2-2}$$

Where i is the intensity in mm/hr, P is the precipitation in mm and d is the duration in hours.

Runoff is the transformation of the rainfall event to the effective rain in the catchment (Butler et al., 2018). Once that the rain events reach the catchment surface two main processes occur to transform the rain event in runoff. The first one is losses due to interception, evapotranspiration, depression storages and percolation (Butler et al., 2018). The second one is generated by the surface routing. For this reason, land use is going to play a fundamental role when it comes of runoff quantity, since the infiltration, evaporation and routing processes are going to depend on the permeability of the surface and the type of vegetation (Chow, 1988). As it was mentioned above, runoff is fundamental for designing stormwater infrastructure, since runoff represents the water flowing in the catchments.

2.1.3. QUALITY

Some metals, nutrients, sediments, and other inorganic compounds are present in the water naturally or as a result of human activity (van der Perk, 2007). However, the pollutant's capacity of producing damage is going to be related to two concepts, toxicity and bioavailability. Its bioavailability is going to define how easily the pollutant can be taken by an organism, while toxicity refers to the way a certain pollutant can interfere in its body, the capacity of causing damage.

To study stormwater quality, it is important to distinguish between the different pollutants to be able to design effective measures to improve the water quality (Pettersson, 1999). They can be classified in many ways, considering their physical and chemical characteristics, persistence in environment, consequences, or toxicity (Erickson et al., 2013; van der Perk, 2007). This work is going to describe the following pollutants:

- Nutrients
- Metals
- Microplastics
- Organic pollutants
- Dissolved phase constituents
- Suspended solids

Nutrients, primarily phosphorus and nitrogen, are responsible for a process called eutrophication, which involves an increase in plant growth in water bodies. The decomposition and oxidation of plant matter resulting from overgrowth can lead to low dissolved oxygen concentrations in the water. The increment of nutrient loads is usually related to the use of fertilizers (Erickson et al., 2013; van der Perk, 2007). Phosphorous causes higher turbidity, since it is associated with high concentration of suspended particles (Griffin, 2018). Turbidity will reduce the amount of light penetrating into the water, restricting the photosynthesis and thereby reducing aquatic biodiversity and dissolved oxygen (Erickson et al., 2013).

Metals can potentially be toxic for humans and ecosystems, affecting the growth, reproduction, and survival capacities of organisms. Some metals (i.e. lead, mercury, nickel and cadmium) are included in the 33 priority substances regulated according the WFD (Swedish Environmental Protection Agency, 2010). These ones are lead, mercury, nickel, and cadmium. However, copper and zinc are also important to limit in the environment (Griffin, 2018). The physico-chemical form of metals, known as metal speciation, is defined by the pH and redox potential of water. If metals are in an ionic form, they are expected to have a high bioavailability (Erickson et al., 2013; van der Perk, 2007). Metals can be present in dissolved or solid phase. It is important to take this into account since it is going to play an important role to define the treatment to reduce metals' concentration (Erickson et al., 2013; Griffin, 2018).

Microplastics are typically defined as plastic particles between 1 and 5,000 µm size (GESAMP, 2019). Textiles, tires, general waste, items containing microplastics, and equipment/products used in fisheries, agriculture, and industry are all potential contributors to microplastic pollution (Bujnicki et al., 2019). Studies identified traffic as one of the main microplastic sources, mostly composed of rubber and bitumen coming from the tires and the road material (Järlskog et al., 2020). There are uncertainties and not clear evidence of damages in humans and ecosystem due to microplastic, which enters organisms via inhalation, food or skin (Bujnicki et al., 2019).

Organic pollutants consist of compounds conformed mainly by carbon, oxygen and hydrogen, and in small amount by other elements (van der Perk, 2007). Potentially, all organic compounds can be toxic, however, some of them can cause directly harmful in living organism and ecosystems. Some direct consequences can be toxicity, cancer, allergies, or damage to the immune, nervous and reproductive systems. These pollutants are mostly man-made, and their emissions are linked to the use of petroleum and pesticides.

Stormwater carries dissolved pollutants. The occurrence of both dissolved and suspended pollutants is important for the design of treatment processes, since suspended solids are going to be removed mostly by sedimentation or filtration, while dissolved pollutants mostly by chemical and biological processes (Erickson et al., 2013; Pettersson, 1999). The dissolved pollutants are mostly formed by inorganic compounds such as ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and carbonate species) (van der Perk, 2007).

Suspended solids can be pollutants by itself or be a vector of other substances that are attached to it (Griffin, 2018). It has been shown that too much sediment can negatively affect aquatic life and fisheries and water bodies used as drinking water sources and recreational activities (Gu et al., 2017a). Suspended solids are going to be effectively removed by sedimentation. Its particle size and density impact the transportability and settling rates of particles (Griffin, 2018). Furthermore, physical effects and health impacts are also related to particle size. The coarse material (sand and gravels between 0.5 mm and 10 mm) will settle in a time between seconds to minutes. Whereas finer material (clay and silt) will need longer times to be able to settle, from hours to days.

Total suspended solids (TSS) is a measure of the suspended particulate material in the water. Some particles, the coarse particles, are going to settle in shorter times than the fine material (Griffin, 2018).

In studies carried out in US it was found that TSS in urban catchments vary from 58 mg/L to 262 mg/L, with average values of 100 mg/L in cities (Erickson et al., 2013).

Dissolved pollutants can be adsorbed on the particle's surface (Winkler, 2005). Adsorption is the process by which dissolved ions attach to the surface of a solid particle, making possible to remove the dissolved pollutants by sedimentation or filtration (Erickson et al., 2013; Winkler, 2005). The finer the sediments are, the higher the adsorption capacity (Winkler, 2005).

A study made in an urban catchment in Brazil conclude that heavy metals are more concentrated in granulometry sizes smaller than 63 µm (Gastaldini & Silva, 2013). Ammonia, nitrates, lead and zinc were present in the granulometry levels between 63µm and 250µm. While for sizes higher than 500 µm high chemical oxygen demand (COD) and phosphate were found. It is important to point out that sand-size sediments (≥63 µm) have short settling times (Erickson et al., 2013).

To sum up, size particle distribution in water is fundamental since it is related to the physicochemical characteristics of the particle and it is necessary to predict the routes of the pollutants in the water (Gastaldini & Silva, 2013).

Suspended solids are important when it comes to road runoff, since they are present in high quantities (Andersson et al., 2018). TSS in road runoff are a result of pavement wear, tires, vehicles abrasion, atmosphere, maintenance, road construction, snow and ice and surroundings (Andersson et al., 2018; Winkler, 2005).

The average concentration of TSS in road runoff considering an ADT higher than 10,000 vehicles is 200 mg/L (Winkler, 2005), however, this value varies depending on the catchment type. Urban areas are going to have higher load of TSS than rural areas considering the same ADT. Additionally, TSS in road catchments is proportional to the ADT.

The particle size in road catchment varies between 0-2 mm (Zanders, 2005), where around half of the material is smaller than 250 µm, one third smaller than 125 µm, and just 6 % smaller than 32 µm. While another study states that most dominant size smaller than 75 µm (Kim & Sansalone, 2008). It was estimated that around 25-80 % of the TSS correspond to particles smaller than 75 µm.

2.2. WET PONDS

This chapter describes wet ponds and the main mechanisms of pollutant removal from stormwater runoff.

2.2.1. GENERAL DESCRIPTION

Wet ponds consist of a depression in the ground, designed to store water during rainfall events and improve water quality (Erickson et al., 2013). The runoff quantity can be controlled by storing runoff in the pond and slowly releasing it. Water can also be reduced by infiltration and evapotranspiration. Infiltration in the pond depends on the material of the pond and the water table in the area.

The treatment in a wet pond is mostly a result of sedimentation processes and uptake mechanisms carried by aquatic vegetation and biological organisms (Erickson et al., 2013). As a result, wet ponds have a high capacity for removing urban pollutants and improving surface runoff quality. A high hydraulic efficiency can be achieved based on a good design of the shape, ratio length-width, baffling, depth of the pond, location inlets and outlets, and the vegetation (Persson, 2000). For optimizing the maintenance task in wet ponds, it is recommended to include one or more sediment forebays (depending on the number of inlets) upstream the wet pond. For a good design it is also recommended to include pond drains, access to the pond and forebay, and a designated on-site disposal place (EPA US, 2009). These considerations in the design will reduce the costs related to maintenance.

Wet ponds are usually more efficient than dry ponds when it comes to sediment retention (Erickson et al., 2013). Dry ponds consist of depressions in the ground, but they store stormwater temporarily. Wet ponds are more efficient than dry ponds due to the longer detention times in the wet ponds. The management of stormwater quantity and quality provided by wet ponds is important for the environment. They also offer environmental value by serving as habitats for many species such as birds, plants, insects, and amphibians, thus generating new ecosystems within cities (Butler, Digman, Makropoulos Christos, & Davies, 2018). Moreover, wet ponds have aesthetic and recreational value as they provide opportunities for activities such as fishing, paddling, and enjoying nature. SWPs are among the most popular centralised stormwater treatment facilities in Sweden and Norway (Andersson et al., 2018).

2.2.2. REMOVAL MECHANISMS

Physical processes

Sedimentation is one of the main processes for removing pollutants used in many different types of stormwater treatment facilities. The process consists of particles settling from a water column to the bottom (Erickson et al., 2013).

Temperature, viscosity of the fluid and diameter and density of the particles are fundamental parameters when it comes to sedimentation processes. The settling velocity can be given by Stokes' (Bridges & Robinson, 2020).

According to Stokes' equation, the settling velocity is proportional to the size of the solid (diameter) and the density, considering gravity as the main physical factor during settling (R. I. Ferguson & Church, 2004). There are different modifications of Stokes' equation adapting it for different size and type of particles, thus different Reynold's number. In these adaptations, the diameter has sometimes less weight in the settling velocity compared to Stokes' equation. Sedimentation is less effective if there is a short-circuiting, thus the water passes through the pond without displacing the old water, or, if the inlet volume is higher than the design volume, which implies that that the incoming runoff passes through the pond without modifications (Schueler, 1987).

Another important physical process that can occur due to wind, waves, vegetation and flow is having a turbulent flow (Bentzen, 2010; Gu et al., 2017a). Turbulence decreases particle settlement while also mixing the water column, resulting in a sediment concentration profile that is a balance of settling and mixing. However, at the bottom of the stormwater pond, turbulence dissipates, and the particles near the bottom settle (Erickson et al., 2013). Thus, it significantly affects the settling process reducing TSS removal effectiveness because it prevents suspended solids from settling and may even promote resuspension of settled particles (Ahadi et al., 2020; Gu et al., 2017a). Turbulence processes intensify when flow velocity is high.

Lastly, resuspension of the settled sediments is another possible physical process. If this happens, it is possible to get negative efficiencies in pollutant removal since the settled materials will return to the water column (Erickson et al., 2013). The settled sediments are resuspended due to the energy from high flows, wind, waves or other stress factors (Chen et al., 2019; Zhang, 2009).

Chemical processes

Pollutants may also be removed from ponds better by chemical methods. Many ions, especially metals, are removed by adsorption or chemical precipitation as response of these changes (Erickson et al., 2013; Marsalek et al., 1992). Moreover, physical and chemical processes between the pond bed sediment and water column occur, affecting the water quality in the pond through sorption/desorption of pollutants. Metals and nutrients are the pollutants of more concern when it comes to physic-chemical interactions.

Biological processes

The presence of vegetation can remove dissolved pollutants from the water column (Schueler, 1987). The plants can transform the nutrients into biomass, which can settle at the bottom of the pond. Once the nutrients and organic matter are settled, the microorganism at the bottom will consume them and remove them from the system. Studies showed that plants in stormwater ponds improved the removal of copper, dissolved phosphorus, and fine suspended particles (and associated turbidity) (Tanner & Headley, 2011). Furthermore, it was studied that vegetation has a positive effect on settling by reducing the resuspension of the particles (Braskerud, 2001). Another biological process is related to the degradation of the organic matter due to the microbial respiration, process in which microorganisms oxidize organic matter to CO_2 (Erickson et al., 2013).

In general, the use of vegetation is incorporated into different BMPs. Plants can concentrate pollutants in their roots, stems and leaves and reduce their amount or toxicity by phytotechnologies (Henry et al., 2013). Plants can convert pollutants to less harmful chemicals metals and organic and inorganic pollutants by different mechanisms (Ali et al., 2020; Limmer & Burken, 2016). However, too much vegetation can lead to short-circuiting in the pond, which reduces the hydraulic efficiency by increasing the retention time (Hart et al., 2014). A higher retention time can result in algal blooms, needing higher maintenance tasks to remove the vegetation (Revitt et al., 2003).

2.2.1. DESIGN CRITERIA

This section presents different criteria to consider when designing a wet pond based on previous research.

Rain event

The pond efficiency will vary depending on the rain event (Pettersson, 1999). For this reason, it is important to make long-period simulations when it comes to studying pollutant removal efficiency. It is difficult to design the pond in a way that provides adequate detention time for a wide variety of storm events (Schueler, 1987). If the outlet is designed to store and release a one-year storm over 24 hours, smaller rain events are going to pass through the pond without enough retention time. The problem is that these smaller rain events are responsible for the majority of the annual runoff volume, thus, pollution. As a consequence, if these smaller events do not have enough detention time in the pond, the majority of the pollutants are not going to be retained in the facility. For this reason, a better design is needed, which can be achieved if the pond is designed to have an average of 24 hours of detention time for a wide spectrum of rain events each year (Grizzard et al., 1986). As a general idea, it is recommended that a rain event of 25-50 mm has at least 6 hours of detentions time (Grizzard et al., 1986). A literature review in Europe suggests that the design rainfall to calculate treatment volume should be the larger between the following options: the volume of 90 % of all the rain events in one year; the volume of a return period of 1 year or 6 months, 25 mm of rain in the whole catchment or 10-15 mm of effective rainfall runoff (Revitt et al., 2003). For heavier events it is possible to design a bypass to avoid high flows into the pond (Larm & Alm, 2014). The bypassed flow is not going to receive treatment, but it increases the treatment efficiency in the pond.

Hydraulic load

Hydraulic load refers to the relationship between the catchment area and the imperviousness area (Al-Rubaei et al., 2017). The characteristic of the incoming stormwater will determine the efficiency of the pond (Marsalek et al., 1992). For this reason, it is important to analyse the percentage of impervious surface, since this is related to a higher accumulation of pollutants (EPA US, 1999; Erickson et al., 2013). A previous study concluded that the optimal size for a stormwater pond is around 250 m^2/ha of the impervious catchment area (Pettersson, 1999). A higher specific pond area than 250 m^2/ha does not affect the efficiency of pollutant removal. Local guidelines from different regions propose a volume of the pond based on different possibilities for pond's depth and impervious area of the catchments (North Carolina Environmental Quality, 2020). Typically, ponds are designed with areas between 200-300 m^2/ha of the impervious catchment area (Erickson et al., 2013).

Hydraulic efficiency

Studying the hydraulic performance in ponds is important for having a design that encourages good flow conditions (well distributed flow, encouraging a water exchange during storm events) (Pettersson, 1999). Usually, flow regimes in pond are a combination between a mixed flow and a plug flow (Persson, 1999). Plug flow would give ideal conditions for the pond, however, it is impossible to achieve it completely (Edward Thackston et al., 1987) and it is not common to have it natural (Persson, 1999). Wind, inlet, outlet, and rain intensity are going to play an important role in the flow regime (Edward Thackston et al., 1987; Pettersson, 1999). Furthermore, the pond's shape also influences the flow regime (Persson, 1999). Avoiding short-circuit is important since they can reduce sediment removal efficiency, since it results in a reduction of the detention time, and they can also generate resuspension of settled sediments (Erickson et al., 2013).

A previous research defined an expression to determine and compare the hydraulic performance for different pond designs (Persson, 1999). The study defines a hydraulic efficiency factor, represented by λ, based on two considerations. The first consideration was to make the hydraulic efficiency factor simple and easy to understand, while the second consideration minimise the effect of having a plug flow or not. Hydraulic efficiency is a combination of two main factors: effective volume ratio and the amount of mixing. Based on the λ value it is possible to classify the hydraulic efficiency of the pond. Values higher than 0.75 indicate a good efficiency, while values between 0.5 and 0.75 indicate satisfactory efficiency.

Size and geometry

Geometry of the stormwater pond plays a fundamental role in the detention time (Marsalek et al., 1992) and internal flow pattern (Persson, 1999, 2000). Therefore, pond geometry plays a vital role in hydraulic performance. The hydraulic efficiency of ellipse-shape and kidney-shaped ponds is likely to be greater than that of rectangular ponds with the same surface area (Jansons & Law, 2007). It is recommended to have a relationship higher than 3:1 (length:width) since it is possible to have a higher residential times and higher efficiency in the settling processes (Al-Rubaei, Merriman, et al., 2017). The higher the relationship “length:width” is, the higher hydraulic efficiency of the pond. The settling processes can be encouraged by extending the flow path by the implementation of baffles, islands, inlet design (Persson, 2000).

Deep ponds are not recommended due to the possibilities of becoming anoxic near the bottom of the pond (Petterson, 1996). Dry periods or winter times are when the pond has higher risk to become anoxic, since no inflow enter to the facility, or an ice layer cover the surface of the pond. Depth’s recommendations vary from 1 m to 2.5 m (Gu et al., 2017a). Shallow ponds are also beneficial since they reduce the probability of stratification.

Inlet and outlet

A previous study shows that a higher accumulation of sediments happens near the inlet (Heal, Hepburn, & Lunn, 2006). Thus, including a forebay in the main inlets will provide an area to accumulate the coarse sediments, and remove them, minimizing the disturbance of the pond ecosystem. Limiting the inlet flow will avoid resuspension of settled sediment and it will diminish the probability of short-circuit regimes (Gu et al., 2017a).

The inlet design is important when it comes to pond efficiency. It is better to have an inlet design that allows for a distribution of the flow throughout the pond (Persson, 1999). Thus, short-circuiting is avoided, and a higher efficiency is achieved of the storage capacity. Previous studies have shown that the best configuration for the inlet and outlet is when they are located at the midpoint of one of the pond’s extremes (Persson, 1999; Su et al., 2009).

Vegetation

The presence of vegetation results in a reduction of water velocity, which encourage particle retention (Larm & Alm, 2014). Furthermore, vegetation diminishes the resuspension of deposit sediments (Gu et al., 2017).

Having aquatic vegetation improves biological processes (Ellis, 1989; Marsalek et al., 1992), since it provides uptake of nutrients and metals in dissolved phase, and the vegetation is the habitat for microorganisms that contribute to treatment processes (Larm & Alm, 2014). Pollutants are absorbed primarily through the roots, where the concentration of contaminants is greatest. Up to one-third of the pond's total area has been suggested for such purposes (Ellis, 1989).

It has been determined that vegetation patches generate preferential flow pathways within the natural pond, resulting in short-circuiting, which leed to a decrease in the pond's effective volume and, consequently, a shorter residence time than the nominal residence time (Hart et al., 2014). Pickerelweed leaf detritus deposition in the fall and algal suspended solids have both been linked to elevated TSS concentrations (Song et al., 2015).

2.2.2. MAINTENANCE

This section presents different aspects of ponds' maintenance. Correct maintenance is fundamental to have a high-quality removal efficiency, flood mitigation capacity and how the pond look, which plays an important role for recreational activities near it (Hunt & Lord, 2006). The main maintenance tasks for wet ponds consist of sediment removal in forebays and main pond, keeping inlet and outlet without obstructions, removal of floating trash and debris, control of vegetations and invasive plant species, mow around the pond, and control pest.

The correct design of the facility includes paths and elements to facilitate maintenance and operation tasks. Both, people and machinery, must be able to reach the facility (Blecken et al., 2017). Even if it sounds as something obvious, previous studies made in US and Sweden found that around 15% of the studied facilities have not considered easy access to the ponds (Al-Rubaei, Merriman, et al., 2017; Hirschman & Woodworth, 2010).

One of the main tasks is related to the sediment removal in the pond and forebay. According to Trafikverket, dredging is typically performed every 15 to 20 years in order to remove contaminated sediments and reduce the risk of contamination escaping into the surrounding environment (Andersson et al., 2018).

There are two possible techniques for dredging: mechanical and hydraulic (Andersson et al., 2018; Eisma, 2005). Mechanical dredging has good precision; thus, it is possible to avoid mixing of the different soil layers. Furthermore, water content of the sediments resulting from this technique is between 30-50%. The second technique, hydraulic dredging, is inaccurate when excavating the soil profile and water content is typically 80% of the total weight since water is added during the transportation. The simplest method of hydraulic dredging is suction. A study carried out in Sweden concluded that it is better a pond's design that permit the sediment removal by mechanical dredging, instead of suction dredging. The reason of that it is that suction dredging increases maintenance cost by near 30 % (Berglund et al., 2022).

A common practice to deal with the sediments removed is to store them next to the facility to allow them to dry/dewater. The aim is to reduce the volume and weight before being transported to the final disposition (Blecken et al., 2017). During the drying/dewatering time, the chemical phase is going to be affected causing a new distribution between solid and dissolved phase (Camponelli et al., 2010). As a consequence, the leachate resulted from dewatering contains a large metal concentration (Karlsson et al., 2010).

There are different visual inspections that can be done in wet ponds. One of the most important one is related to the inlet and outlet structures (Erickson et al., 2013). Both should be free from debris, trash, sediment, and vegetation, ensuring that the water can enter and leave the facility without any problem, as it was designed. If the outlet structure is clogged, it can result in a flooding situation and polluted water by-passing the pond.

The presence of some invasive species can be an indicator of an incorrect functioning of the wet pond, which are more tolerant to poor water quality conditions such as low dissolved oxygen levels and turbidity. This indicates that water is polluted and remediation actions to improve water quality need to be taken. Moreover, vegetation in poor conditions or dead vegetation can be another indicator that the water conditions differ from the original design. Lastly, the presence of sand and sediments downstream of the outlet indicates a poor design or incorrect function of the wet pond.

Since wet ponds usually retain water for long periods (from 12 hours to days), the orifice that controls the outlet is of small dimensions, which make it susceptible to being clogged (Hunt & Lord, 2006). If this happens, several problems can occur such as loss of storage capacity, flood of desirable plants encouraging the appearance of invasive species, loss of aesthetical value, and decrease of the pond performance.

A study carried out in Sweden, where 25 municipal stormwater wet ponds and wetlands were studied, concludes that almost 50% of the facilities were in need on maintenance mostly due to minor sediment accumulation near the inlet and outlet, and all of them had sediment accumulation at the inlet (Al-Rubaei, Merriman, et al., 2017). Four of the studied facilities were inaccessible, being difficult to maintain.

2.3.FOREBAY

A forebay consists of an extra storage volume located upstream of the inlet of the BMPs (ponds are one type of BMPs). Forebays are designed to trap the particles in a confined area and reduce sediment accumulation in the pond, since the coarse material accumulates in this upstream unit (Department of Environmental Protection, 2006). EPA, US, defines forebay as "*an additional storage space located near a stormwater practice inlet that serves to trap incoming coarse sediments before they accumulate in the main treatment area*" (EPA US, 2009). The forebay has two possible configurations: it can either be a section located inside the pond, which is isolated by a suitable barrier like a berm/embankment, or it can be a distinct structure situated upstream of the primary pond (Woods-Ballard et al., 2007).

Forebays are fundamental to increase the efficiency of wetlands, ponds, and infiltration basins. Forebay's location is important since they must be accessible to facilitate the maintenance (EPA US, 2009; Virginia Department of Environmental Quality, 2011). Forebays are the most common pretreatment for ponds (Environmental Protection Agency, 2021), and they have two main functions: first, to capture entering coarse sediments, encouraging heavier particles to settle, prior to their accumulation in the primary treatment area, and second, to dissipate energy from the inflow (EPA US, 2009; Minnesota Pollution Control Agency, n.d.). A research study suggested that two different and individual zones in the forebay must be defined. Firstly, a zone for energy dissipation, followed by a sedimentation zone (Johnson, 2006). The use of forebay also diminish the possibility of short-circuiting in the pond (Pennsylvania Stormwater Best Management Practices Manual, 2006).

2.4.MODELING OF PONDS

This chapter presents the theory of computational fluid dynamics related to wet ponds and a brief summary of ponds modeling. The purpose of modeling a wet pond is to gain a comprehensive understanding of the hydraulics within the facility and to predict different behaviours for various rain events and configurations. This analysis allows for the examination of how the hydraulic behaviour changes when a forebay is added to the wet pond.

2.4.1. COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CDF) involves the study of fluids, mathematics, and computer science (Tu et al., 2012). It describes flow behaviour and processes that influence the flow, such as chemical or physical reactions. To determine the fluid-flow behaviour, CFD solves mathematical equations by the use of computer science. Thus, CFD is a numerical method for solving the fluid dynamic and sediment transport equations in a water body as a pond. It is a valuable design tool for assessing a wet pond. It allows to have previous information to understand some flow characteristics at any place inside the pond (Yan, 2014; Zhang, 2009). Most of the times, it is important to have field lab validation to implement a CFD model. It is an important part of CFD modeling to have a reliable model (Ahadi et al., 2020). To ensure a release model input data as geometry, initial and boundary conditions and mesh and time independency are reviewed and analysed. The results obtained from the CFD model are also compared to the experiments data. The mesh is an important element to study since its characteristics are fundamental to have an accurate solution and in the required modeling time, thereby, in the modeling costs. Therefore, mesh resolution is an important consideration to evaluate, and it is necessary to ensure that the obtained results are independent of the mesh resolution used (Jarman et al., 2008; Yan, 2014) Ideally, the mesh should aim to identify the smallest scale mesh possible that matches to the level of accuracy required. Some errors that can appear indicating an incorrect selection of mesh or time-step are computer errors, not enough spatial discretization, too large temporal advancement or a not converging solution.

2.4.2. PREVIOUS STUDIES

Popular CFD software for modeling flow and sediments in ponds, lagoons and lakes are FLOW-3D, DELFT3D, MIKE 3, FLUENT, EFDC-3D (Bentzen, 2010; Bollaert & Schleiss, 2001; Chen, 2017; Gu et al., 2017b). Previous studies showed that 3-D modeling is necessary when it comes to pond modeling, since just 2-D modeling will not consider the bottom variations and not considering the pond bathymetry will produce unrealistic flow patterns (Pettersson, 1999). However, 3-D modeling is time consuming. Many researchers have studied different characteristics of ponds and determined the detention time by modeling in 2-D and 3-D (Jansons & Law, 2007; Laurent et al., 2013; Persson, 1999). Many authors have proved successfully results in modeling in stormwater ponds. Some of them studying wind effects (Bentzen et al., 2005; Chen et al., 2019), while others studying deposition and resuspension of pollutants in the facilities (Bentzen, 2010; Bentzen et al., 2005). Bentzen et al. (2005) showed that it is possible to model a pond, its hydrodynamics and transport of pollutants using MIKE 3. Big difference in the results were observed after considering or not wind. When wind is applied, the concentration peak is underestimated, concluding that wind has an important effect on mixing of the pollutant in the pond. The research implies that the model contributes to represent the behaviour of settleable soils in the pond. Petterson (1996) researched about the flow behaviour in a pond for two rainstorm events, obtaining flow patterns similar to measurements by the use of a finite element method model called FIDAP. Bentzen (2010) investigated about pollution in wet ponds by modeling hydrodynamics and transport of dissolved pollutants and particles. It was considered during the study physical phenomena such as wind, deposition, waves, and settle sediments using MIKE 3. Including the wind and the bottom sediments consolidation is fundamental to model resuspension processes. The model results showed agreements compared with the measurements. Chen (2017) investigated the impact of wind on dissolved oxygen in two wet stormwater ponds in MIKE 3, using the water quality module. He concludes that the wind effect is more noticeable when flow is lower, and that a high wind speed encourages full mixing conditions. Furthermore, reduced wind speed affected current directions more so than velocity magnitude and it motivates vertical stratification. It is possible to notice that most of the 3-D modeling in wet ponds were carried out using the software MIKE 3, and most of them used the k-ε model for turbulence modeling (Ahadi et al., 2020; Bentzen et al., 2005; Laurent et al., 2013). Delft3D has been applied just in wastewater lagoons (Mahyari et al., 2023), its main advantage respect to the other software is that the source code is free (Deltares, n.d.).

2.4.3. MIKE 3

MIKE 3 is the most used CDF software model the hydrodynamic in SWPs by solving the 3-D incompressible Reynold averaged Navier Stokes equations, known as RANS, considering the Boussinesq assumptions (DHI, 2023a). The model combines continuity and momentum equations, taking into account a turbulent model. An eddy viscosity idea is used to model the turbulence. MIKE 3 proposes two possible solutions: κ-ε and κ-ω models (DHI, 2023a). Both models use equations for the kinetic turbulent energy κ and either for the turbulent dissipation ε or for the specific dissipation ω, are two often used turbulence models (Menter, 1993). While the κ-ω model performs better close to walls but struggles with free shear layers and negative pressure gradients, the κ-ε model performs well in free shear layers but problems with coping with areas of separation. Another way to express the eddy viscosity is using the Smagorinsky model, this model is used to determine a sub-grid eddy viscosity value (DHI, 2023a).

3. METHODOLOGY

This chapter presents the methodology applied in this thesis. It consists of three main parts. First, the methodology used for the literature review. Secondly, a description of methodology applied during the questionnaire/interview process. Lastly, the description of the modeling of Järnbrott pond, which was selected as the case study.

3.1.LITERATURE REVIEW

A literature review was performed to fulfil specific aim A1 (*To research international guidelines and previous studies*) and A3 (*To examine the recommendations and available information regarding maintenance frequency for forebays and ponds*) using the methodology described in this chapter. The main topics are forebay's international applications and design criteria.

Google, Google Scholar, and Web of Science were used to search for grey literature and research papers. Furthermore, since one of the aims is to investigate current guidelines, some official websites were also used during the research. It is important to point out that guidelines are often written in the official language of the country, therefore, guidelines where English is the official language were researched.

The methodology applied to find information about forebays studies and design criteria was based on the use of a combination of the key words presented in Table 3-1. Based on the design criteria that were found during the research process, some key words were included during the research such as "volume", "embankment", "berm", "maintenance" and more. These key terms are included in Table 3-1 as "research expansion".

It is also important to point out that searching for information is an iterative process. Snowballing was applied to search for additional information. In snowballing, references in initial information sources lead to new sources in an iterative process until sufficient information is obtained. The last steps of this part consist of data analysis and control.

Table 3-1 General key words related to forebay literature review.

	Key words
Forebay	Pre-treatment; forebay; primary treatment; wet ponds; stormwater ponds.
Design criteria	Design criteria; guideline; recommendation; size; dimension.
Mechanisms	Sedimentation; energy dissipation; coarse sediments; coarse material.

Forebay characteristics (research expansion)	Volume; area; shape; depth; embankment; berm; maintenance; paths; accessibility.

3.2. INTERVIEW STUDY

The aim was to obtain information concerning forebays implemented in Sweden, their design criteria and maintenance of the facilities. Additionally, to identify the existing pond with forebay in the country for a posterior analysis.

Selected water companies and Trafikverket (Swedish Transport Administration) have been interviewed. The water companies were selected based on the size of the municipalities that they are in charge of. The initial aim was to contact the 12 largest municipalities in Sweden. However, contact information could only be obtained for 7 of the 12 most populated municipalities. A smaller municipality, Växjö, was also included as many researchers have studied water quality in facilities located in this municipality (Al-Rubaei, Engström, et al., 2017; German & Svensson, 2007). Table 3-2 and Figure 3-1 present a summary of the water companies/municipalities that were part of the initial questionnaire, which ones have pond with forebay, and which ones were interviewed.

The interviews with the water companies were carried as follows:

1. A first email was sent out in Swedish and English. This email included a definition of forebay units and inquired whether the municipality/water company is responsible for managing any of these facilities. See initial questionnaire in Appendix A. Next, an interview was carried out with the municipalities/water companies that answered affirmatively. One of the cases that answer affirmatively to the question of having forebays, did not answer later to have the interview.
2. The interviews were held in English. During the interviews, a guideline of questions and information to ask was used. However, the methodology was changing case by case, since in some of the cases the interviewee prepared presentation with their facilities or information that they wanted to share. The main points to research were specific cases of pond with forebay, design criteria and maintenance. See guideline of question in Appendix A.

The interview with Trafikverket was carried out as follows:

1. Trafikverket (Swedish Transport Administration) was interviewed, since wet ponds are common BMPs used for cleaning road runoff in Sweden (Andersson et al., 2018). For this interview, the main questions were sent by email and during the meeting the interviewee presented issues and specific cases, pointing out some drawbacks of wet ponds administration by Trafikverket.

Table 3-2 Water companies considered for the questionnaire.

Water company	**Do they have ponds with forebay?**	**Municipalities**
VA-SYD	Yes	Burlöv; Eslöv; Lomma; Lund; Malmö
NSVA	Yes. No interview was made, since no more answers were given by the company.	Bjuv; Båstad; Helsingborg; Landskrona; Perstorp; Svalöv; Åstorp; Örkelljunga
SVOA	Yes	Stockholm; Huddinge
NODRA	Yes	Norrköping
Kretslopp och vatten	No	Gothenburg
Växjö kommun	Yes	Växjö
Uppsala Vatten	Yes	Uppsala

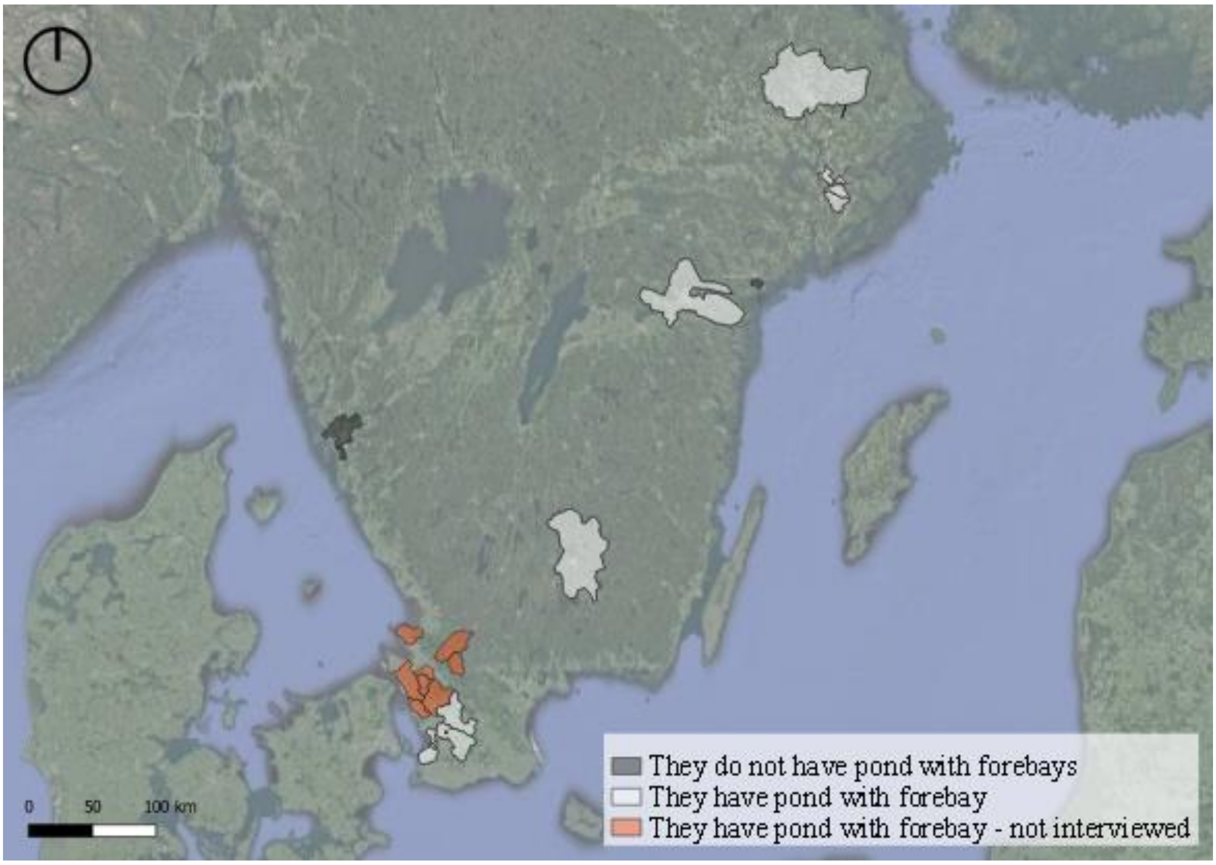

Figure 3-1 Municipalities where the questionnaire was made.

3.3.MODELING

This chapter presents the methodology applied to model Järnbrott pond (chosen as study case) in MIKE 3 FM. Firstly, a description of Järnbrott is presented, followed by its implementation in MIKE 3 FM, how it was set-up and the studied scenarios.

3.3.1. STORMWATER POND JÄRNBROTT

The stormwater pond Järnbrott situated in Gothenburg was chosen as a case study area. Järnbrott was constructed in 1996 for stormwater treatment purposes and it is located a few kilometres south of Gothenburg (see Figure 3-2), next to the intersection of two roads: Söderleden and Dag Hammarskjöldsleden (German & Svensson, 2005). The pond discharges into the stream Stora Ån. The facility has a surface area of 6,200 m^2 and 6,000 m^3 of volume during dry weather.

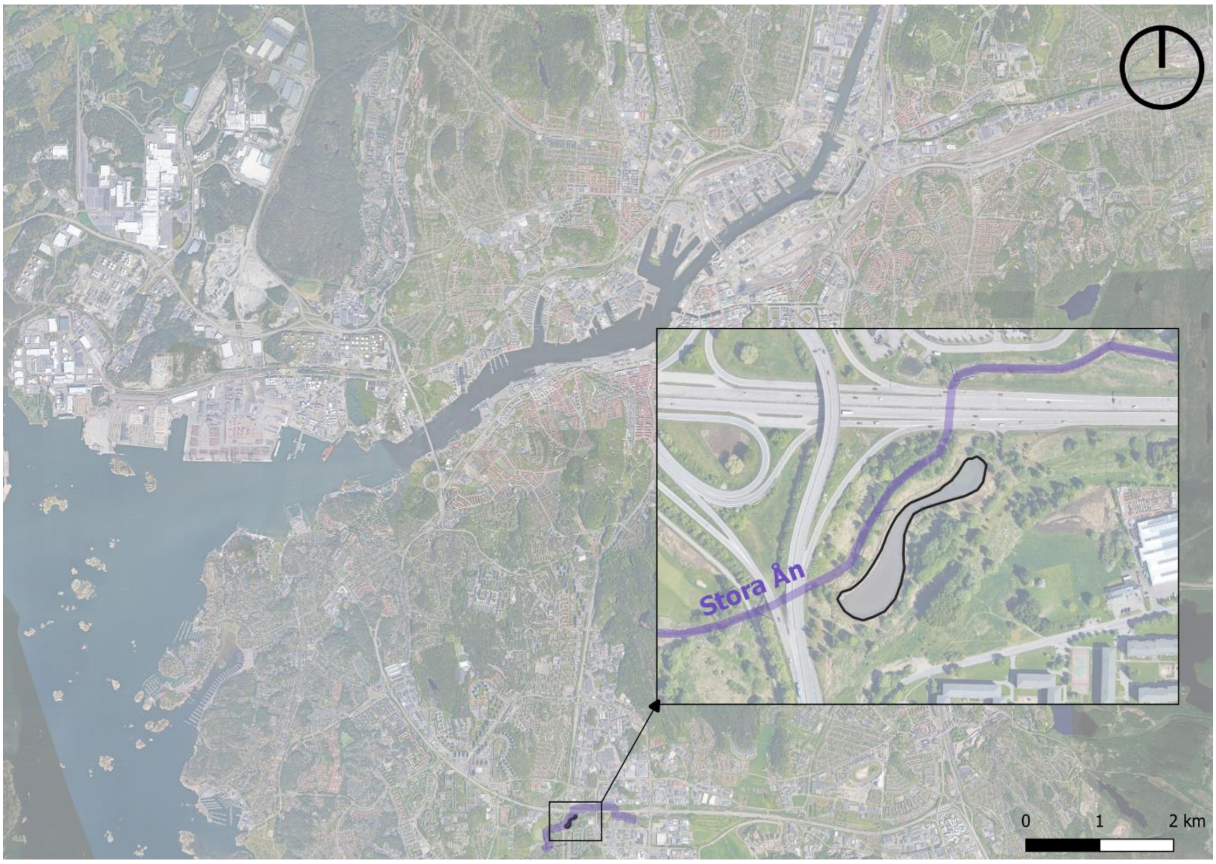

Figure 3-2 Location of Järnbrott pond.

The catchment area to the pond has an area of 478 ha . The land use in the catchment is mostly residential and commercial areas, divided by a road that has an annual average daily traffic of 40,000 vehicles. Around 30 % of the catchment is impervious area (Pettersson, 1999).

The inlet to the pond consists of a submerged steel pipe Ø1,000 mm (Pettersson, 1999). When the inflow exceeds a flow of 700 l/s, part of the inflow starts to discharge directly to the river Stora Ån. The maximum inflow into the pond is 1,100 l/s (German & Svensson, 2005), that happens when the overflow reaches 8,000 l/s (German & Svensson, 2005; Pettersson, 1999). Around 80 % of the annual stormwater enters and is treated in the pond, the remaining 20 % is discharging directly to the stream without any treatment, due to the overflow. The outlet consists of a concrete crest of 8 m broad.

The bottom topography varies from 0.5 m to 1.6 m in dry conditions (Pettersson, 1999). The bottom of the pond was constructed using three different materials, see Figure 3-3, and the pond slope is 30 % made by clay. At the inlet section, the depth is around 1.5 m and the bottom of the pond is covered with concrete slab. The section in the middle has a depth of 0.5 m and it is of macadam. While in the outlet section the depth is 1.6 m with a bottom of clay.

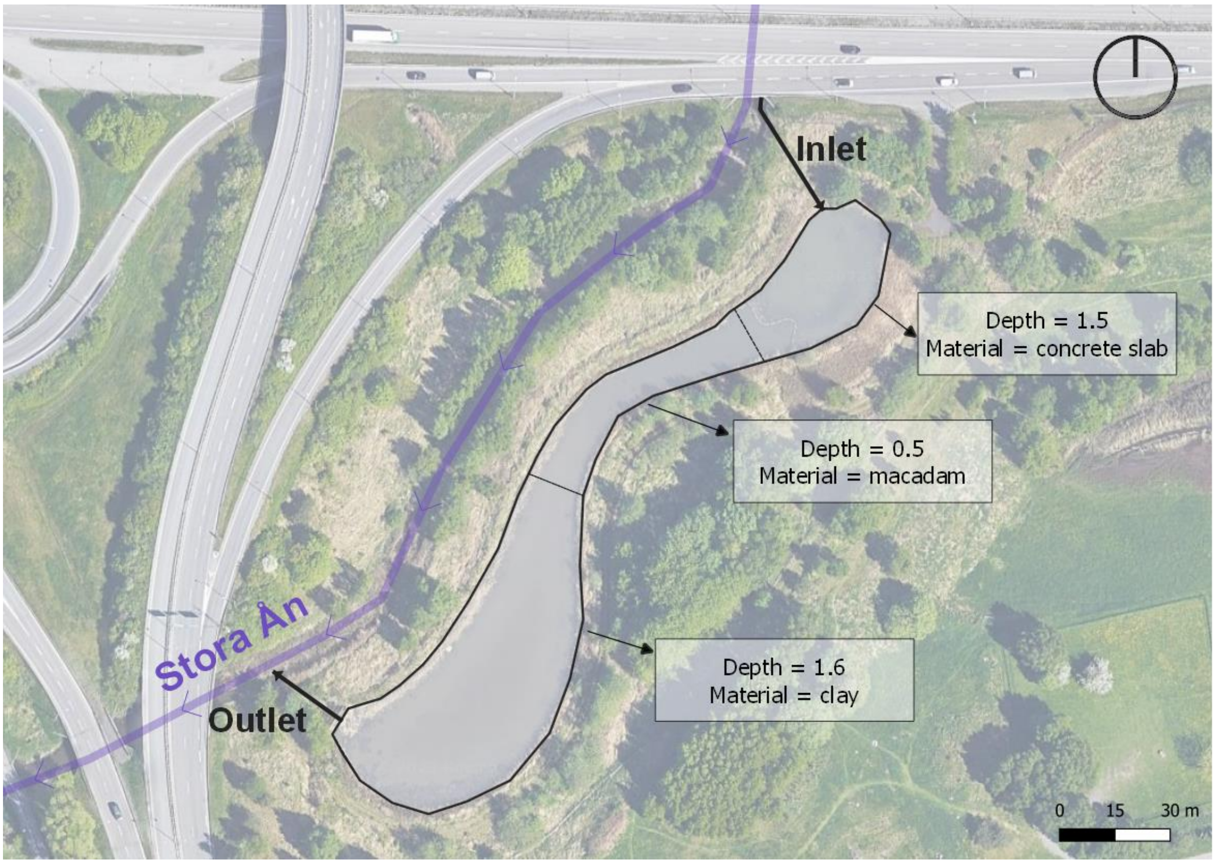

Figure 3-3 Järnbrott characteristics.

Flow measurements in Järnbrott were made during a previous study (Petterson, 1996). The study examined two different inflows and their corresponding velocities and flow paths. For an inflow rate of 800 l/s, the velocities were observed to be approximately 0.20 m/s in the surface layer, while at depths of 0.5 m and 1.0 m, the velocities ranged between 0.10 m/s and 0.12 m/s. In the second case, an inflow of 20 l/s was measured, and the velocities were recorded to be around 0.02 m/s. For both cases the water path follows a clockwise direction near the inlet of the pond.

3.3.2. SETUP AND DOMAIN

In order to simulate the water flow in the pond using MIKE 3 FM (Flow Model), the bathymetry of the pond was created based on the depth and zones presented in previous studies of Järnbrott (see Section 3.3.1), a simplification of the bathymetry is presented in Figure 3-4.

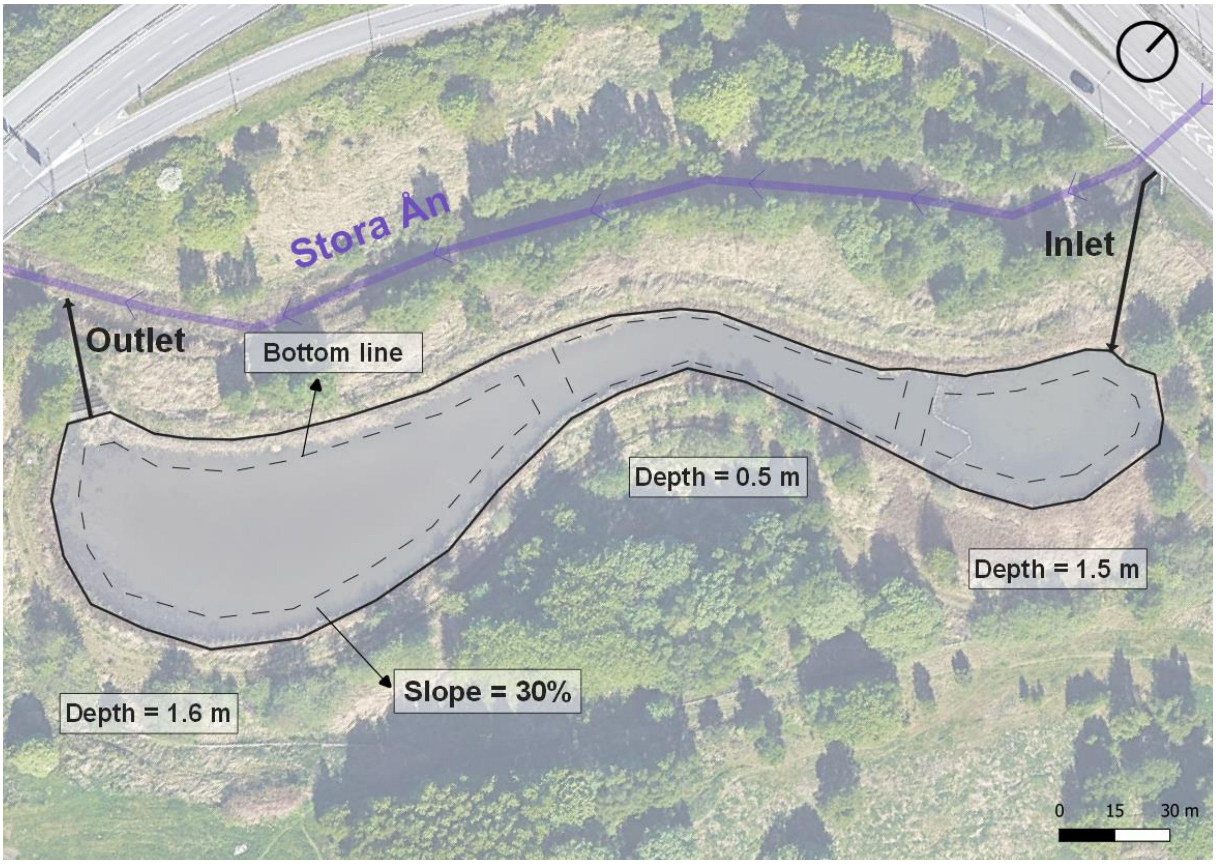

Figure 3-4 Järnbrott bathymetry simplification.

A triangular mesh was generated using Mike Zero. Figure 3-5 presents the mesh and bathymetry. The mesh has in total 1,376 elements and 781 nodes in 2-D, and 11,008 and 7,029 in 3-D. The maximum area of an element of the mesh was set up in 6 m^2, while the smallest possible angle was set up as 26°. For the vertical mesh a sigma domain was used with 5 equidistant layers (5 z-levels). It is important to provide a suitable mesh in order to achieve reliable results from the model. For this reason, it was verified that the flow is independent of the mesh. The boundary conditions were set as constant level 0 m at the outlet, and zero velocities at the bottom. The inlet was included as a point source, specifying the inflow and inlet velocities. The position of the point source was at the inlet coordinates and 0 m z-level. Two inflows were modelled, 800 l/s and 20 l/s. These inflows were chosen since measures of flow path from previous studies was available, see Section 3.3.1. For both inflows, the inlet velocity was determined by modeling in EPA SWMM a 1000 mm diameter pipe with 0.3 % slope. The velocities are presented in Table 3-3, where the direction u indicates the horizontal velocity being positive from west to east, and v indicates the vertical velocity from south to north, see Figure 3-5. Parameters such as temperature, wind and roughness were not considered in the simulations. These scenarios with a flow of 800 l/s and a base flow of 20 l/s work as base scenarios of Järnbrott pond in the current situation.

The time step also plays an important role when it comes to result reliability. The model was run for 10 hours, with a time step of 60 seconds, verifying the time independency. The steady-phase is achieved in the model after 4 hours. The CFL (Courant-Friedrichs-Levy) number obtained with the mentioned setup is lower than 0.8, recommended value according to MIKE 3 FM.

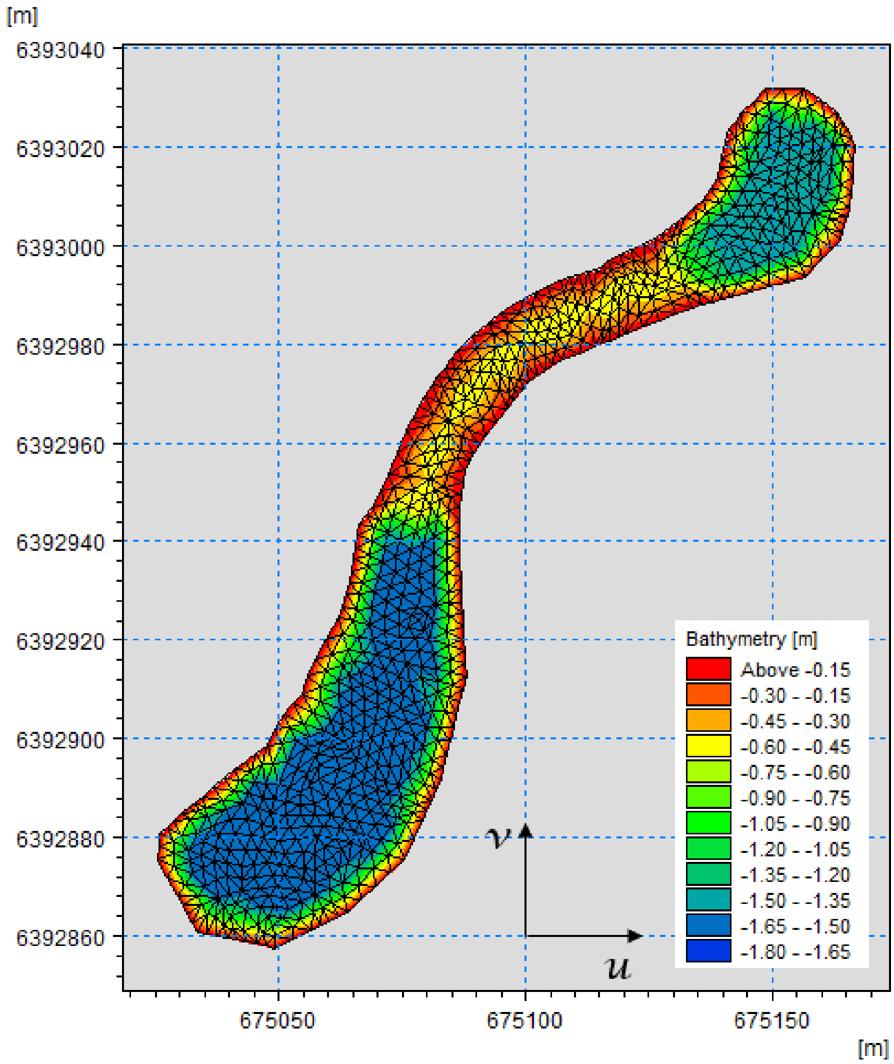

Figure 3-5 Bathymetry and mesh in MIKE 3 FM.

Table 3-3 Inflow and inlet velocities.

Flow (l/s)	Total velocity (m/s)	u velocity (m/s)	v velocity (m/s)
20	0.60	0.32	-0.51
800	1.78	0.94	-1.51

3.3.3. SETUP EQUATIONS

The model solves the three-dimensional incompressible RANS to determine the flow pattern (DHI, 2023b). For vertical viscosity it was specified the two-equation turbulence mode, which determines the eddy viscosity using k-ε model and k-ω model. While for the horizontal viscosity is specified with the Smagorinsky formulation.

3.4.FOREBAY IMPLEMENTATION IN JÄRNBROTT

One aim is to suggest recommendation of how to implement a forebay in Järnbrott pond. The recommendations are going to be proposed based on the results obtained from the literature review, the questionnaire in Sweden and the model. The suggestions are going to be given taking into account the Järnbrott characteristics and surroundings. The velocity over the embankment is going to be verified by approximating it as a weir.

4. RESULTS AND DISCUSSION

4.1. LITERATURE REVIEW

This chapter presents the results from the literature review for forebays. First, the identified guidelines are introduced. Second, the design criteria and maintenance recommendations are presented. Last, a summary of all the guidelines is presented.

4.1.1. STUDIED GUIDELINES

Table 4-1 presents the most complete guidelines found as a result of the strategic literature search. In addition, information from other guidelines and studies is also presented during the next sections. The guidelines are from countries where the official language is English, and the majority of the guidelines are from local and regional authorities. In the case of UK and EPA US, the guidelines are from national entities.

Table 4-1 Studied guidelines.

City / Country	Reference
Auckland, NZ	(Auckland Regional Council, n.d.)
Charlotte, US	(City of Charlotte, 2023)
Georgia, US	(Atlanta Regional Commission et al., 2016)
IOWA, US	(IOWA Department of Natural Resources, 2019)
Minnesota, US	(Minnesota Pollution Control Agency, n.d.)
North Carolina, US	(North Carolina Environmental Quality, 2020)
Pennsylvania, US	(Department of Environmental Protection, 2006)
UK	(CIRIA, 2015)
US (EPA)	(EPA US, 2009)
Virginia, US	(Virginia Department of Environmental Quality, 2011)
Wisconsin, US	(Wisconsin Department of Natural Resources, n.d.)

4.1.2. FOREBAY DESIGN CRITERIA

This section describes the design criteria for forebays. They are presented for each forebay element or characteristic. Figure 4-1 presents the main components of a pond, including the forebay.

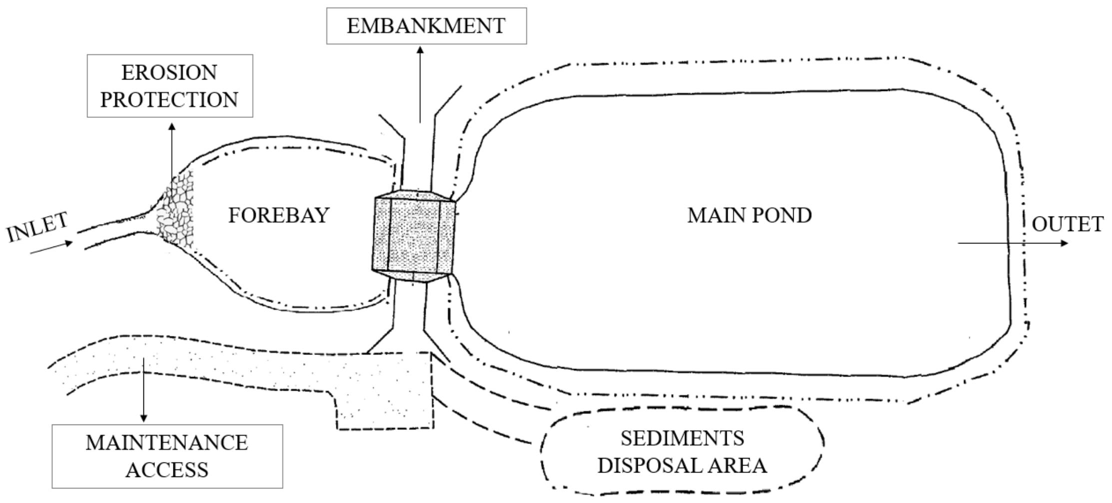

Figure 4-1 Recommended elements in the pond design, including forebay. Based on (Virginia Department of Environmental Quality, 2011)

Shape and dimensions

Size is one of the most important parameters when it comes to forebay design. Some of the guidelines establish a range or minimum volume, while others propose a surface area range. The majority of the studied guidelines agree that the volume of the forebay must not be smaller than 10 % of the main pond volume, and usually the upper limit is 20 %, while few of them also include a recommended area of around 10 % of the whole facility area, see Table 4-3 in Section 4.1.3. In some of the guidelines the recommended volume of the forebay is considered as part of the pond volume, while in other cases is independent.

When it comes to forebay depth, the recommended values vary from 1.0 to 1.8 m, see Table 4-3 in Section 4.1.3. North Caroline's guideline states that forebay height in the inlet must be higher than in the outlet (North Carolina Environmental Quality, 2020). A study carried out in US about wet pond with forebay conclude that in the studied ponds, the depth of the forebay was similar to the depth in the wet pond, while most forebay volumes were less than 30 % volume of the main pond, value recommended by North Caroline (Johnson, 2006).

In cases where the pond has multiple inlets, one forebay per inlet is required, see Figure 4-2. It is recommended that the sum of all the forebay volumes should be equal to the total recommended volume for the forebay (NCDEQ Stormwater Design Manual, 2020). However, when an inlet provides less than

10 % of the total inflow to the pond, it is not necessary to construct a forebay for this inlet (Atlanta Regional Commission et al., 2016). Furthermore, the distribution of the total forebay´s volume must be proportional to the watershed areas. Figure 4-2 presents an example in case of two inlets, where Forebay 1 receives a flow that it is a percentage “X1 %” of the total flow, and Forebay 2 a flow “X2 %” of the total flow, thus, the forebays’ size should follow the same proportion as the flow, being the forebays’ area X1 % and X2 % of the total forebay’s area respectively.

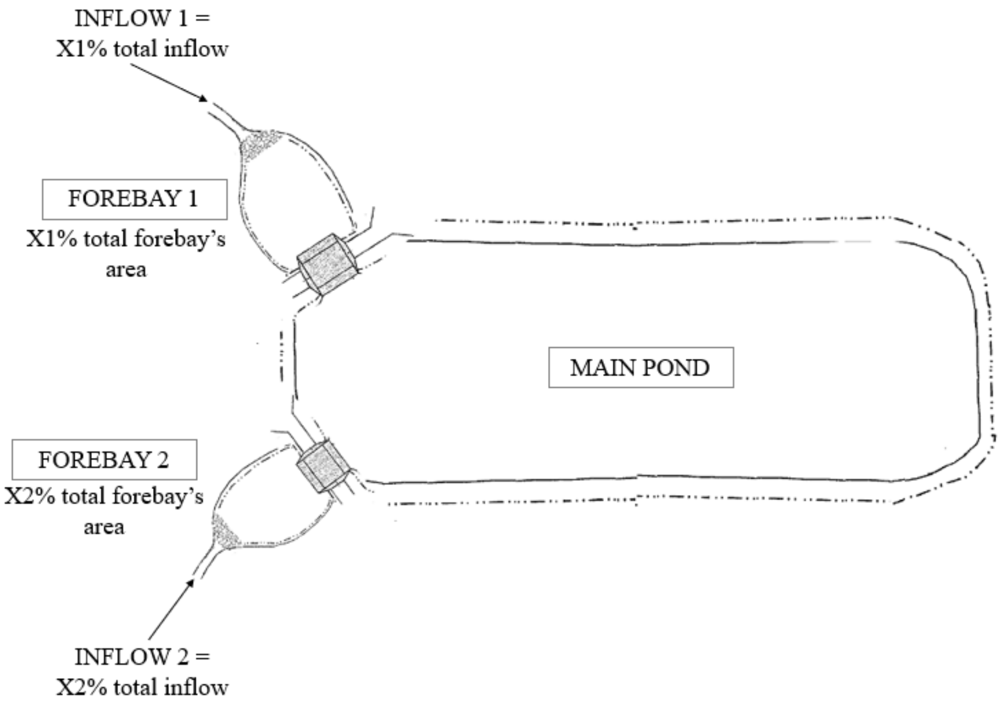

Figure 4-2 Forebay’s distribution in case of having two different inlets.

It is recommended to make forebays longer than wider (Hunt & Lord, 2006). This is to facilitate maintenance, being able to reach at least the middle part of the forebay from each side with a trackhoe or backhoe arm. Just one guideline recommends a longer than wider forebay to provide enough length for encouraging sedimentation processes (IOWA Department of Natural Resources, 2019).

A previous research states that a forebay size based on the fraction of the total pond area is not enough as a design criteria (Johnson, 2006). The research also emphasizes the importance of two well defined zones in the forebay: one for dissipate energy and the other one for sedimentation processes. One of the guidelines states that when construction activities are present in the catchment, the criteria of forebay volume as 10 % of the total volume is not sufficient to size it (IOWA Department of Natural Resources, 2019).

UK and Australia’s guidelines present formulas to determine the volume of the forebay for a bioretention system and dry detention area respectively (Department of Water, 2005; Woods Ballard & Construction Industry Research and Information Association., 2015). To calculate the volume or area of the forebay, these guidelines state the importance of considering a target of sediments that want to be removed, the diameter/settling velocity of the sediments, the catchment area, the load of sediments, the time between maintenance and the flow conditions. All these different considerations will define the volume of the forebay.

Embankment

A pond's forebay can be separated from the main pond by including in the design a forebay embankment/berm, see Figure 4-1 (Department of Environmental Protection, 2006; Virginia Department of Environmental Quality, 2011). This could be achieved using barriers such as earthen berms, concrete weirs, rip-rap wall, or gabion baskets, Figure 4-3. It is important to control the velocity on top of the embankment to avoid erosion. The state Virginia, US, recommends designing the embankment for non-erosive velocities during a 2 and 10-year return period events (Virginia Department of Environmental Quality, 2011). Furthermore, the embankment has the function of distributing the inflow across the main pond. A proper design of the embankment will ensure that the forebay has always a permanent pool to reduce flow velocity, thus an increment in detention time, and it also provides enough volume for sediment storage (Derwent Estuary Program, 2012).

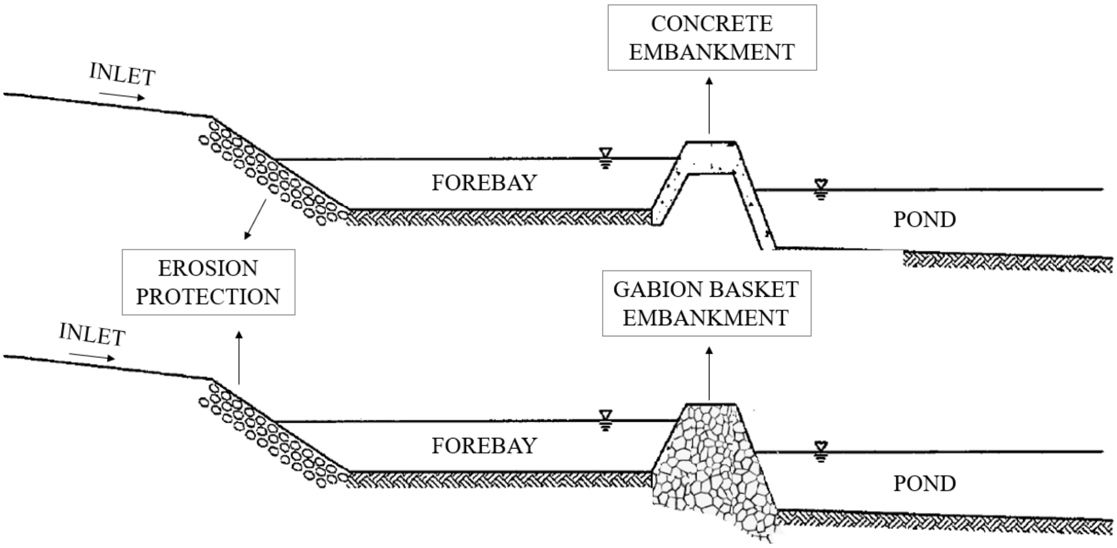

Figure 4-3 Section view of a pond with forebay. Based on (Virginia Department of Environmental Quality, 2011).

The flow over the embankment can be determined by approximating it as a broad-crested weir presented in Equation (4-1) (Introduction to Highway Hydraulics HDS 4 June 1997 Metric Version, n.d.; IOWA Department of Natural Resources, 2019):

$$Q = C\ x\ L\ x\ H^{3/2} \tag{4-1}$$

Where Q is the flow in m3/s, C is a coefficient for broad crested weir (≈1.44 for international units), L is the length of the weir in m (length refers to the bottom width of the weir), and H is the height of flow over the weir.

Material

To facilitate maintenance and sediment removal, forebay should be constructed of hard materials such as concrete (Department of Environmental Protection, 2006), and in this way avoid over excavation of the bottom (Virginia Department of Environmental Quality, 2011).

Energy dissipation zone

The forebay should be composed of an energy dissipation zone to reduce water velocity in the unit, encouraging sedimentation processes, and to avoid resuspension of the settled sediments in the downstream part (CIRIA, 2015; Johnson, 2006; North Carolina Environmental Quality, 2020). The energy dissipation zone should be located after the inlet and before the forebay sedimentation area (Johnson, 2006). To achieve this, some guidelines propose that the forebay should be deeper at the inlet than at the outlet of the forebay or having submerged inlet pipes (Atlanta Regional Commission et al., 2016; North Carolina Environmental Quality, 2020). However, two guidelines specify that submerged pipes should be avoided (City of Charlotte, 2023; Department of Environmental Protection, 2006). Other measures can be rip-rap aprons, loose stone, or a performed hole (CIRIA, 2015; Li et al., 2019). According to the research by Johnson (2006), a preformed hole can be excavated during the construction phase downstream the inlet, and its size is going to depend on the inlet pipe diameter. The preformed hole size can vary from 50 mm to 400 mm in depth and have a diameter at least the same size as the diameter of the pipe (Johnson, 2006). It is necessary to have non-erosive velocities from the forebay into the main pond (Atlanta Regional Commission et al., 2016). Furthermore, it is recommended to design these units off-line to reduce resuspension events for large flows (North Carolina Environmental Quality, 2020).

Maintenance

It is important to include in the design a path to give easy access to machinery needed for sediment removal. Forebay shape is important to facilitate the maintenance tasks (Virginia Department of Environmental Quality, 2011). Most of the guideline emphasize the importance of paths for the machinery to reach the facility, being more important accessibility for forebay, outlet and embankment (Department of Environmental Protection, 2006; Minnesota Pollution Control Agency, n.d.). The paths should have 2.7 m of width and a maximum slope of 15 % to access the forebay according with recommnedations. Vehicles should be able to turn around. Paths must also be constructed to support machinery and vehicles.

Three main activities should be carried out when it comes to forebay maintenance (North Carolina Environmental Quality, 2020). First, it is important to remove the sediments for the forebay once that a certain depth is reached, this sediment depth depends on the design of the facility. Second, if erosion is observed, additional erosion protection measures will be needed. Last, control and remove weeds if necessary, being preferable to avoid the use of pesticides.

The sediment removal is one of the main tasks when it comes to forebay maintenance. If the forebay capacity is exceeded, settled sediments will escape the forebay and accumulate in the pond, which has value from a biological and ecological point of view (Hunt & Lord, 2006). Removing the sediments in the forebay is usually made using a track hoe or backhoe, and it is usually done between one day and one week. Some guidelines recommend installing a sediment depth market to facilitate the settled sediment depth control (Department of Environmental Protection, 2006; Minnesota Pollution Control Agency, n.d.).

A research carried out by North Caroline State indicates that the forebay sediments can be typically removed each 5-10 years period, while this number is reduced to one time per year when the catchment has construction activities (Hunt & Lord, 2006). However, guidelines recommend periods from 1-3 years to 5-10 years, see Table 4-2. Usually, guidelines state a recommended time and a percentage of the forebay capacity lost, specifying that the sediments must be removed when one of the two criteria is achieved. Nevertheless, it is important to take into account that the frequency of maintenance is going to depend on the sediment incoming load and the forebay size (Hobart City Council, n.d.). The ponds maintenance changes from 5 years when forebay is not present, to 10-50 years when forebay is present, see Table 4-2.

Once that the excavated sediments dry, they will be either disposed it in the watershed away from the banks of the pond and use it as soil, or transported it to a landfill (Hunt & Lord, 2006). The quality of the soil removed can vary significantly with the basin area, since an industrial catchment may contain pollutants that must be disposed of in a landfill, whereas an urban catchment can be less polluted. An area to allow sediment removed to dewater must be included in the design (see Figure 4-1 called as sediments disposal area) (Virginia Department of Environmental Quality, 2011)

Existing research suggests that sediments removed from a forebay have lower metal concentration compared to sediments near the outlet (McNett & Hunt, 2011). Therefore, forebay sediments will not present a threat for the environment considering the metal concentration. However, only metals were considered in the research by McNett & Hunt (2011). Furthermore, the type of metal and its concentration will be related to the catchment type and use of land.

Table 4-2 Frequency of maintenance of forebay and pond.

Place	MAINTENANCE FOREBAY		MAINTENANCE POND	
	Frequency of sediment removal	**Sediment accumulation for removal**	**Frequency of sediment removal**	**Frequency of sediment removal**
Auckland, NZ		50 % capacity lost		
Charlotte, US		25 % capacity lost		25 % capacity lost
IOWA, US	5 years	50 % capacity	10-20 years	25 % capacity lost
Minnesota, US	5-7 years	50 % of capacity	25 years	50% of capacity
North Carolina, US		75 % of total depth		
Pennsylvania, US	5-10 years	50 % of the volume		
UK	1-5 years		25-50 years with forebay, 5 without forebay	
US	1-3 years			
Virginia, US	3-5 years	0.15 - 0.30 m of sediment accumulation		

4.1.3. SUMMARY

Table 4-3 presents a summary of the main design criteria for the guidelines analysed during this research.

Table 4-3 Summary of design criteria of the most completed studied guidelines.

Place	Is mandatory to include a forebay?	Forebay purpose			Depth	Volume	Area	Material	Extra information
		Coarse material removal	Energy dissipation	Oil barrier					
Auckland, NZ	Yes	X	-	-	> 1 m	15 % *	-	-	-Velocities in forebay should be less than 0.25 m/s in TR10 to avoid resuspension.
Charlotte, US	Yes	X	X		≈ 1.2 - 1.8 m	For 12.6 mm per impervious ha of catchment ***		Hard material at the bottom	-Non-erosive velocities between structure that divides forebay from main pond. -Include a disposal area for sediment removed. -A forebay per main intel, sized with catchment area. - Inlet pipe not submerged.

Place	Is mandatory to include a forebay?	Forebay purpose			Depth	Volume	Area	Material	Extra information
		Coarse material removal	Energy dissipation	Oil barrier					
Georgia, US	No need if another pre-treatment	X	-	-	≈ 1.2 - 1.8 m	sized to contain 6.3 mm per impervious ha of catchment ***	-	Hard material at the bottom	-Fix sediment depth marker. -Forebay for all inlets where Q is higher 10 % of Q total. -Non erosive velocities after forebay. -Inlet pipe can be partially submerged. -Access for maintenance
IOWA, US	No need if another pre-treatment	X	X	-	≤ 1.2 m	10 % *	-	Hard material at the bottom	-Fix sediment depth marker. - Access for maintenance. -Non-erosive velocities between structure that divides forebay from main pond. - long forebays to encourage settling.
Minnesota, US	No need if another pre-treatment	X	X	-	≈ 1.2 - 1.8 m	10 % *	10 % of the pond surface or 0.1 % of	Hard material at the bottom	-Fix sediment depth marker. -Forebay for all inlets where Q is

Place	Is mandatory to include a forebay?	Forebay purpose			Depth	Volume	Area	Material	Extra information
		Coarse material removal	Energy dissipation	Oil barrier					
							the catchment area		higher 10 % of Q total. - Access for maintenance -Non-erosive velocities between structure that divides forebay from main pond.
North Carolina, US	-	X	-	X	≈ 1 - 1.5 m	15 - 20 % **	-	-	-Forebay entrance deeper than the exit. - Access for maintenance. -Non-erosive velocities between structure that divides forebay from main pond.
Pennsylvania, US	Should be included	X	-	-	≈ 1 - 1.5 m	10 - 15 % *	-	Hard material at the bottom	-Vegetation in the forebay. -Fix sediment depth marker. -Forebay offline. -Inlet pipe partially submerged or at the surface.

Place	Is mandatory to include a forebay?	Forebay purpose			Depth	Volume	Area	Material	Extra information
		Coarse material removal	Energy dissipation	Oil barrier					
UK	Optional	X	X	X	-	-	10 % *	-	-Fix sediment depth marker. -Multiple inlets: forebay when high sediment load are expected.
US	-	X	-	-	-	≈ 10 % **	-	-	-
Virginia, US	-	X	X	-	≈ 1.2 - 1.8 m	Sized for 15.7 mm (a minimum of 6.3 mm) per impervious ha of catchment area. For small ponds, a 10 % of the volume.	-	-	-Non-erosive velocities between structure that divides forebay from main pond. -Include a spoil area for sediment to dewater.
Wisconsin, US	No need if another pre-treatment	X	-	-	> 0.9 m + sediment storage	5 - 15 %	-	Hard material at the bottom	-Forebay for all inlets where Q is higher than 10 % of Q total.

* *of total area/volume.*
** *of the main pool area/volume.*
*** *considered in the total treatment volume.*

4.2. INTERVIEW STUDY

This chapter presents the main results obtained during the questionnaire and interview part of this work. Firstly, the design criteria, guidelines and maintenance aspects are presented. Secondly, some ponds with forebay in Sweden are presented and described.

It is important to point out that the information presented is based on the data obtained from the interviews during the meeting and extra information that was given during some interviews. In the case of the guidelines, the information is presented based on the material provided from the water companies/municipalities.

In the case of Trafikverket, the information from the interview is presented in Subsection 4.2.2.

4.2.1. WATER COMPANIES / MUNICIPALITIES

General aspects

Considering all the design criteria for the studied water companies and municipalities, it is possible to observe that the recommendations from most of the local guidelines from different regions were mentioned during the interviews. However, it is important to note that the criteria can vary among different water companies, with some being more complete than others based on their specific cases and experiences. Three of the water companies follow a specific manual, others rely on previous experiences for design considerations.

Among the water companies, two have developed their own guidelines, while another company utilizes the design criteria proposed in a report published by Svenskt Vatten (Larm & Blecken, 2019). Although one of the internal guidelines briefly mentions forebays, it does not provide detailed specifications for their design. On the other hand, one of the internal guidelines emphasizes the importance of adapting the design to each specific case and site conditions.

All of the water companies/municipalities stated that the main function of forebays is to facilitate the maintenance of the ponds, allowing the coarse sediments to accumulate in these smaller units. Additionally, some companies highlight the importance of forebays in dissipating energy. One of the interviewed persons mentioned as a purpose of the forebay the installation of an oil barrier.

One of the interviewees pointed out the advantage of the use of forebays when it comes to water quality. Forebays are design to trap mostly coarse sediments, diving the sediment storage of coarse and finer sediments, which allows to manage them separately.

This also implies the mixing of these sediment that are not so dirty, with the finer sediments that contain more pollutants.

One water company distinguishes between design criteria for ponds intended for treatment purposes and those designed for flow delay. Additionally, another water company highlights the importance of considering the pond's specific use in determining the forebay design, although the water company has not established explicit criteria for different situations.

One of the interviewed persons and one of the guidelines (Larm & Blecken, 2019) mentioned the possibility of two different configurations for the forebay: it can be separated from the main dam by constructing an embankment such as a concrete wall, ski table, or floating screen, or the forebay and main dam can be delimited by a ditch or pipe.

Three of the interviewed persons agreed that forebays are always wanted. One of them pointing out that a forebay must be present when a pond is constructed for treating stormwater. While the remaining water companies did not explicitly state the necessity of forebays, they generally expressed a preference for including them.

Design criteria

Regarding the dimensions of the forebay, only one of the guidelines differentiates the sizing based on the purpose of the pond. According to their guidelines, if the pond is designed for flow reduction, the forebay must be designed based on the inflow, and in such cases, including a forebay is not mandatory. However, if the pond is intended for treatment, a forebay must be present, and it is recommended that the forebay volume constitutes a percentage of the pond's total volume. Just two water companies suggested values for forebay’s volume, ranging from 5 % to 20 % of the total volume. VA-SYD's internal guideline recommends a forebay's area equivalent to approximately 10 % of the total permanent water surface.

When a minimum depth was recommended, it was around 1 - 1.2 m. The main respond is to avoid plant growth. One of the companies’ criteria establishes that the forebay should have a deeper part near the inlet.

Two of the water companies emphasize that having a correct design in terms of accessibility is more important than the aesthetics of the pond, and the shape of the facility plays a crucial role in facilitating maintenance. Ideally, the forebay should not be too wide, as it should be accessible to a standard digging machine, eliminating the need for specialized machinery for maintenance tasks. Consequently, if local conditions and space permit, the preference is for narrow and long forebays.

Some water companies highlight the importance of having pathways for the machines to empty the forebay. Both the inlet and outlet must be accessible to machinery and personnel, and the paths should be dimensioned to support the weight of the machines and allow for manoeuvrability. Furthermore, vegetation, benches, or other elements should be located in a way that they do not impede accessibility.

The guideline based on the Swedish report (Larm & Blecken, 2019) recommends a bottom constructed with hard material to facilitate sediment removal and prevent plant growth. Some other municipalities/companies also recommend to construct the forebay with concrete or other hard material for the same reasons. However, one municipality utilizes clay for forebay construction due to its easy availability in the region. Two interviewed persons and one guideline mentioned the need to avoid macadam since it tends to mix with sediments, requiring both to be removed during maintenance.

When the purpose of the pond is to treat stormwater, the rain event used to design the pond and forebay corresponds to small return periods, frequent rain events. Most interviewees mentioned a rain event with a return period of 1 or 2 years. As stormwater treatment facilities are typically sized to optimize treatment on an annual basis, the design should include a bypass/overflow for higher rainfall events. This also helps to prevent resuspension of settled sediments. One water company utilizes a 20 mm rain event over the impervious area of the catchment (reduced catchment) for designing the facility.

Energy dissipation

According to one of the internal guidelines, the inclusion of a slab at the bottom after the inlet is necessary, with the width and depth depending on the size of the inlet. This slab serves as a means of energy dissipation.

Maintenance

When it comes to maintenance, the majority of existing facilities with forebay facilitated by the companies interviews are relatively new. For this reason, there are only a few instances where sediment removal from the forebays has been carried out by the companies. All companies have the idea that forebays significantly facilitate pond maintenance, emphasizing that the inclusion of forebays leads to longer maintenance intervals for the main ponds compared to situations where forebays are absent. Some water companies, such as VA-SYD and Uppsala Vatten, highlight that the frequency of maintenance is dependent on the usage and area of the catchment. During an interview, it was pointed out that the amount of sediment generated in industrial or urban catchments differs significantly.

For sediment removal, some companies emphasize that mechanical dredging usually damage the bottom of the units, since they are usually made of clay and gravel. However, some companies pointed out that nowadays machinery has advance and allows a more precise excavation.

One of the interviewees emphasized the ecological significance of ponds, as they serve as habitats for various species such as frogs and birds. Therefore, each time pond maintenance needs to be done, it must be planned carefully. The inclusion of forebays in the design can significantly reduce the need for frequent maintenance in the main pond, thereby minimizing disruptions to the ecosystem.

To facilitate sediment transportation, it is advisable to include designated areas for sediment dewatering in the design. Some interviewees mentioned that including these areas is a challenge for some ponds, but it is important to have it when is possible to avoid the transport of water with the sediments. This approach reduces both the volume of material to be transported and the associated costs of transportation and sediment management. The internal guideline of VA-SYD also recommends the installation of these areas, emphasizing the importance of dewatering the sediments before their transportation to reduce costs.

In general, companies/municipalities do not have a fixed time for sediment removal. Most of the companies decided when sediment removal is needed based on the sediment height. On the other hand, many of them agreed that they are behind on maintenance.

4.2.2. TRAFIKVERKET

Trafikverket manages more than thousand pond facilities, however, not many of the ponds have a forebay. Despite having so many facilities, Trafikverket does not have defined design criteria. During the interview the importance to differentiate the reason of installing a pond was emphasized. It was pointed out that the poor understanding of the different reasons of designing a pond, results in poor pond designs. Furthermore, in the current facilities design it is difficult to identify the pond purposes, if they were design for flow delay, treatment or a combination of both. Moreover, it was emphasized the importance of understanding the system upstream before designing a pond. Usually, road sand traps are located upstream of the ponds, and these units are acting as pre-treatment of the ponds, catching the coarse material upstream. However, sand traps are not always present. Furthermore, the quantity of coarse sediments that will reach the pond depends on various factors, including the road design and the path through which water will flow into the system. Therefore, it is crucial to comprehend both the entry points of runoff into the system and the configuration of the system itself. Consequently, when designing a pond, it is essential to include a well-functioning sediment trap system that is easily accessible.

While there are no formally established material specifications, the interviewee shared their experience suggesting that a small forebay made of concrete or similarly hard and smooth material will facilitate the maintenance tasks such as sediment removal through excavation or suction. The interviewee speculated that if the design and forebay maintenance are properly done, the main pond would probably not fill up in more than 100 years. Lastly, it was highlighted that the sediments removed from the forebays are often suitable for repurposing, such as for road shoulders or construction, as they are typically classified as less polluted (less sensitive materials).

4.2.3. SOME CASES OF PONDS WITH FOREBAY IN SWEDEN

This chapter summarizes the main information related to design criteria of ponds with forebays. More information about the ponds is provided in Appendix II.

General information

A total of 18 cases were identified out of which 17 were recognized as forebays during the questionnaire process. Among these, two were associated with lakes, one with a wetland, and 14 with wet ponds. Figure 4-4 presents the 18 cases that were identified during the interviews, where 17 are forebays and one consists of two ponds in series (located in Växjö). A more detailed description of each of these cases can be found in Appendix II.

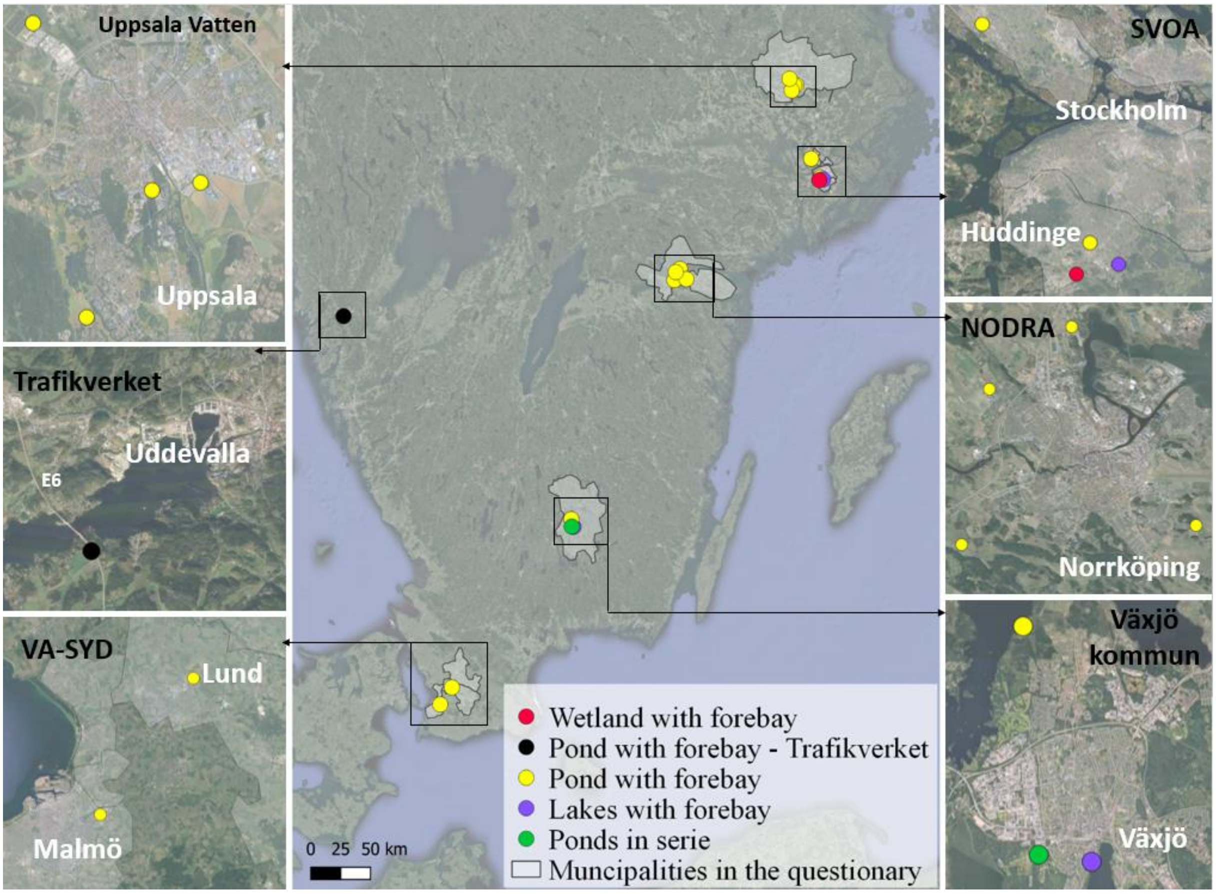

Figure 4-4 Forebays identified during the questionnaire.

In both cases of forebays upstream lakes, they were added as a measure to control sediments in the lake and improve the water quality. For the pond located in Malmö the forebay was constructed some years after the main pond, to facilitate maintenance in the main pond. In all other instances, the ponds were initially designed with forebays as an integral part of the pond’s design, to be able to handle sediments and facilitate pond’s maintenance.

Sizing of the pond's forebays

This chapter presents an analysis of the main design criteria for fourteen of the ponds and sixteen forebays in total, since one of the ponds has three forebays. The areas of the forebays and ponds were measured using Google Earth or QGIS, while the depth (used to calculate the volume) was provided by the water companies just in a few cases. Consequently, the volume could not be calculated for all the studied forebays. Additionally, for one of the ponds it was not possible to measure the area since it was difficult to delimit the pond due to the presence of trees and vegetation.

In total, thirteen ponds with forebay are analysed to study the relationship between areas. Just three of the thirteen (23 % of the cases) have a forebay with an area between 5 % and 15 % of the total area of the pond. Although the recommended value is around 10 %, due to the uncertainties in the area values (they were measure using QGIS and Google Earth) a range of ±5 % was considered. Six forebays (46 % of the cases) have an area that is above 10±5 % and four (31 % of the cases) forebays have an area that is below 10±5 % . The average value of area relationship is 14 %.

When considering the volume of the units, which is the most commonly used criterion, it was only feasible to determine it for five facilities. Among these cases, only two fell within the range of 10-20 %, while one was below this range and the remaining two were above it. It is important to point out that certain ponds presented varying areas, for example comprising a main sedimentation part and a shallower part. In order to determine the volume, both areas were considered in the calculations. Moreover, for the cases were the forebay depth was known, the value was always equal or higher than 1 m.

Limited information is available regarding the material of the forebays. Among the known details, it is known that the forebay in the pond located in Växjö was constructed using concrete. Similarly, in the case of the Gottsunda pond located in Uppsala, the forebay's walls were constructed using hard material. However, specific information regarding the material used in the remaining cases was not specified.

While no specific length-to-width criteria were officially recommended for forebays, several companies acknowledged the benefits of opting for a long and narrow forebay whenever feasible to enhance maintenance tasks. To classify the investigated forebays, they were grouped into four categories based on their length-to-width ratios. The first category included ponds with a ratio smaller than 1, which accounted for five out of the total fifteen ponds analysed. Additionally, three ponds fell into the category with a ratio close to one. Another three cases have ratios ranging from 1 to 2. Lastly, five forebays were identified with ratios greater than 2.

Year of construction

Out of the fourteen ponds analyzed, seven of the forebays were constructed in the last 5 years (50 % of the cases), while six of them were constructed around 2010 (43 % of the cases), and just one was constructed more than 17 years ago (7 % of the cases).

Accessibility

To study the accessibility, satellite images taken from Google Earth and the material provided by the water companies was used. It is considered that a pond is accessible when it has paths to have access with machinery to the forebay, outlet and embankment. In addition, the presence of platforms constructed with durable materials that can support machinery transit is essential. Thus, a pond is not accessible when no clear paths are present, while it is classified as "not complete" accessibility when there is a path, but just for a part of the pond. Out of the fourteen ponds with forebays, it is notable that eight of them are considered accessible, meeting the criteria for paths and platforms. However, one pond only has a single path leading to the forebay, indicating incomplete access. The remaining five ponds lack both paths and platforms, rendering them inaccessible. It is important to point out that many of the ponds that are inaccessible are in the same municipality and most of them were constructed nearly 15 years ago.

Forebay configuration

In terms of forebay configuration, it is notable that in only four of the study cases, the forebay is not integrated into the main body of the pond. Instead, these four cases feature a configuration where the forebay is separate from the main pond, connected by a ditch or pipe. Specifically, this configuration can be observed in the ponds located in Växjö, Uppsala (Kungsängen and Gottsunda), and Lund (Kunskapsdammen), see Figure 4-5.

It is interesting to point out the difference in the shape of the four of them. In the pond located in Växjö the relationship length to width of the forebay is near to one, the forebays in Uppsala's ponds are narrow and long, while the pond in Kunskapsdammen is wide and short, see Figure 4-5.

(a) Pond in Växjö.

(b) Kungsängen pond with forebay, located in Uppsala.

(c) Kunskapsdammen pond, located in Lund.

(d) Gottsunda pond with three forebays, located in Uppsala.

Figure 4-5 Cases where the forebay is connected to the pond by a ditch or pipe. Source: Google Earth.

Among the studied ponds, Gottsunda is the only one that features multiple forebays. The multiple inlets in Gottsunda can be attributed to the fact that each pond has different catchment types, leading to varying amounts of sediment accumulation. The presence of multiple forebays in Gottsunda allows for a more efficient sedimentation management. Every forebay in Gottsunda was designed based on its own catchment area. However, all the forebays in Gottsunda were designed using the same criteria, a percentage of area depending on the impervious catchment area, without depending on the system upstream, nor the expected sediment load due to the different catchment land uses.

The other forebays are part of the main pond body. Some cases are presented in Figure 4-6. It is possible to see how the forebay and main pond are divided by the presence of a berm. Usually, these forebays have a relationship length-to-width smaller or near 1.

(a) Loddby pond, Norrköping.

(b) Polacksbacken, Uppsala.

(c) Kyrkdammen, Huddinge.

(d) Uddevalla bridge, Trafikverket

Figure 4-6 Pond with forebay divided by an embankment.

Energy dissipation

Erosion protection measures are visible in certain ponds, such as the Kunskapsdammen pond situated in Lund (Figure 4-7). It is possible to see the inlet ditch and a riprap for energy dissipation upstream the forebay. Additionally, based on the information provided by the water companies, several other ponds employed erosion protection materials on the bottom after the inlet, often accompanied by a deeper section compared to the forebay's bottom. This practice can be observed in ponds like Loddby, Rambodal, and Bergslagsplan.

Figure 4-7 Rip-rap for energy dissipation upstream of Kunskapsdammen's forebay, Lund.

Maintenance tasks

There are three cases that are interesting from a maintenance point of view. The first case is are two ponds in series located in Växjö. The first pond acts as a "forebay" of the second one. According to the information provided from the municipality, the sediments in the first pond were more polluted than the sediments obtained from the second pond.

The second case is the pond located at the Uddevalla bridge, managed by Trafikverket, and it is the oldest pond that was analysed. According to the information provided during the interview, maintenance tasks have been carried out in this forebay. One of the particularities of this pond is that it receives much more sediments than for what it was designed for due to the drainage design upstream the pond with forebay (a wider explanation of this system is provided in Appendix II). Thereby, sediment accumulation in the forebay was higher than expected during the design. To solve this problem, it was decided to increase the area of the forebay (the relationship area forebay and total area is the highest in all the studied cases, being higher than 40 %). This case emphasises the importance of understanding the catchment area and runoff generation, to be able to make a design according to the specific case.

Lastly, SVOA measured sediments in Bergslagsplan pond. The settled sediment depth was 50 cm in the forebay and main pond, except one point in the pond where the sediment depth was 80 cm. The fact that in the forebay and pond, the sediment height was the same, brings out one question: if this is because of a lack of maintenance in the forebay, or an inadequate design. Understanding existing cases will help to improve the designs in the future, and to adjust the maintenance frequency according to each specific case.

4.2.4. SUMMARY

Table 4-4 shows a summary of the design criteria given during the interview process for the different companies/municipalities, while Table 4-5 presents the characteristics of some of the ponds with forebay described above.

Three of the seven companies/municipalities interviewed have established design criteria. However, for one of these three the information related to forebay was brief.

Table 4-4 Summary of main design criteria per water company/municipality.

Company / municipality	Forebay always as part of the design?	Forebay purpose			Depth forebay	Vforebay / Vtot (%) (V= volume)	Aforebay / Atot (%) (A= area)	Material of the forebay	Do they have a guideline?	Extra information
		Coarse material removal	Risk erosion reduction	Oil barrier						
VA-SYD	Just when pond is for treating stormwater	X	X	-	≥ 1.2 m	5-10 %	10 %	No	Internal guideline	Oil barrier in case of leakage risk.
SVOA	Yes	X	-	-	No information given.	No information given.	No information given.	Hard material near the inlet. Macadam must be avoided.	Swedish report*	Bypass for high return periods.
NODRA	-	X	-	X	No information given.	No information given.	No information given.	No information given.	No	Design return period 1-2 years.
Uppsala Vatten	Yes	-	-	-	≥ 1 m	around 10-20 %	No information given	Usually clay. Macadam must be avoided.	Yes. However, few specifications of forebay are given in the guideline.	Paths for machines. Forebay's shape: more long than wide. Bypass for high return periods.

Company / municipality	Forebay always as part of the design?	Forebay purpose			Depth forebay	Vforebay / Vtot (%) (V= volume)	Aforebay / Atot (%) (A= area)	Material of the forebay	Do they have a guideline?	Extra information
		Coarse material removal	Risk erosion reduction	Oil barrier						
								Hard material for forebay walls.		Oil separator is better to include it in forebay than main pond.
Växjö	Ideally	X	-	-	No information given.	No information given.	No information given.	Preferably concrete, at least the bottom.	No	Accessibility, paths for maintenance. Bypass for high return periods. Design return period 1-2 years.

* (Larm & Blecken, 2019)

Table 4-5 Summary of ponds with forebay dimensions and design.

Place	Name	Total area* (m^2) (Atot)	Area forebay* (m^2) (Aforebay)	Aforebay / Atot	Total volume (m^3) (Vtot)	Volume forebay (m^3) (Vforebay)	Vforebay / Vtot	Construction period	Ratio length-to-width in forebay	Accessibility for machinery
Malmö (VA-SYD)	Toftanäsdammen	n/d	n/d	n/d	n/d	n/d	n/d	2018-2021	0.7	Yes
Lund (VA-SYD)	Kunskapsdammen	10,425	265	2.5 %	n/d	n/d	n/d	2020	0.4	Yes

Place	Name	Total area* (m^2) (Atot)	Area forebay* (m^2) (Aforebay)	Aforebay / Atot	Total volume (m^3) (Vtot)	Volume forebay (m^3) (Vforebay)	Vforebay / Vtot	Construction period	Ratio length-to-width in forebay	Accessibility for machinery
Huddinge (SVOA)	Kyrkdammen	4,290	90	2 %	7,293	153	2 %	2022	0.5	Yes
Stockholm (SVOA)	Bergslagsplan	2,000	290	7 %	3,280	522	16 %	2009	0.8	Yes
Norrköping (NODRA)	Lobbdy	8,250	2,100	25 %	8,360	2,730	33 %	2009	1.3	No
	Rambodalsdammen	2,600	750	29 %	2,600	750	29 %	2009	2.1	No
	Tråbrunna dammen	280	50	18 %	n/d	n/d	n/d	2009	1.0	Not complete***
	Dammarna i Klinga (III)	1,115	225	20 %	n/d	n/d	n/d	2022	1.7	No**
Uppsala (Uppsala Vatten)	Libroback	2,075	105	5 %	n/d	n/d	n/d	2020	0.7	Yes
	Polacksbacken	1,935	450	23 %	n/d	n/d	n/d	2020	0.3	No
	Kungsängen	8,920	230	2.5 %	n/d	n/d	n/d	2009-2010	4.0	No
	Gottsunda (I)	5,525	230	12 %	7,164	276	11 %	2021	5.9	Yes
	Gottsunda (II)		305			366			4.2	
	Gottsunda (III)		120			168			3.8	

Place	Name	Total area* (m^2) (Atot)	Area forebay* (m^2) (Aforebay)	Aforebay / Atot	Total volume (m^3) (Vtot)	Volume forebay (m^3) (Vforebay)	Vforebay / Vtot	Construction period	Ratio length-to-width in forebay	Accessibility for machinery
	Gottsund (total)		655			810				
Växjö (Växjö Kommun)	Id (I)	6,405	205	3 %	n/d	n/d	n/d	2011-2013	1.4	Yes
Uddevalla bridge (Trafikverket)	-	365	150	41 %	n/d	n/d	n/d	Before 2006	1.2	Yes

** Values measured from Google Earth or QGIS.*
*** The area of the facilities was under construction.*
**** Access to just one of the parts.*

4.3.DISCUSSION OF LITERATURE REVIEW AND INTERVIEWS

This section discusses the results obtained during the literature review and interviews. It discusses the design criteria, and the application of these criteria in the studied ponds in Sweden.

Some of the local guidelines from different regions were created over 15 years ago, while others are more recent. However, no older forebay recommendation were found. In Sweden, only three of the studied water companies have guidelines, and forebays were briefly mentioned in one of them. Furthermore, the majority of the studied forebay in Sweden were constructed in the last years. These results confirm that forebay implementation has been increasing with the years, being more common to consider them when designing a pond.

The results during the questionnaire and interviews support the idea of lack of unification in design criteria for forebays. One notable advantage of incorporating forebays is the controlled accumulation of sediments, thereby facilitating easier and more cost-effective maintenance of the pond. All the guidelines and interviewees agreed on the main purpose of forebays: to capture coarse material and facilitate maintenance tasks by reducing the frequency of sediment removal from the main pond. Another purpose that was pointed out during the literature research and interviews is the importance of forebay for energy dissipation. Usually, energy dissipation measures are included to avoid erosion, however, it is also important to include them in forebays to reduce inflow velocities and encourage settling processes. The different alternatives to dissipate energy do not specified the advantages of each one, to be able to decide in which cases it is better to apply them. For example, one of the measures mentioned in the literature is to have an underwater inlet pipe, however, in other guidelines is mentioned that pipes must discharge in above water level or partially submerged, not underwater. This differentiation might be related to different inlet conditions, since the effects in the flow pattern would not be the same if the inlet pipe is 1 m diameter or 0.3 m. Lastly, it was mentioned that forebays can include an oil barrier, but no specification about the oil barrier design and maintenance requirements is mentioned in the guidelines or was described during the interviews. How to install the oil barrier is important since it can affect the flow pattern in the forebay. While the embankment encourages a flow pattern above the crest level to flow to the main pond, the oil barrier encourages a flow pattern under the barrier, to retain the oil in the water surface.

This study found that no differentiation of pond purpose is mentioned in the international guidelines, and most of the interviews. Just one Swedish guideline distinguishes between forebay design criteria depending on if the pond is for treatment or flow reduction. Further studies are needed to evaluate the impact of forebays depending on its purpose and evaluating if the found design criteria are adequate for all the cases.

Generally, there have been no studies on the sizing and implementation of forebays, or how they are affected by shape, different land uses in the catchment or the presence of vegetation. Most guidelines and some Swedish companies state that the design criteria for sizing the forebay consist of a percentage of the volume and/or area of the wet pond, while others use a rain event over the area or impervious area. Since wet ponds are sized based on the catchment area or the impervious catchment area, forebays indirectly take this criterion into account when a percentage of the area/volume is used. Forebays are designed to capture coarse material, and stormwater quality will depend on the type of catchment and activities, particularly the coarse material associated with this stormwater. However, the guidelines do not differentiate between catchment uses. Only one of the international guidelines studied mentions that percentage criteria are insufficient when there are active constructions in the catchment. Some interviewees emphasized the importance of understanding the upstream system to design the forebay correctly. The pond with a forebay managed by Trafikverket serves as an example of an incorrect initial design due to not considering the system upstream. In this case, the forebay's size had to be increased due to the high sediment load. Furthermore, it is possible to conclude that a percentage of area/volume is not an enough as design criteria. This idea also accords with earlier observations made by Johnson (2006).

Regarding the depth of forebays, similar results were obtained considering the international and Swedish design criteria. Most of them agreed that the depth should be between 1 m and 1.8 m. Only one international criterion mentioned a maximum depth of 1 m, while the rest mentioned a minimum depth. Interestingly, based on the interview results, the main reason for setting a minimum depth is to prevent vegetation growth, while one international studied guideline mentioned that the presence of vegetation in forebays encourages sedimentation processes. This leads to the question of how more difficult the maintenance tasks would be if plants are implemented in the forebay.

While many investigations have been conducted on the hydraulic efficiency of wet ponds, none of them have focused on forebays. Thereby, there is no research of forebay hydraulic, which are fundamental to define a design to avoid resuspension and encourage settling. In wet ponds, geometry is an important criterion, but most guidelines do not mention its significance in forebay efficiency. Only one international studied guideline mentioned that a long and narrow forebay would result in a higher detention time for settling, without specifying a recommended ratio. One interviewee mentioned that a long and narrow forebay facilitates maintenance. Based on the studied cases in Sweden, it is evident that the majority of forebays have a length-to-width ratio smaller than 2. It is important to determine how small ratios could affect forebay efficiency, and the consequence that has on facilitating or not the maintenance of the forebays; this is an important issue for future research. Both international studied guidelines and Swedish criteria agree on using hard material for the forebay or its bottom. They emphasize the importance of facilitating maintenance tasks, which is the main objective behind implementing forebays.

It is interesting to discuss the two cases related to maintenance resulting from the interview information. The first one is the pond located in Uddevalla, managed by Trafikverket. As mentioned, the forebay of this pond was enlarged due to the high sediment load into the facility. The high sediment load can be attributed to the characteristics of the catchment, system configuration, and how the stormwater enters the facility. These factors were not taken into account during the design of the pond and forebay. It is intriguing to question why the chosen solution was to increase the size of the forebay instead of increasing the frequency of maintenance in the original forebay. In this case, the relationship between the area of forebay and area of pond was the highest among the cases studied, exceeding 40 %. It might be worthwhile to analyse if maintenance would still be manageable even with an increased forebay size. This case highlights the importance of understanding the upstream system and designing the forebay while considering the goal of facilitating pond maintenance. Furthermore, it underscores the significance of considering the expected load of coarse sediment and the target maintenance frequency when determining the size of the forebay. Establishing a relationship between maintenance frequency and the size of the forebay could be useful in evaluating whether the size does not become too large that requires special equipment for sediment removal, while maximizing the time between such removals.

The second case that is worth to discuss is the Bergslagsplan pond. Despite being constructed over 10 years ago, no sediment removal has been carried out in the forebay. Interestingly, the sediment accumulation in one part of the main pond is now higher than that in the forebay. This suggests that resuspension of settled sediments in the forebay may have occurred, and that sediment removal tasks in the forebay were neglected. It is worth highlighting that, probably, due to the lack of maintenance in the forebay, the entire facility now requires maintenance. Consequently, the advantage of having a forebay was not utilized.

Another noteworthy finding is the lack of maintenance experience in forebays. Most of the interviewees emphasized that no maintenance tasks had been performed, despite the fact that 50% of the studied ponds with forebays in Sweden were constructed over 10 years ago. This observation aligns with the responses obtained during the interviews regarding maintenance frequency, where many of the answers indicated that the water companies were behind of their desired frequency. This result is unexpected, since if a forebay is not maintained, sediments are going to accumulate or resuspend into the main pond, and both units are going to require maintenance. A bad maintenance of the forebay will imply a frequent need maintenance in the main pond.

The majority of the guidelines and interviewees mention the implementation of paths to facilitate maintenance tasks. One interviewee emphasized that in today's context, having an accessible pond is more important than its aesthetic aspects. However, it is crucial to strive for solutions that consider both aspects, taking into account also the importance of social acceptance and value of ponds. Regarding the accessibility results of the studied ponds with forebays, it is important to note that the findings may be somewhat limited due to the available information. In most cases, Google Earth was utilized to visualize potential access points, which means that paths constructed with materials such as green blocks or non-concrete materials may not be visible in satellite images.

4.4. APPLICATION TO JÄRNBROTT POND

This section presents and discusses the results of implementing a forebay in Järnbrott pond (chosen as the study case). It describes the resulted obtained from the modeling and which aspects are important to consider when it comes to implement a forebay focusing on the study case. The presented results are limited to the lack of information about topographic levels, drainage system upstream, and precise data of pond water level.

4.4.1. MODELING

The results obtained from modeling Järnbrott in MIKE 3 are a flow pattern and velocities similar to the measured in previous works. For both flows, 800 and 20 l/s, the flow pattern was circular near the inlet, see Figure 4-8, while the velocities and flow pattern follow the same tendency as in the previous study. Figure 4-9 shows the flow pattern in the current and previous study at the surface layer.

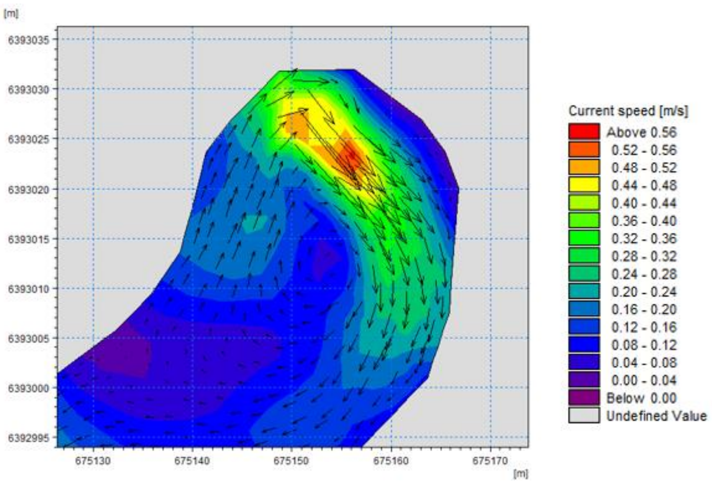

Figure 4-8 Flow pattern and velocities near the inlet for an inflow equal to 800 l/s at the surface layer.

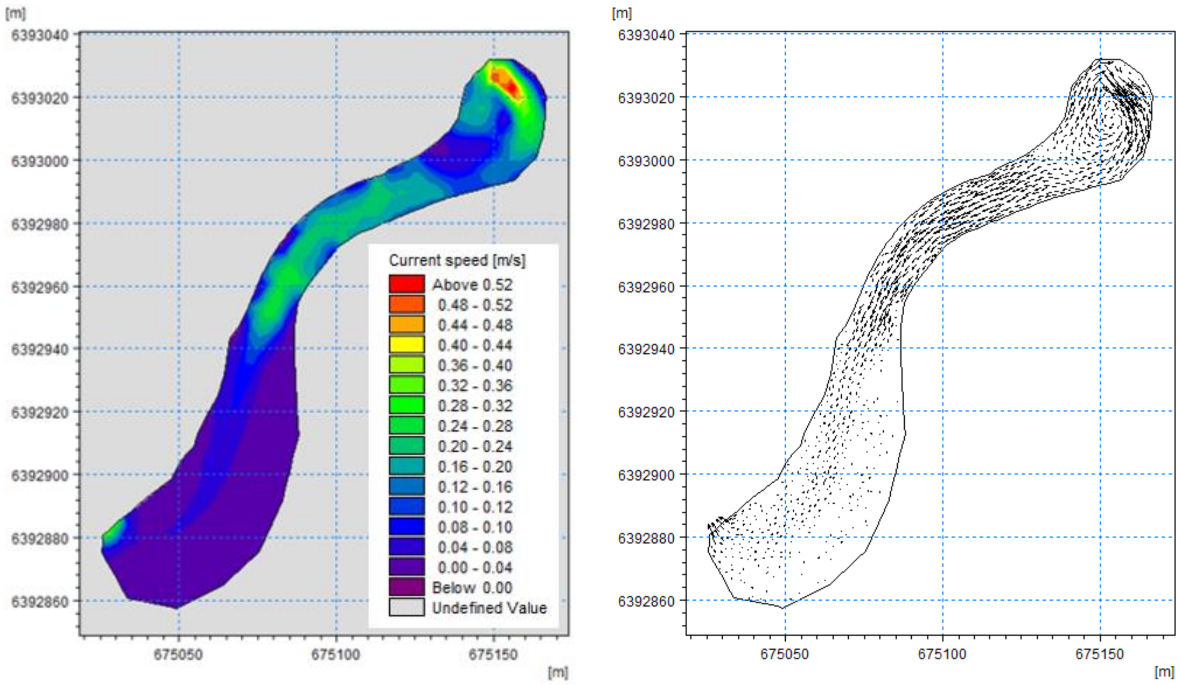

Figure 4-9 Flow pattern and velocities in Järnbrott pond for an inflow of 800 l/s at the surface layer.

4.4.2. DESIGN

There are three main aspects to consider in the design. First, size and shape of the forebay. Second, embankment, pipe or ditch connecting the forebay with the main pond. Lastly, design of accessibility of the facility.

Due to Järnbrott location, the space is a limiting factor to implement a forebay. For this reason, it is difficult to implement a narrow and long forebay for Järnbrott pond. The suggested solution consists of installing an embankment in the current pond and increasing the inlet section to achieve a longer shape, as it is presented in Figure 4-10. The enlargement of the original pond will need a modification of the inlet pipe discharging in the pond, as it is shown in Figure 4-10. The length-to-width ratio is a bit smaller than 2 for the purposed forebay.

The purposed forebay consists of a volume of 810 m^3 (14 % of the total volume), which has an area equal to 540 m^2 (9 % of the total area). The depth is 1.5 m and the material of the forebay is concrete. The energy dissipation zone is constructed in the inlet of the facility and consist of a hole of 0.30 cm depth and 1 m diameter, see location in Figure 4-10. The suggested design is considering the international criteria from the English speaker countries presented in Subsection 4.1.3.

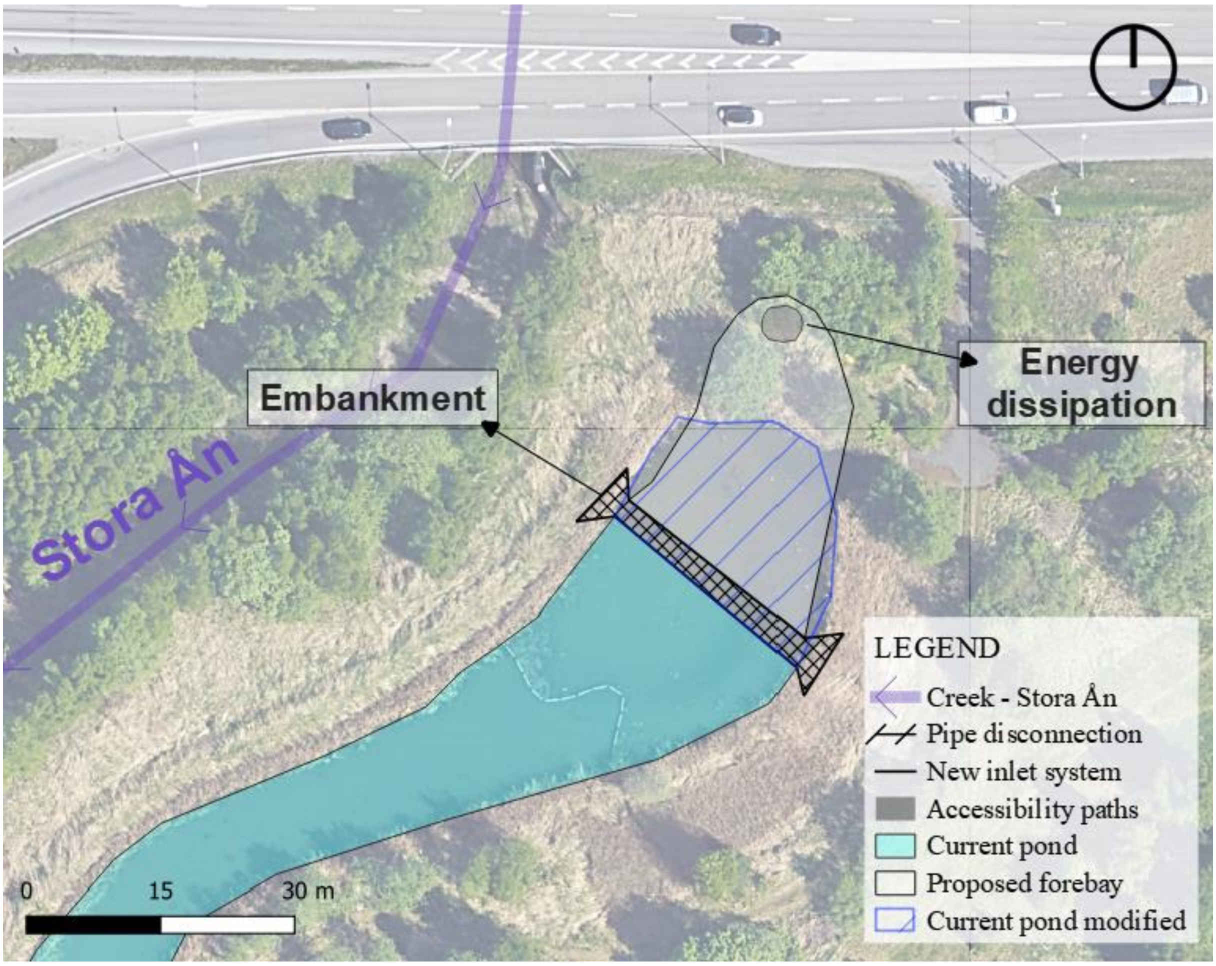

Figure 4-10 Proposed forebay implementation in Järnbrott.

The forebay is divided from the main pond by an embankment. It consists of a riprap wall with an extension of 25 m length. The maximum velocity over the embankment is calculated for the maximum inflow to the pond (1,100 l/s) by approximating it as a broad-crested weir, see Equation (4-2).

$$Q = C\ x\ L\ x\ H^{3/2} \rightarrow H = \frac{Q}{(C\ x\ L)^{2/3}} \rightarrow H = \frac{1.1}{(1.44\ x\ 25)^{2/3}} = 0.10\ m \qquad (4\text{-}2)$$

The water level over the embankment is equal to 0.1 m. Determining the velocity with the expression $Q = A\ x\ v$, the velocity is equal to 0.44 m/s, which is not erosive according to French (1988).

A path of 3 m is proposed to be able to reach the forebay and embankment with machinery. To facilitate maintenance, it is also necessary to include a sediment marker. It must be resilient and placed deep enough into the bottom, its location must be in an accessible and visible area. See access in Figure 4-10.

4.4.3. DISCUSSION

The obtained results using MIKE 3 are similar to the measured values. However, near the discharge of the inlet the velocities are a bit higher than expected which can be improved including the correct roughness and more precise information about the pond. It is important to point out that the bathymetry was created considering the information presented in previous works and no vegetation was included in the model. Moreover, further works must be carried out to implement a forebay and analyse the differences in flow pattern. During this work a weird was included in the model, however, the obtained flow pattern was not reliable, indicating a possible error. Therefore, future studies have to be done.

When implementing a forebay the most limiting consideration is the available area and the current inlet system upstream. Furthermore, due to the lack of theory behind the design criteria of forebays, it is difficult to justify and decide when evaluating the different consideration for implementing a forebay. Just by the information presented in the guidelines makes difficult to make a design that takes into account important factors such as frequency of maintenance of the forebay and how important is the shape and design from a hydraulic point of view. In other words, implementing a forebay of a certain volume is not as challenging if it is just a volume indication or also a certain shape. It is important to highlight that the suggestion of implementation in Järnbrott is limited by the little information about the pond and system upstream.

5. CONCLUSIONS

This study has identified different international guidelines and forebay design criteria applied in Sweden. In general, guidelines recommend sizing the forebay as a percentage of the pond treatment volume/area or based on a rain event. This research argues that a methodology to size the forebay taking into account expected maintenance frequency, system upstream and expected sediment load is missing. The literature research results and the study cases analysed in Sweden have shown that no criteria related to forebay's shape for hydraulic reasons have been define. In some cases, it was mentioned the importance of having a narrow and elongated design to facilitate forebay maintenance, but the hydraulic implications of different configurations have not been addressed. An issue that was not addressed in this study was the difference in design criteria in function of the purpose of the pond.

In general, during this study it was found that technical material about forebay implementation and design is missing. Considering the information obtained from the questionaries, most of the studied international criteria are applied in Sweden. This study has identified fourteen ponds with forebay, one of them with three forebays. Two types of forebay configurations were observed in the study cases in Sweden, one where the forebay and main pond are divided by a berm, and the second where they are divided by a pipe or ditch. The result of analysing the design criteria show that most of the forebays size are not in the recommended range of area and volume, while the depth was higher than one meter in all of the studied cases where the depth was known. In terms of accessibility, this research identified that most of the pond with forebay count with paths to reach different parts of the facility. Lastly, no common criterion has been found related to the pond shape. The relation length-to-width in the units vary from less than 1 to more than 5, being in most of the cases smaller than 2. The results show a tendency of include forebays in the pond design. A limitation of this part of the study is the limited water companies and municipalities considered during the investigation and the lack of information for the studied facilities.

Studied international guidelines usually recommend a frequency time and a percentage of the capacity of the forebay to indicate when it is necessary to do sediment removal. While the results of the questionnaire indicate that no sediment removal was made in most of the facility, despite almost half of the studied cases were older than 10 years. These findings suggest that there is a general delay when it comes to forebay maintenance in Sweden. According to the guidelines and reasoning of some of the interviewed persons, the pond sediment removal frequency will be reduced with the implementation of forebays.

The available area near Järnbrott pond and the current inlet pipe were the most limiting aspect of the possible designs. Furthermore, the lack of theory behind forebay limit the possibilities of considering different design.

To sum up the results obtained of forebay implementation in Sweden, even if most of the international design criteria are considered taking into account all the results from the questionnaire, there is a lack of criteria unification and monitoring of the facilities, its design and maintenance.

5.1. FURTHER WORK

To begin with, further work needs to be done to establish a design criterion to size the forebay that takes into account the expected sediment load of the catchment considering different catchment characteristics, the frequency of maintenance target, minimizing the cost and time of maintenance needs of the forebay depending on its dimensions and shape. Additionally, further CFD modeling will have to be conducted to determine how hydraulic efficiency varies for different forebay configurations. Furthermore, modeling is needed to investigate how the relation length-to-width affects the efficiency of the forebay. During this thesis MIKE 3 was used to model the pond with forebay, however, the obtained results when a forebay was implemented were not reliable to draw conclusions. Future research should be undertaken to explore how sediment quality in the forebay and pond differs.

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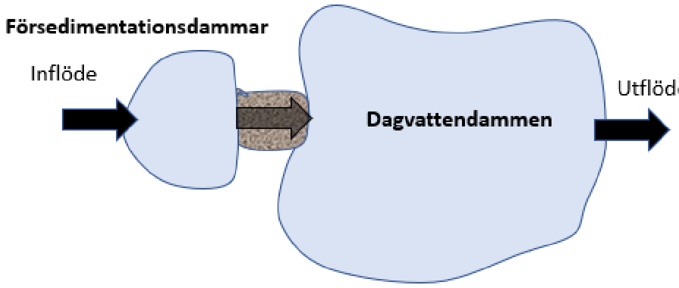
APPENDIX

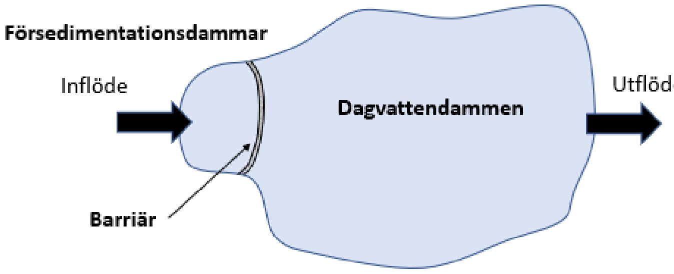
A. QUESTIONNAIRE

This section presents the first questionnaire that was sent by email to the water companies and municipalities, and the guidelines considered while the interview process.

<u>First questionnaire sent by email</u>

Jag studerar försedimentationsdammar. En försedimentationsdamm består av en mindre damm/magasin, uppströms den huvudsakliga dagvattendammen, vars syfte är att fånga grövre sediment och på så sätt undvika dess ackumulation i det huvudsakliga behandlingsområdet. Volymen av en försedimentationsdamm är vanligtvis mellan 10-20 % av den totala volymen av den huvudsakliga dammen. Illustrativ figurer:



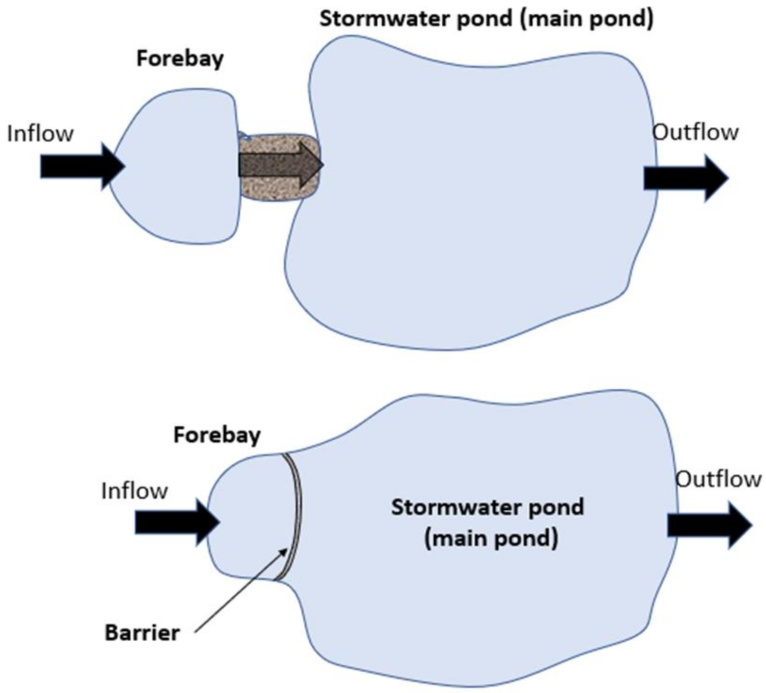


Har ni försedimentationsdammar bland era dagvattendammar?

___________________________________ENGLISH______________________________________

I am studying forebay units. A forebay consists of a smaller pond/storage unit upstream of the main pond, which aim is to capture coarse sediments and, in this way, avoid their accumulation in the primary treatment area.

The volume of the forebay is usually between 10-20% of the main pond. Illustrative figures:



Do you have stormwater ponds with a forebay among your stormwater ponds?

<u>Guidelines during the interview process</u>

The following points were used during the interview process:

1. Role of the interviewee in the company.
2. Site-location of the pond with forebay.
3. Design criteria used:
    a. Guidelines.
    b. Dimensions of the units.
    c. Material.
    d. Purposed of the forebay.
    e. Rain event.
4. Maintenance aspects of the forebay: frequency and tasks.
5. Final disposition of the sediments.

B. DESCRIPTION OF SOME CASES OF PONDS WITH FOREBAY IN SWEDEN

This chapter presents some ponds with forebay in Sweden. Figure A summarises the ponds that were identified during the interviews.

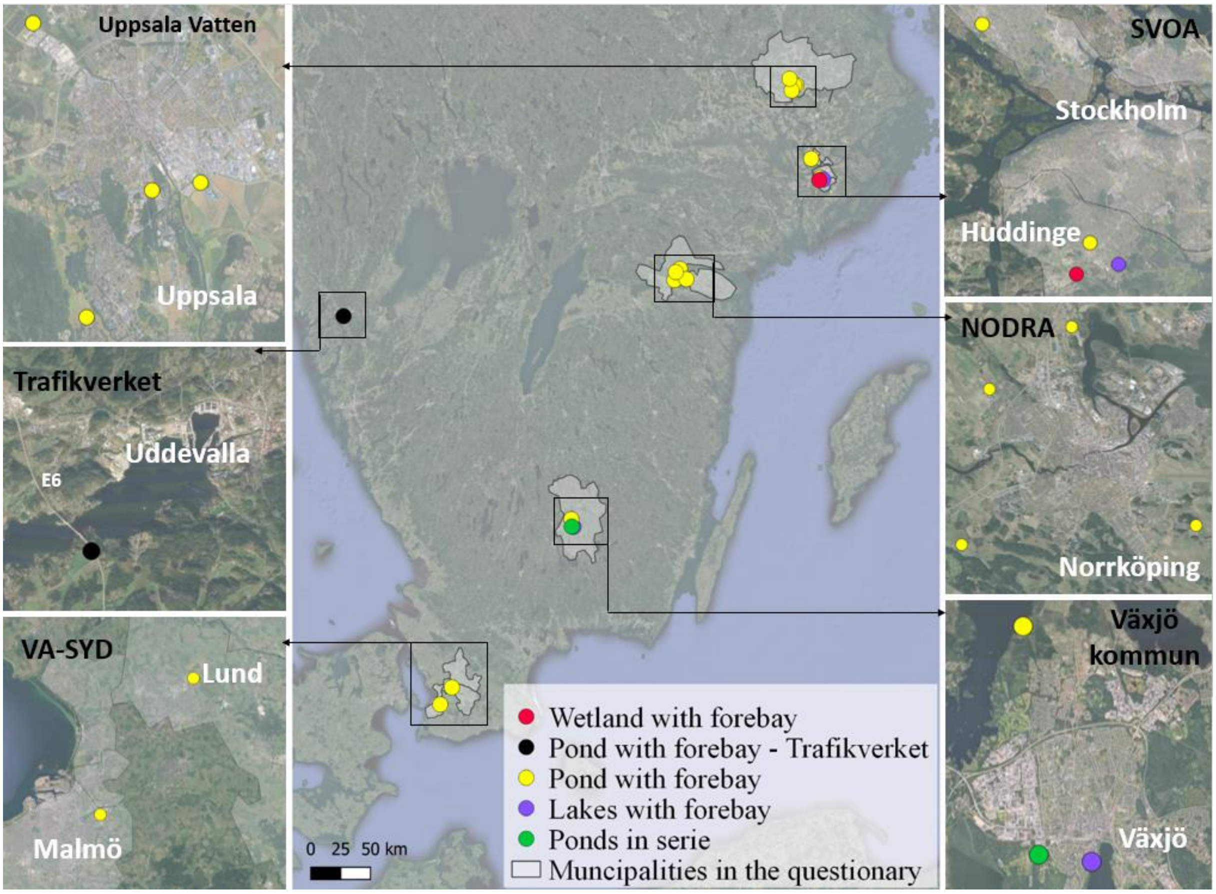


Figure A Forebays identified during the interview process.

<u>VA-SYD</u>

Figure B presents two ponds with forebay managed by VA-SYD water company.

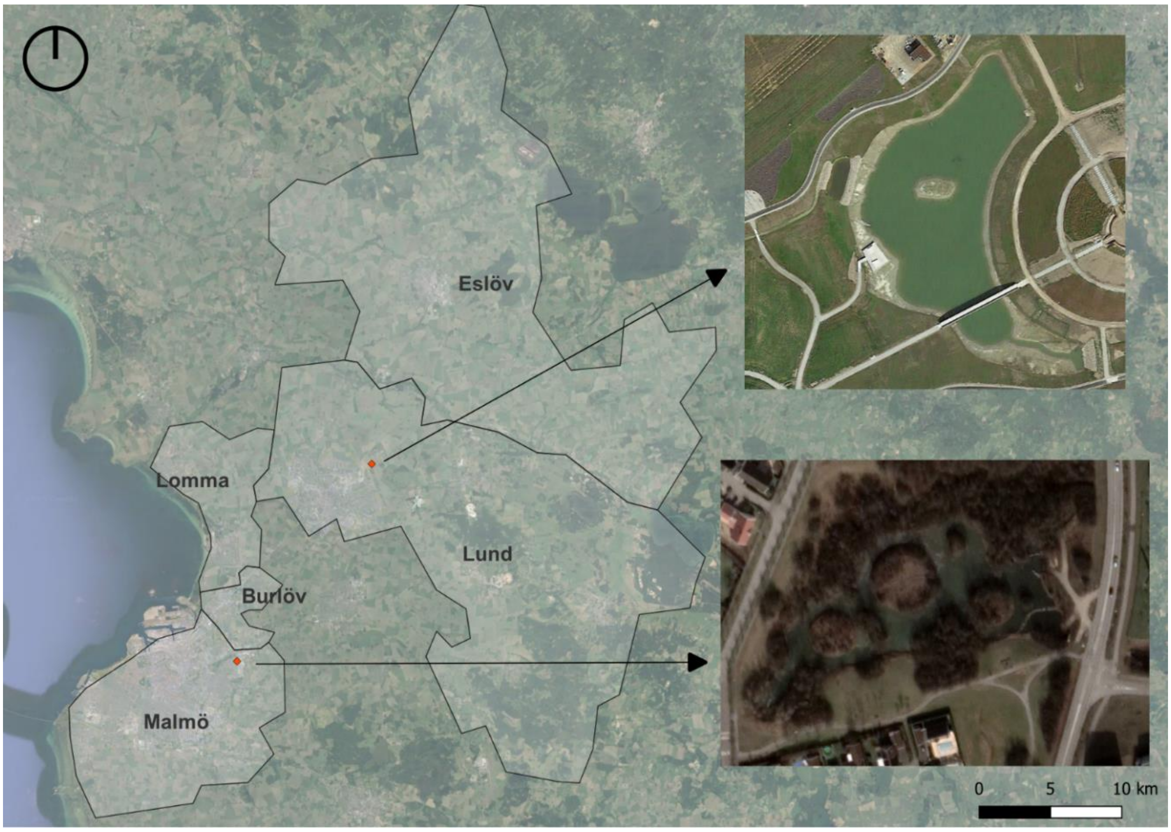


Figure B Two ponds with forebay in Lund and Malmö.

Kunskapsdammen

One of the ponds with forebay is in Lund, it is called Kunskapsdammen, and consists of a new pond with forebay. Based on the data provided in Google Earth, it was constructed after 2019 and before 2021, see Figure C.

Figure C Kunskapsdammen pond with forebay in Lund. Left image is a satelital photo of April 2019, while the right image is from July 2021. Source: Google Earth.

Toftanäsdammen

The second pond is an existing pond in Malmö called Toftanäsdammen. It consists of an existing pond, where a forebay was built between 2018 and 2021. Figure D presents a satellite image of 2009 and other one from 2021, being possible to see the new forebay in the newest one.

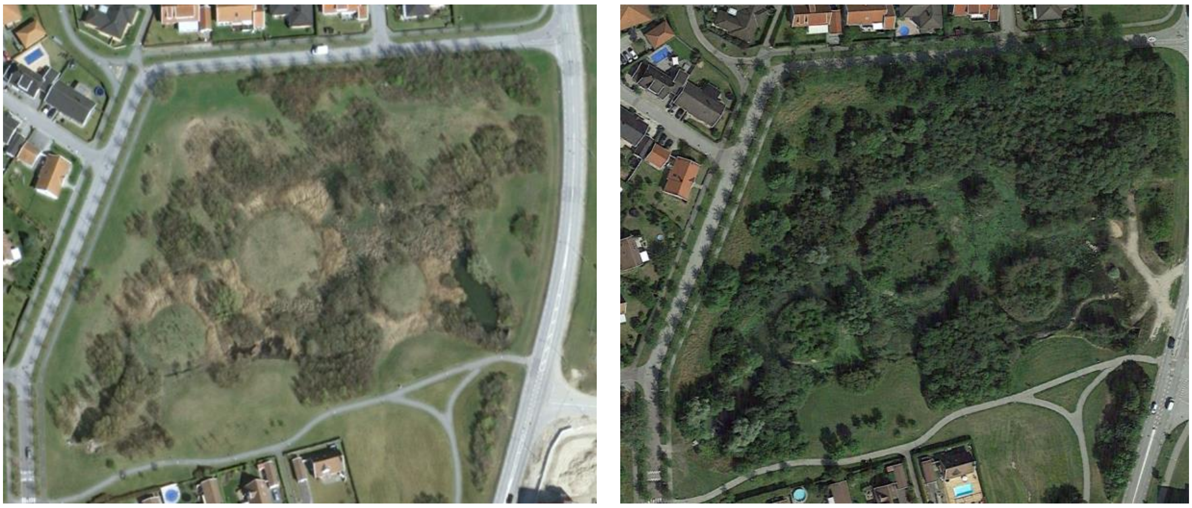


Figure D Toftanäsdammen pond before and after the forebay construction. Left image of 2009, while right image is from 2021. Source: Google Earth.

SVOA

Figure E presents four forebays that are administrated by SVOA. Two of them are from wet pond (Bergslagsplan and Kyrkdammen), while the other ones are upstream a lake (Trehörningens) and a wetland (Flemingsbergs våtmark). Since this thesis focuses on pond's forebay, just the two first have been analyzed.

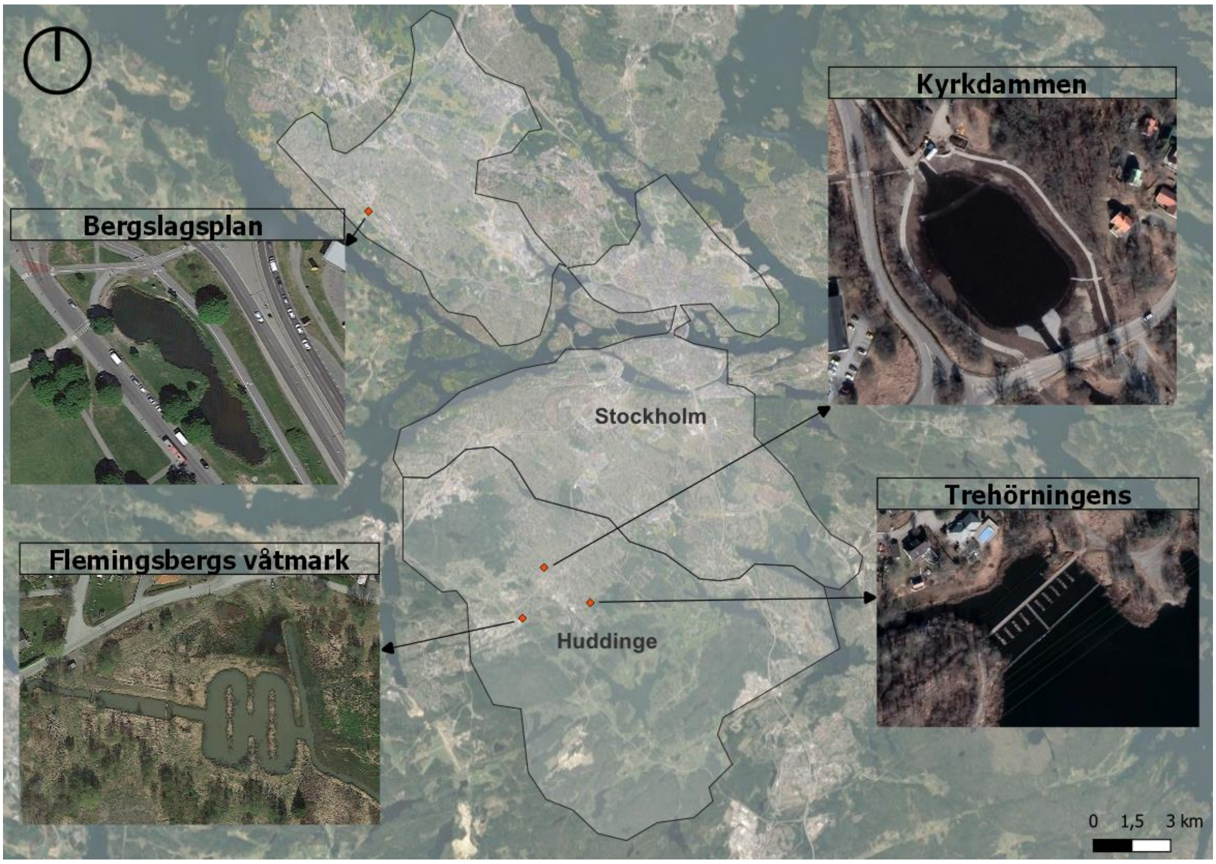


Figure E Forebays in charge of SVOA.

Bergslagsplan

Bergslagsplan pond is located in the north part of Stockholm and it was constructed between 2009 and 2010. It consists of four parts, first a forebay, followed by a sedimentation pond, then a wetland and at the end post-polishing pond, the configuration is presented in Figure F. The catchment area is near 78 ha, and the reduced area is approximately 15.6 ha (since the runoff coefficient is 0.2).

The main purpose of the dam is to treat stormwater coming from an existing pipe system. The flow is pumped from the previous stormwater system to the facility. In this way it is possible to have control of the inflow, since the total control volume of the pond is small. The facility is designed to treat between 85-90 % of the annual flow. The forebay also has a oil barrier. The material of the forebay is not described, while the pond bottom is made of macadam.

The configuration and dimensions are presented in Figure F. It is possible to determine that the total sedimentation pond volume is around 2,700 m^3, while the forebay volume is around 520 m^3, approximately 19 % of the main pond volume.

The inlet is not located in the opposite extreme from the embankment. Thus, the location of the inlet it is not optimizing the detention time.

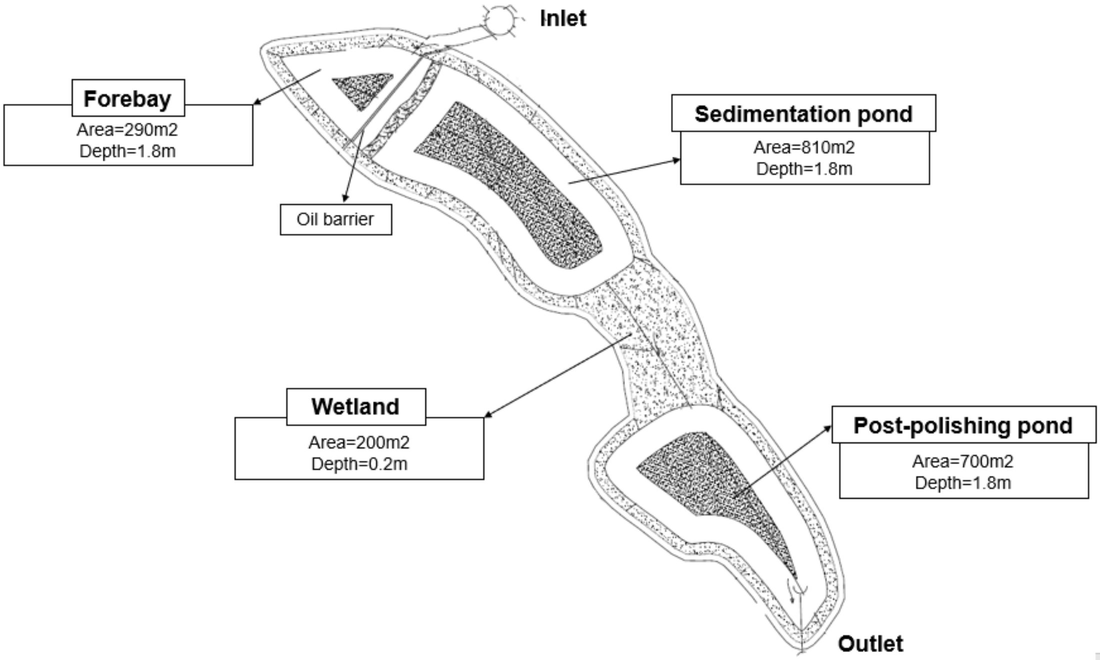


Figure F Bergslagsplan facility configuration and dimensions.

The depth of the sediments was measure during 2020, having a constant sediment depth of 50 cm in all the pond, less upstream the wetland zone, where the depth was 80 cm. These results are unexpected, and they can be due to many reasons, such as resuspension of the settled sediments in the forebay, bad design, too much time between maintenance. It is important to point out that it is not possible to visualize the embankment either the oil barrier in all of the satellite images in Google Earth. Figure G presents Bergslagsplan pond in two different times.

Figure G Bergslagsplan facility. Left image from 2014 and right one from 2020. Source: Google Earth.

Kyrkdammen

Kyrkdammen pond is located in Huddinge, and it was constructed between the last part of 2021 and first month of 2022. The pond was constructed to achieve the EQS of the lake Trehörningen, which did not achieve a good chemical status. The main purpose of the pond is phosphorus removal.
The catchment area is 680 ha. The land use is mostly forest and vegetation (almost 60 % of the area), being the rest mainly residential area. While the forebay is 40 m wide and 15 m long (opposite of narrow and long).

The dimensions of the pond is 160 m length and 80 m wide, being the relationship length:width = 2:1. The depth varies from 1.5 to 1.70 m, being 1.85 m at the highest water level.

Kyrkdammen pond has a forebay in the inlet, see Figure H. It is important to point out that the areas presented were measured using Google Earth. There is an embankment with plants dividing the forebay and the main pond. In the middle of the embankment the vegetation is higher than in the borders, this is to encourage a better inflow distribution.

The bottom of the forebay is constructed with clay, and an erosion protection made with pebble is constructed around the inlet and outlet.

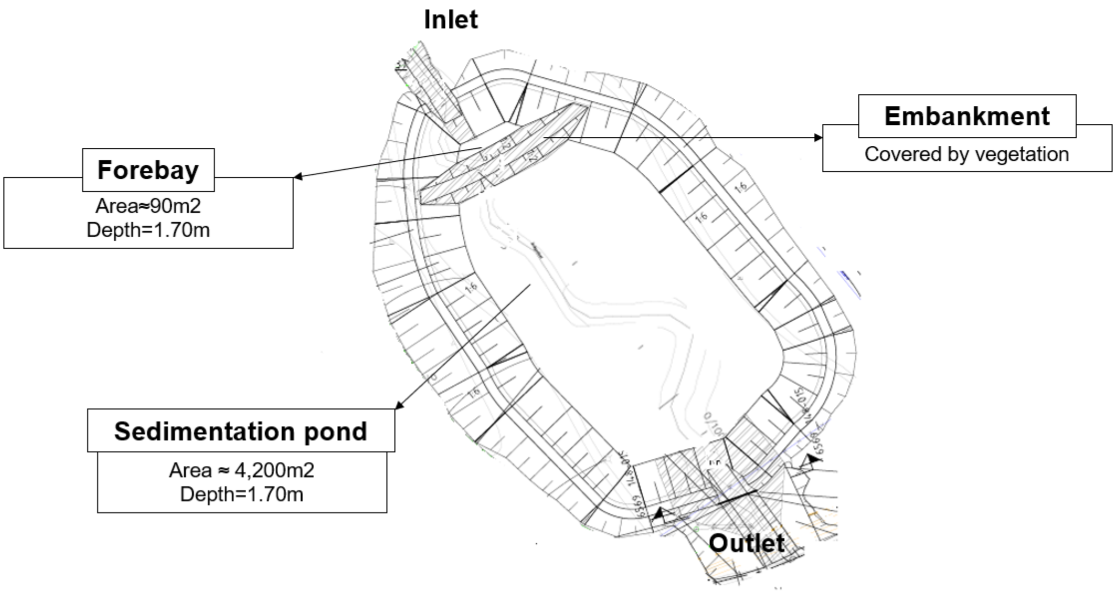


Figure H Kyrkdammen pond configuration and dimensions.

The design inflow is 1,104 l/s. However, the maximum possible outflow is 2,200 l/s. An overflow in the outlet is included to avoid flooding situations in case of obstruction.

The technical description of the technical design report of the pond includes maintenance recommendations. Firstly, to check the following general aspects as the inlet and outlet structures and possible obstructions, debris and vegetation in forebay, every yearly before, in the middle and after the growing season. It also emphasises extra control after heavy rain events.

The sediment depth has to be checked in the forebay every 2 years, and the pond for 5 years. This period must be adjusted after seeing how much is accumulating in the first maintenance periods.

NODRA

Figure I presents four ponds with forebay managed by NODRA in Norrköing.

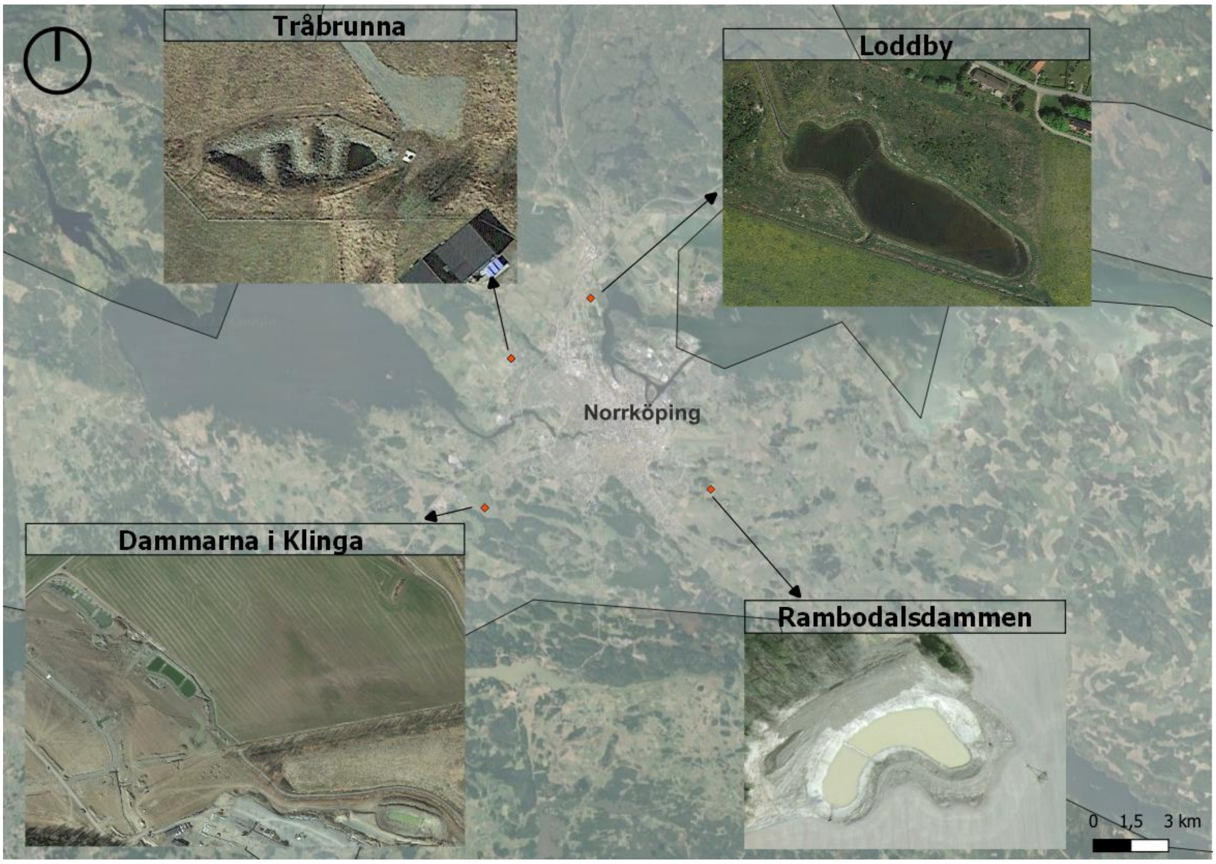


Figure I Forebays in charge of NODRA, in Norrköping.

Loddby

Loddby pond was constructed in 2009. Figure JFigure J shows a satellite image of the pond in different moments, while Figure K presents the configuration and main elements in the pond. The maximum depth is 1.1 m in the pond and in the forebay.

Figure J Satelital view of Loddby pond.

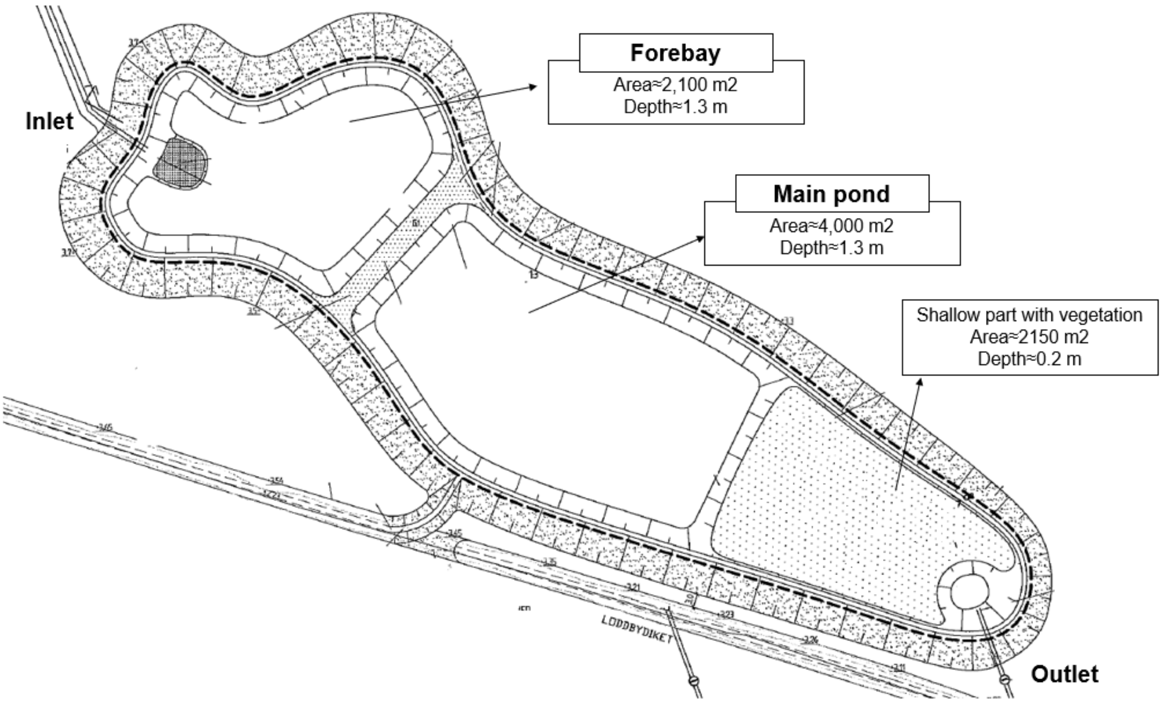


Figure K Loddby pond configuration and dimensions.

Rambodalsdamme

Rambodalsdammen was constructed in 2009, see Figure L. Figure M presents the areas and depths.

Figure L Rambodalsdammen satelital image. The left one is from December 2010 while the right one is from May 2018. Source: Google Earth.

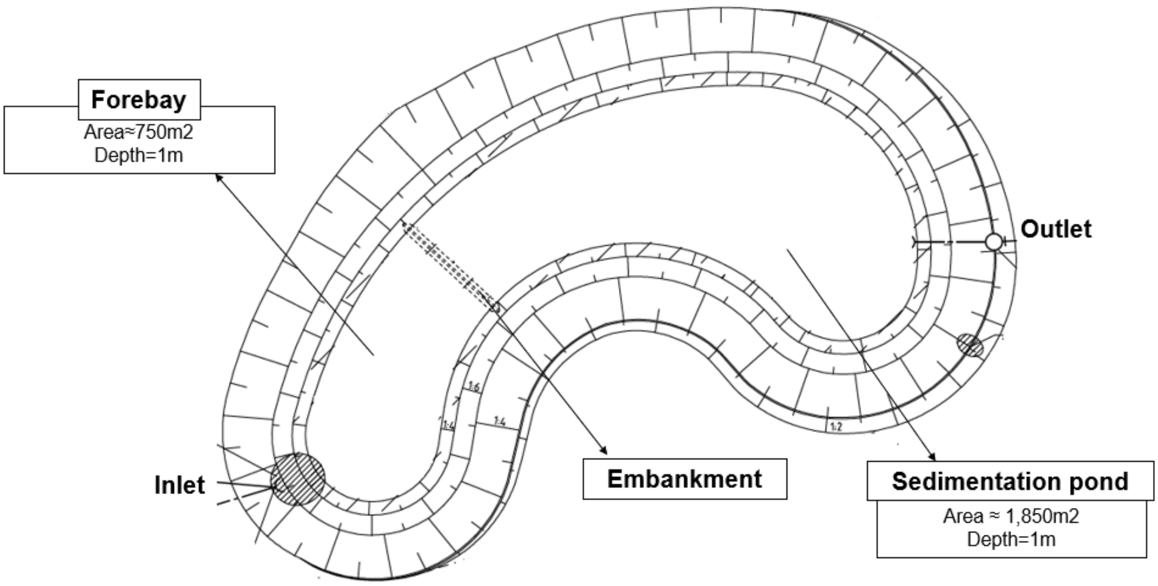


Figure M Rambodalsdammen pond configuration and dimensions.

<u>Tråbrunna</u>

Tråbrunna dammen is a pond which main objective is to delay the flow. However, it has a forebay to facilitate maintenance. It was constructed in 2009. In Figure N it is possible to see the forebay in the east (right part in the images).

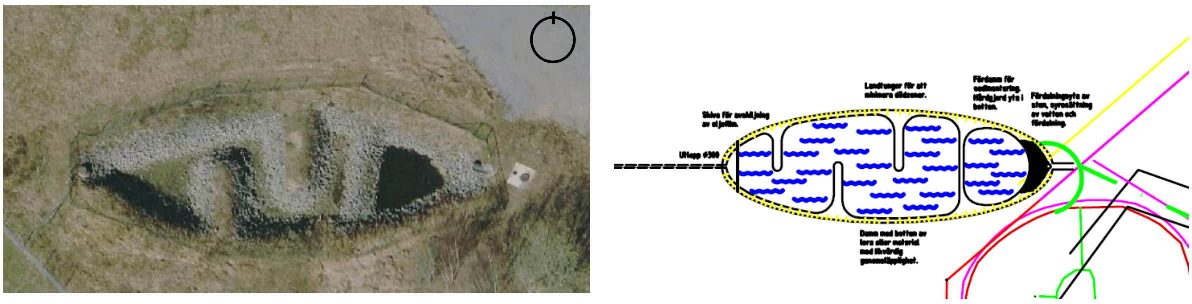


Figure N Tråbrunna dammen.

Lastly, Dammarna i Klinga ponds are not finished yet. There are three constructed ponds, and one is still missing, see Figure O. All of them will have an oil barrier when finished. These ponds are located in an industrial area, and the idea is to dispose the sediments from the pond near their location. Before disposing the sediments, quality analysis are going to be made to be sure that it is possible to dispose them. The plan is to put mainly the sediments for the forebay, since it is going to be maintained frequently. No forebay cleaning were made yet.

Figure O Dammarna i Klinga. Industrial area with three current ponds.

<u>Uppsala vatten</u>

Figure P presents four ponds with forebay administrated by Uppsala Vatten. The company uses ponds to improve stormwater quality.

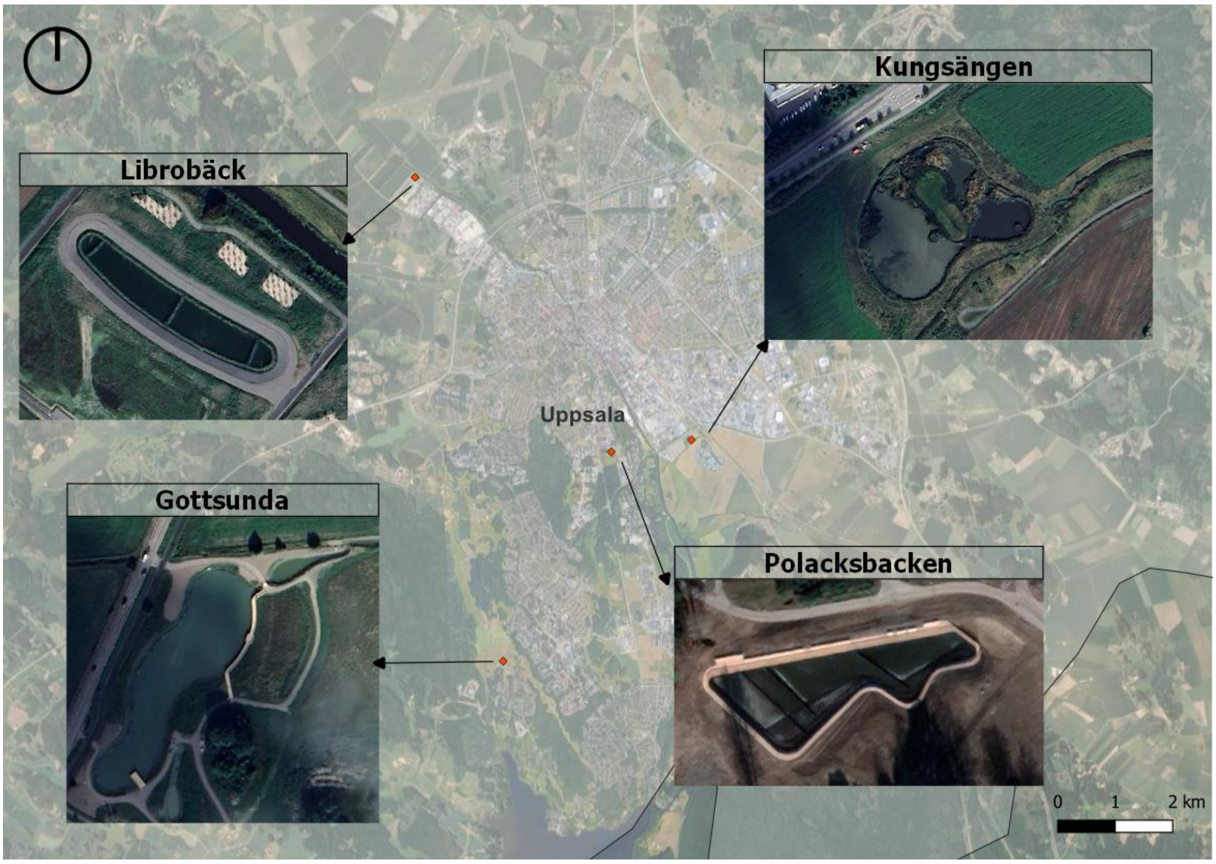


Figure P Ponds with forebay in Uppsala.

The four ponds are very different. Libroback is a rural pond constructed in 2020. Kungsängen has a forebay upstream, and it is connected to the main pond by a ditch. The forebay was constructed between the period 2018-2021.

Gottsunda is a pond in the city with solid walls and three forebays, see Figure Q. It was constructed in 2021. One of the forebays receives stormwater from a road catchment (runoff expected to be much more polluted) and the other ones for an urban area. The difference of water quality in the different areas is the reason why two forebays are included in the design. It is important to point out the shape of these forebays, being both long and not wide which facilitate maintenance tasks.

Figure Q Gottsunda forebays.

Polacksbacken pond is made by macadam. It was constructed in 2020 it is located in an industrial area.

Växjö

Figure R presents three forebay managed by Växjö kommun. One of them is upstream a pond (identified as I), another upstream a lake (identified as II), and the last one upstream a wetland (identified as III).

The pond with forebay, identified as I, was constructed between 2011 and 2013. The forebay is built with concrete to facilitate maintenance, and it is accessible to machinery and inspections.

The forebay upstream the lake was constructed since the municipality wanted to reduce the phosphorus and control the sediments in an easier way. The municipality put a lot of effort to improve the water quality in the lake and they found the forebay reconstruction as a good option to reduce sediments and phosphorus. The barrier dividing the forebay for the pond was designed in a way that the water level was not too high (to avoid that the inlet was not underwater) either too low (to not be affected by the lake/pond level).

The municipality has experience in the maintenance of the two divided ponds upstream the wetland in Bäckaslövs (identified as III). According to the interview information, the sediment amount of the upstream pond is much higher than in the downstream, needing frequent sediment removals. Also, they found a difference in the sediment quality between the two ponds, being the downstream sediments more polluted.

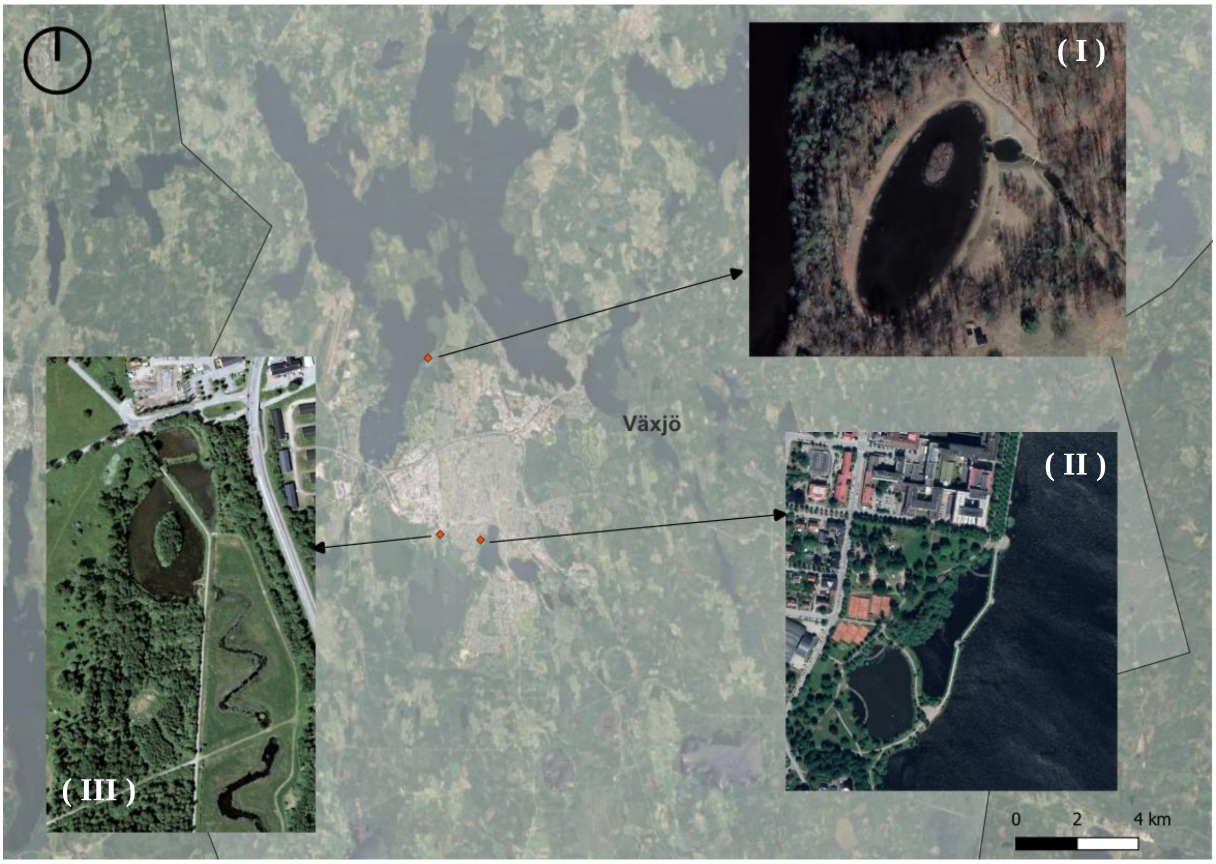


Figure R Forebays in Växjö.

Trafikverket

Figure S presents a pond with forebay located on the E6 road south of Uddevalla bridge. It has the particularity of collecting a large amount of sediments, more than for what it was designed. Figure T presents an image of the pond, its outlet and embankment.

Since the sediment load was higher than the design one, the forebay size was increased some years ago. It is possible to appreciate this in Figure SFigure S.

Figure S Pond with forebay near Uddevalla Bridge administrated by Trafikverket. Left image is a satellital photo of 2007, while the right image is from 2022. Source: Google Earth.

Figure T Pond with forebay to treat stormwater from E6 south Uddevalla bridge. Source: Street View.

The large load of sediments is due to the road design. As it is showed in Figure U and Figure V, the road has the walls, thus, all the runoff generated in the road is capture in the drainage pipes, which discharge in the forebay.

This points out the importance of understanding the system. Usually, road drainage designs count with sand traps that capture part of the sediments upstream. In this case all the runoff is treated in the pond. Furthermore, all the pollutants and sediments generated in the road, due to its configuration, are conduced into the pond. In many other cases, part of the sediments finish next to the road, as is presented in Figure W. It is possible to see that these road designs allow natural sediment accumulation next to the road, due to runoff and physical conditions (wind for example).

Figure U Road design - E6 south Uddevalla Bridge. Source: Street View.

Figure V Road drainage pipes – E6 south Uddevalla Bridge. Source: Street View.

Figure W Other road designs. Source: Street View.

This example of pond with forebay points out the importance of understanding the design for each case, since the sediment and pollutants amount is going to be dependant of the system and configuration. The solution taken to manage the sediment accumulation is questionable, since there are doubts why the decision of increasing the forebay was better than just increase the frequency of maintenance.