Master Thesis

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Balances for water and phosphorus in Lake Vomb, south Sweden

A box model approach

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Department of Building and Environmental Technology
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Acknowledgments

They say that when Saint Augustine was walking on a beach while he was struggling to understand the mysteries of The Holy Trinity, he found a child that had made a hole in the sand. The child ran from the sea to his spot in the sand several times. When Saint Augustine approached him to ask what he was doing, the child answered: “I´m trying to put the water of the sea in this hole.” Laughing, Saint Augustine replied that it was an impossible task; then the child asked, what do you think about trying to understand mysteries beyond your human brain skills.

I want to thank God for this learning opportunity, researching and presenting this work in such a beautiful country that taught me so many new and amazing things as important as academic learning.

I want to thank my parents because their teaching is the lighthouse that guides my life. I want to thank my sisters for reminding me where to see on dark stormy nights, walking, and for smiling with me in peaceful sunrises. The dreams and confidence of my father points me far too amazing and new horizons, and my mother's strength made me follow those horizons. She taught me that we are all like cathedrals, and even the most amazing cathedral is made from small bricks. Thanks to my sisters for being the amalgam for my own bricks and always supporting me to keep on constructing.

Thanks to my supervisor and examiner, Professors Magnus Larson and Kenneth M. Persson, for taking their time to be part of this process. Thanks to every person that, through comments, ideas or suggestions, collaborated to make this work. Thank you very much to Jessica Trump and her patience in making this work readable.

And last but not least, thanks to my supervisor, his patience, wisdom, concern, knowledge, and humility shows that, in his case, a great mind is accompanied by a great human being. Thanks for guiding me through this learning experience that I was learning something even during the jokes. I know that maybe not the sea but thanks to his guidance, at least I have my glass of seawater in my own sand hole.

Abstract

Eutrophication caused by nutrients such as phosphorus has become a major issue over the years. Dealing with this phenomenon is a major concern in many countries, and municipalities are establishing strict rules to cope with this problem in water bodies. However, the development of cities has a cost, and supplying the food needs of people is essential. In order to optimize agricultural lands, the use of fertilizers is a basic requirement. The presence of nutrients such as phosphorus in these chemical products cannot be avoided. Then, to struggle with eutrophication, there must be options that manage the phosphorus in water bodies as a trouble that we have to live with. To deal with this situation, an accurate measurement of phosphorus in water bodies must be carried on. But not only measurements are necessary, but also an understanding of the behavior of the nutrients in the hydrological systems and water bodies. This work attempts to analyze the behavior of phosphorus in Lake Vomb from a box model approach. In order to reach that goal, a water balance of the lake is developed. Once the water balance is done, phosphorus concentrations are added to the flows, and, compared with measured concentration data, and an explanation of the behavior of this nutrient is proposed.

Sammanfattning

Övergödning orsakad av näringsämnen som fosfor har blivit ett stort problem genom åren. Att hantera detta fenomen är en stor oro i många länder och kommuner upprättar strikta regler för att kämpa mot detta problem i vattendrag. Utveckling av städer har dock en kostnad och det är viktigt att försörja människors matbehov. För att kunna optimera jordbruksmarker är användning av gödningsmedel ett grundläggande behov. Förekomsten av näringsämnen som fosfor i dessa kemiska produkter kan inte undvikas. Sedan, för att kämpa mot övergödning, måste det finnas alternativ som hanterar fosforn i vattendrag som ett problem man får leva med. För att hantera denna situation är en noggrannhetsmätning av fosfor i vattendrag något som måste fortsätta. Men inte bara mätningar är nödvändiga, även förståelse för beteendet hos detta näringsämne över hydrologiska system och vattendrag. Detta arbete föreslår att man analyserar beteendet hos fosfor i Vombsjön utifrån en boxmodell. För att nå det målet utformas en vattenbalans av sjön. När vattenbalansen är gjord läggs fosforkoncentrationer till flödena och, jämfört med uppmätta koncentrationsdata, exponeras en förklaring av detta näringsämnes beteende.

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Chapter 1

Introduction

Background

When a water body is overloaded with nutrients such as nitrogen and phosphorus, there is an explosion of algae growth due to the nourishment of this kind of plant with these nutrients. Phosphorus is the key nutrient for eutrophication in fresh waters. (European Environment Agency, 2008). The presence of algae changes the lake's environment due to the production of toxic substances, the limitation of light penetration in water, the consumption of oxygen, and the cover of the surface with decomposition algae. These effects change the environment of bottom-dwelling animals and the chemical features of the water body generating hazardous conditions that could kill part of the biota. This new ecosystem with a changed environment and different chemical characteristics makes water bodies unsuitable for human consumption, and also water could become unacceptable for recreational and other uses (European Environment Agency, 2008). Eutrophication also affects the fishing conditions due to the decrease of fish and other animals that feed the consumption chain because of the decrease in the oxygen conditions.

Eutrophication is related to oxygen deficiency because algae putrefaction consumes all the dissolved oxygen present in water. The absence of oxygen generates chemical processes where phosphorus allocated in the bottom sediments reacts and generates phosphates that are released into the water. The absence of oxygen also originates from the stratification of water that normally occurs in spring or autumn due to the difference in temperatures between warm surface water and cold bottom water and vice versa. This stratification encloses zones generating isolated parts where there cannot occur a mix of surface water with bottom water; then due to oxygen consumption in chemical reactions in isolated bottom parts of the lake, encompassed water bodies with a lack of oxygen are formed. It is important to consider that water with a deficiency of oxygen occurs when it has less than 2 mg/l of oxygen, according to Swedish Environmental Protection Agency (Ekologigruppen Ekoplan AB, 2021)

To ensure the health of a water body, the control of nutrients is an important issue. The starting point is to measure and analyze the behavior of nutrients and their relation with water and sediments. In the present work, a box model for water balance will be made, and inside this model, the behavior of in and outflows of phosphorus will be studied. According to water balance and mass balance, the quantity of external load is going to be studied and based on the total quantification of the external load, an analysis of the internal load is going to be shown. The response of the lake is going to be studied, and it will be shown if the external load is enough to make a mass balance or if the internal load processes are necessary or relevant to show the phosphorus behavior over the lake. Quantities of transported, diluted, sunk, or resuspended phosphorus will be shown.

Lake Vomb is located in the southern part of Sweden; it is a source of drinking water for the city of Malmö. Sydvatten takes approximately 1 m3/s for this purpose.

Since this water is for human consumption, it must fulfill healthy requirements that are harder to reach if the water is contaminated with toxic substances produced by eutrophication like cyanobacteria. Also, Lake Vomb is a source for fishing and recreational activities that also are affected by eutrophication because when there is an uncontrolled growth of algae, activities such as fishing, sailing, or swimming turn risky.

Lake Vomb was classified as an unhealthy water body by the Swedish Ambiental office. Due to the importance of this lake, it is necessary to keep it under healthy conditions despite the surrounding circumstances, like having a large extension of agricultural land that leaks phosphorus from the fertilizers used for sowing the seeds.

A clear study that allows knowing how the mass balance of phosphorus over the lake is important to keep the water body under healthy conditions, and this research is an attempt for this.

Objectives

To avoid or diminish eutrophication, controlling the quantity of phosphorus in a water body is crucial. In order to maintain the quantity of phosphorus, understanding the behavior of this mineral over the water body helps show the lake's responses to external factors. There are two ways in which phosphorus interacts with a water body: internal and external load. Internal load is all the processes that occur inside the lake, and external is the processes that bring new elements to the lake. The main objective of this study is to analyze the external processes of phosphorus over the lake.

Phosphorus is a mineral that dilutes on water. In that sense, it is transported through streams that carry particles of this mineral that can be found naturally in the environment. Also, phosphorus is found in sewage and fertilizers that farmers use to increase the productivity of the land. With the improvement of wastewater treatment plants, the quantities of phosphorus in sewage were diminished, but despite control in the use of fertilizers, they still have significant phosphorus quantities that are transported directly to water bodies through their influents. In that sense, to fulfill the main objective of an external mass balance of phosphorus over the lake, a water balance is going to be made to measure the quantity of inflow and outflow that occurs over the lake. Data of flows is obtained in many ways, and a correct definition and description of the data used is important to make a more accurate water balance.

Establishing a hierarchy of the more important inflows and their charge of phosphorus will give an idea of the most important factors which depend on the phosphorus load. Also, analyzing the behavior of the outflows will show how the phosphorus is washed out from the lake. Understanding both processes together will give an idea of the influence of internal load over the general behavior of phosphorus. In this study, there is no approach to internal load, but this phenomenon will explain some results that are obtained.

Procedure

The main objective of this research is to determine the behavior of phosphorus over Lake Vomb. For this purpose, the analysis of phosphorus concentrations in the inflow and outflow rivers is going to be made. With this data, a model of how this mineral is transported through the lake will be developed. It assumes fully mixed condition in the water body, and then the whole analysis is going to be made through concentration equations. Also, the sediment influence on the phosphorus concentration will be pointed out. According to outflow data, an estimation of what percentage of phosphorus could precipitate in the lake bottom or how much quantity is transported to the water body in a resuspension process is going to be made.

To achieve the main objective, a water balance will be made through a box model. For this purpose, it will be designed as a program with an output showing the lake height. The input for this program is data obtained from SMHI of flows in tributary and outflow rivers. A study and analysis of the measures and modeled flow data will be carried out in order to estimate the most accurate values for making the water balance. Finally, with the more accurate and processed data, the phosphorus quantities are going to be added to the water balance to observe the behavior of the mineral over the lake.

The first step in this process is understanding the lake's water balance. Analyze the hydrographical conditions, despite the many water sources, and establish the main tributaries that will be taken into account for this study to develop a total inflow.

Secondary, an analysis of the outflow is going to be studied to determine what are the main discharges of the lake and what physical processes collaborate in the draining of the lake.

As input data, the historical registers of SMHI are going to be used. In that sense, a relation between the modeled data obtained through the software S-HYPE and measured data in the field of flows and the actual height measures over Lake Vomb is going to be established. A program designed with python software will obtain the behavior of the height level of the lake at the base of inflows and outflows of the lake. Then, Python software is going to be used to establish a relationship between total inflow, outflow, and height levels. A program is going to be developed, through equations, to establish the height level of the lake.

This obtained data is going to be compared with the actual levels measured over the lake for a period of 17 years. Once the relation is verified and ensuring that the program offers a water balance over the lake, the data of phosphorus quantities are going to be added to this water balance to measure how it behaves over the lake and find the variation of concentration of phosphorus in the lake.

Finally, a water balance will be made, and with an established relationship between the heights of the lake and the total net flow, the phosphorus quantities will be added to see how this nutrient is mixed, dissolved, and carried out from the lake.

Limitations

The study of flows is based on SMHI and Sydvatten information, the points of measure of tributary rivers are in two obtained through S-HYPE model, and there are no actual measurements. In the modeled information, there are error margins in the obtentions of flows, and that could generate a super or sub estimation of values. This situation is going to be studied to increase the accuracy of the results.

The are many physical processes that take in and out water from the lake. Phenomena such as groundwater or infiltration from closer creeks also occur, but it is difficult to measure them. In that sense, the correction of those flow types will be made through precipitations values.

The lake profile varies along with the increase or decrease of the lake height, but this variation is complicated to describe and is not significantly important in the influence of the model if it is not taken into account. This means that the volume of the lake is taken as a cube, and in the increase or decrease of height, there is a constant surface area.

For the phosphorus balance, there is incomplete data. Measures of phosphorus concentration of influents and affluents are incomplete, and some values were taken, extrapolating values of phosphates and no total phosphorus quantities. The period of study for the phosphorus mass balance is one year. The samples were taken monthly, differenced from flows that have daily measures. In order to match this difference, an interpolation through the software MATLAB was made to get daily values.

There were no measures of the height level of the lake for the period of study of phosphorus concentration 2021, so the water balance works with the calibration made up until the year 2020.

For the phosphorus balance, the study only takes into account the external load, which means only the phosphorus concentration of inflows and outflows, the internal load in processes like sedimentation or resuspension wasn't studied due to the lack of data and samples.

Chapter 2

Hydrology and water quality of lakes

Physical processes

Water balance

Catchments that feed water bodies usually have complex parameters; soil moisture, the slope of surfaces, type of soil, vegetation, and surface use. Some studies show general characterizations for using these parameters like curve number to link coefficient values according to some general types of soil, but this gives only referential numbers. Nowadays, with the repercussion of global warming, values of precipitation or drought are increasing significantly, and it is necessary to make field studies in the catchment of study to analyze the type of soil, transmissivity of soil, presence of groundwater, the height of water table and other features that accompany precipitation values to estimate the flows generation. In the same sense for the outflows, there are other sources of the decreasing of a water body than only its surface outflows. Also, groundwater streams or infiltration collaborates for the draining of the lake. A constant measure of instantaneous values in streams helps to have an idea of these processes, and sometimes, the water balance is done through measurements of inflow and outflows of the main streams in a catchment.

Circulation

There are many dynamic processes carried out over a lake. "The dynamic processes in a lake are governed by forces exerted on the water body and forces acting within the water mass" (Bengtsson, 2015). Wind, currents of rivers, atmospheric pressure, and stratification are some phenomena that generate circulation in the lake. The wind is the most important generator of currents over a steady water body like a lake. It transfers energy as momentum over the water surface. The intensity of the current depends on the wind velocity and the water depth. These currents of circulation are important in the mixing processes of inflow and outflow solutes during the time of residence (the time that takes the lake to renew all the water mass). Circulation is important for the health of a water body because it also oxygenates it. A different process is stratification which limits circulation over all of the lake and generates isolated zones of deficiency of oxygen.

Stratification

When solar energy is absorbed by water, there is a change in the temperature of surface water. In big lakes, it generates a stratification of water which means that there are zones with different temperatures in the same water body. These vertical temperature gradients encompass volumes of water separating surface and bottom water.

Source: eemodelingsystem.com

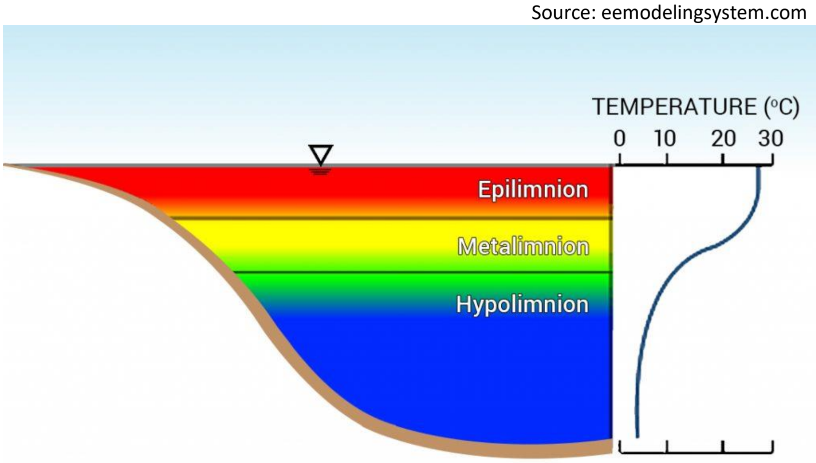

Figure 1 Stratification in a lake.

Epilimnion is the upper zone that receives heat directly from the sun. As this layer is in contact with atmospheric conditions, it is faster affected by external features, in warm seasons it gets warmer faster than other~~s~~ parts of the lake, and in cold weather, it gets cold faster.

Metalimnion is the layer where the temperature gradient values change drastically, and this layer separates the layers of the lake in the upper and bottom parts. Upper with a temperature closer to the atmospheric one and lower with a more stable temperature.

Hypolimnion is the lower part of the lake. This layer remains with a more constant temperature than the upper layer, but like it has a different temperature, this water volume remains encompassed by the Metalimnion from the Epilimnion. This phenomenon isolates processes in the layer and avoids mixing with other parts of the lake.

Oxygen level

Like it was explained above, stratification isolates different zones in a lake. When bottom water volume is isolated, the processes that are carried out with oxygen consumption deplete the dissolved oxygen present in that water volume. Like this bottom water volume is not in contact with the atmosphere, it can not get aerated, so it is mixed with water with more dissolved oxygen, so it develops an anoxic condition. These change the environment of this layer completely and generate the release of phosphorus present in the sediments as phosphates. The oxygenation of water occurs when the temperature of the water body becomes uniform again, and there is a full mixing and circulation of water, but during stratified periods the lack of oxygen in eutrophicated water generates a hazardous environment for a healthier water body. “Oxygen conditions at the bottom of the lake are a key condition for the occurrence of so-called internal phosphorus load” (Ekologigruppen Ekoplan AB, 2021)

Source: Platinum Lake management

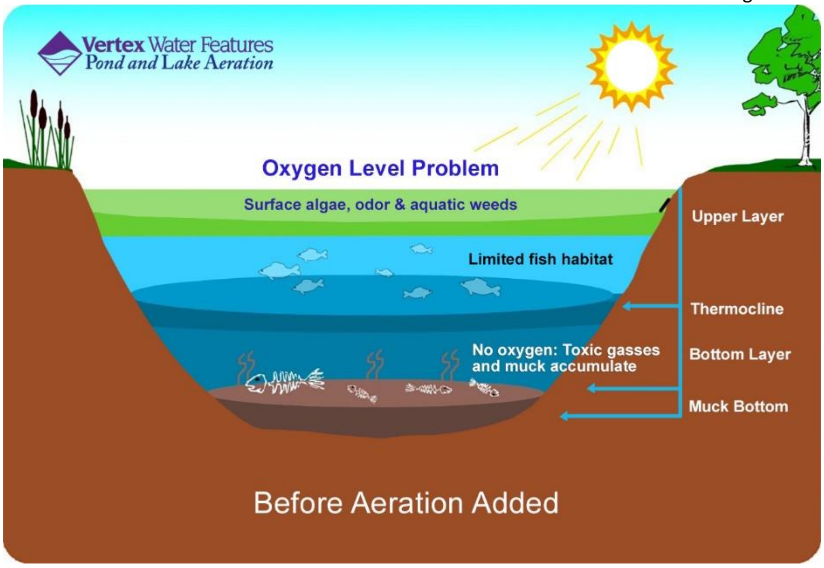

Figure 2 Eutrophication in a lake

Sedimentation

Streams in tributary rivers bring sediments into lakes; these sediments contain all the elements that flow picks along the way as it travels to the water body. If there are agricultural zones that the tributary rivers go over, there is a high rate of nutrients carried in sediments with water flow. These sediments shape the lake profile and are the repositories of dissolved phosphorus in water flow. When wing and stream currents act over water bodies, a phenomenon like resuspension brings phosphorus back to the water, increasing the phosphorus concentration of the water body and consequently the outflow. Also, the absence of oxygen in the bottom layers allows that through chemical processes, phosphorus is released into the water body from sediments.

Water Quality

Eutrophication

Eutrophication in lakes is a phenomenon that describes a boom in algae production. There are big consequences for this situation. Consumptions of dissolved oxygen in water are one of them. Eutrophication originated from the presence of large quantities of nutrients like phosphorus or nitrogen. When a water body has a high concentration of phosphorus, it increases the reproduction of algae that are fed by this nutrient. The overpopulation of these organisms generates high rates of putrefaction of the dead elements that consume all the dissolved oxygen in the water. The sum of a covert surface that doesn't allow sunlight to penetrate deep parts of the water body for carrying out photosynthesis of bottom organisms and the lack of oxygen produced by dead algae consumption of this element generates a hazardous environment that kills part of biota in the lake. Also, this situation encourages the production of toxins in water produced by algae and cyanobacteria, making the water not only hazardous for human consumption but also useless for recreational uses.

> "In cases of eutrophication, depth of visibility is one of the best indicators of lake condition. Shallow healthy lakes should have plants growing on the lake bottom, providing refuge for animal plankton from fish. The animal plankton keeps plant plankton

under control, thus preventing the harmful algal blooms characteristic of eutrophication." (Crouzet et al., s. f.)

Figure 3 Eutrophication in Lake Vomb

Phosphorus transport

The primary sources of phosphorus in water bodies are diffuse sources. Water used for irrigation carries the phosphorus used for fertilizing land to the principal stream, and then it ends in water bodies like lakes or sea. A secondary source of phosphorus is point sources like industries and households. There are some studies like the one made by the European Environment Agency in 2008 where it is shown that the quantity of phosphorus concentration in several lakes has decreased over the years due to the limitation of substances like phosphate in detergents, control in the outflow of wastewater from industries and the improvement of wastewater treatment plants. Although it is shown that the phosphorus quantities in rivers have decreased in urban areas due to this improvement and prohibitions, there is something to output here: "In relatively sparsely populated areas with low agricultural activity, such as the Nordic countries, only half the phosphorus loading is due to human activities. The other half comes from diffuse run-off from forested and uncultivated land." (European Environment Agency, 2008). Then, almost 50% of the phosphorus contamination in rivers comes from forest and agricultural land in non-dense populational regions.

Source: EEA-ETC/IW

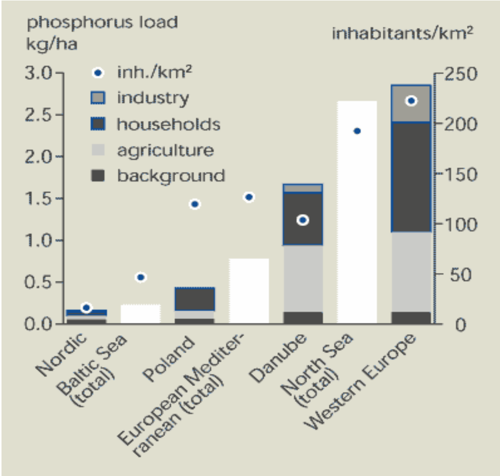

Figure 4 Principal Sources of phosphorus

Despite the above affirmation of the decrease of phosphorus contamination, the measures in lakes still show a very big quantity of this nutrient in lakes, that could be generated for the diffuse sources of phosphorus in agricultural land, forest and also because of the remaining tons of phosphorus in the sediment at the bottom of lakes.

The presence of phosphorus generates eutrophication, damaging the water bodies' environment. It's important to follow up on the behavior of this nutrient in order to maintain water accessible to biota development and for full use of the water body, whether for drinking water or recreational activities. The presence and indicators of phosphorus concentrations in different lakes over the years are shown in the below graphic.

Source: EEA- ETC/IW

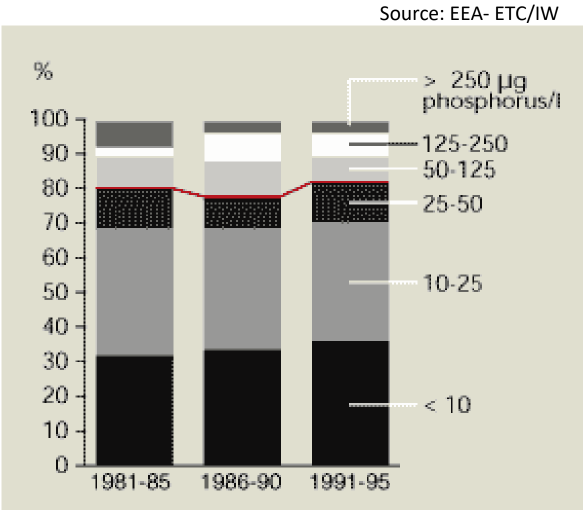

Figure 5 Phosphorus in lakes

The above explanation of the presence of phosphorus indicator and the hazard conditions it generates is important to understand why the control and monitoring of the mineral are important. In Hjälmaren, a study made by Mikael Malmaeus and Magnus Karlsson showed that despite the decrease of phosphorus in superficial water, the quantity of this nutrient in lakes remains the same, and through a mass hydrodynamic balance, they outpointed those sediments play an important role in the phosphorus cycle. It is possible that in some parts of a lake, depending on the geomorphological features, the sediment cycle rules the quantity of phosphorus in the lake. (Malmaeus & Karlsson, 2015).

Source: (Malmaeus & Karlsson, 2015)

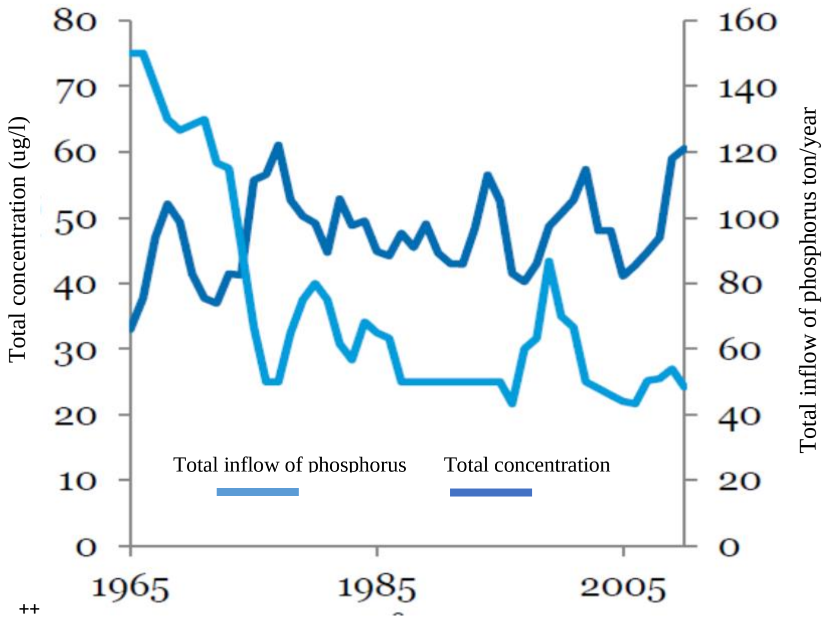

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Figure 6 Decrease of inflow of phosphorus vs. total concentration

The light blue line shows how the supply of phosphorus has decreased, and the dark blue show how despite this decrease, concentration remains almost invariable. Source: (Malmaeus & Karlsson, 2015)

According to Malmaeus, previous studies show that the type of soil of the sediments and bedrock influences the phosphorus dynamic.

Source: (Malmaeus & Karlsson, 2015)

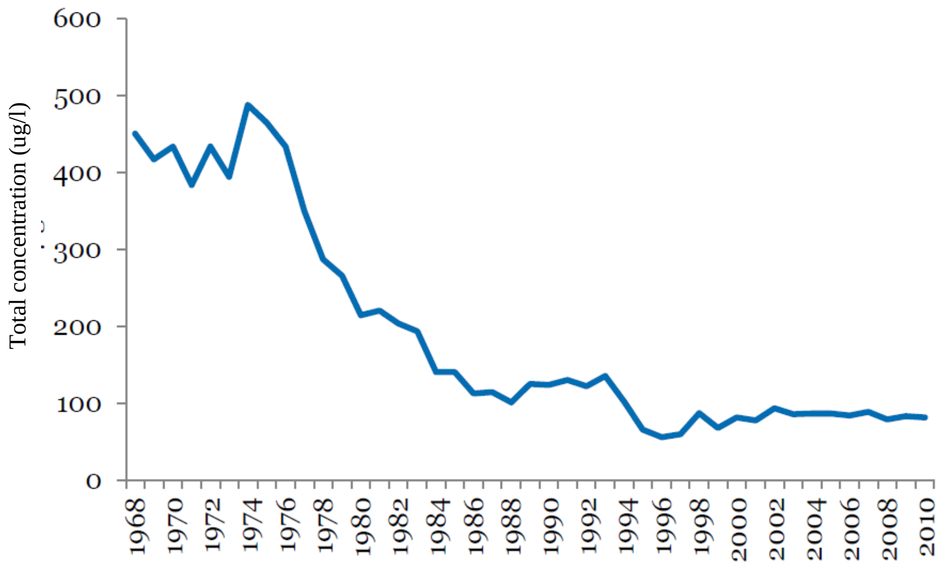


Figure 7 Decrease of inflow of phosphorus over the years

In Hjälmaren, according to the model described by Malmaeus, the interchange of phosphorus is bigger between the water body and the bedrock than the inlet and outlet of phosphorus from the basin. That could be because of the big area of the water body. This is a signal that the relationship between sediments and phosphorus in the storage or release of the nutrient must be taken into count for better accuracy in the modeling process. For big water bodies, the internal interchange is important; for small water bodies, the in and outlet are more important.

Source: (Malmaeus & Karlsson, 2015)

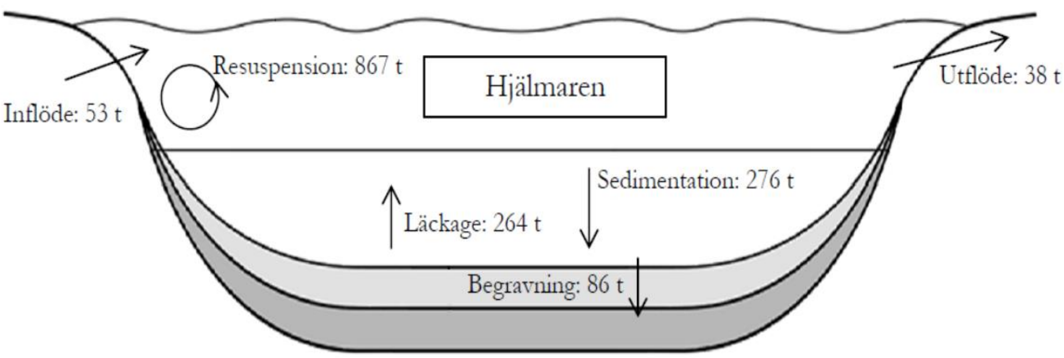


Figure 8 Mass balance of phosphorus in Hjälmaren

Chapter 3

Lake Vomb study area

Hydrology and catchment properties

Kävlingeån is a S-HYPErtrophic, rich in nutrients catchment due to the presence of mainly agricultural land in the surroundings. Its catchment area is around 447 km2

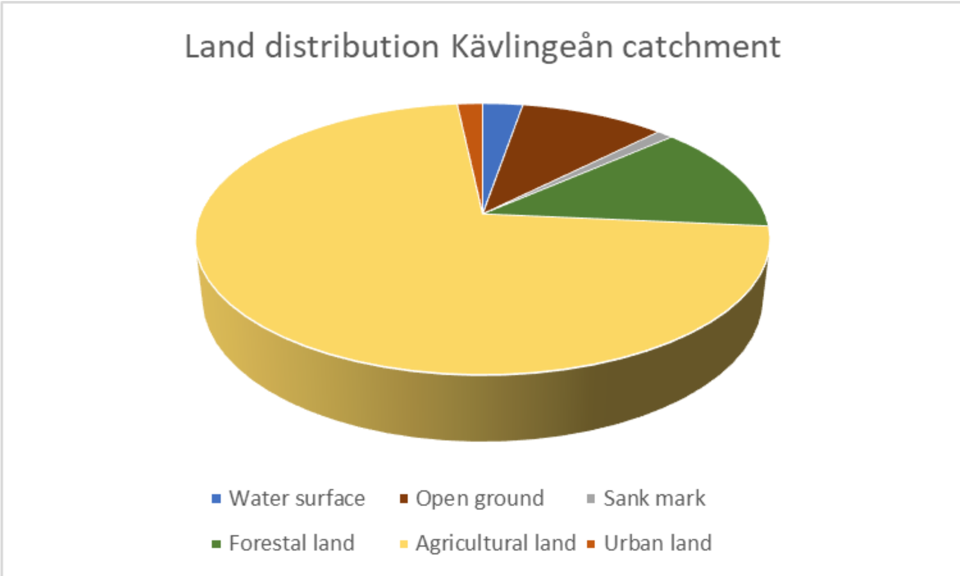


Figure 9 Land distribution

The following table shows the average precipitation, evapotranspiration, and net flow that turns into runoff in the catchment.

Water Balance for Kävlingeån catchment (1991-2020)	
Precipitation [mm/year]	854
Evapotranspiration [mm/year]	575
Net [mm/year]	279

Table 1 Hydrological conditions in catchment

The temperature of water in the catchment for the period of study is shown in figure 10.

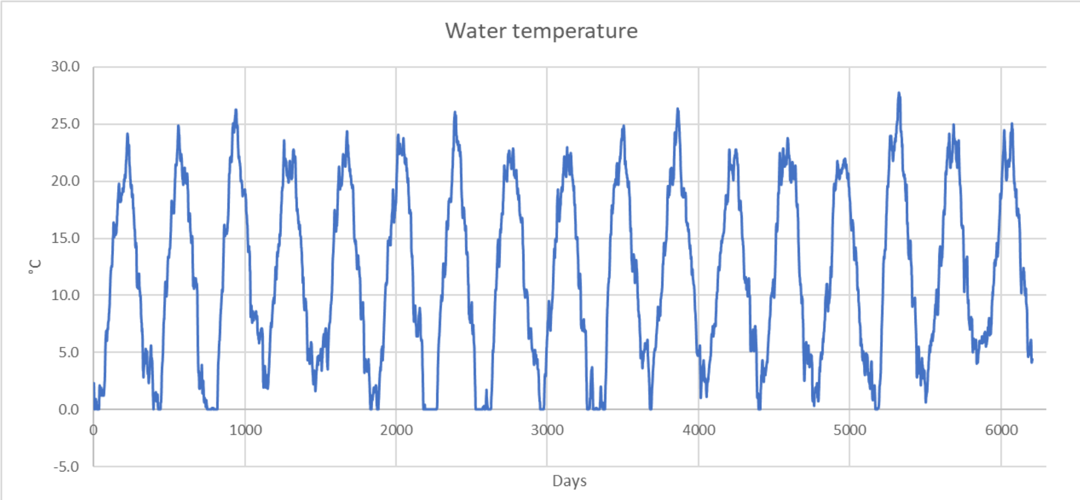


Figure 10 Water temperature measured at the outflow of Lake Vomb

The lake has perch, bream, pikeperch, pike, roach, eel, and trout. Fishing in the lake is an important activity, and it practices professional fishing. Lake Vomb is a resting place for many species and is qualified as a nationally valuable water body in Sweden.

Lake properties

Lake Vomb is a lake located in the Kävlingeån hydrographic basin in the municipalities of Eslöv, Lund, and Sjöbo. The average depth is 6.6 m. The surface area is approx. 12 square kilometers, and the volume of water is close to 80 million cubic meters. It is important to mention that the lake has a regulated outflow, a gate built in 1940. The total catchment area is around 447 square kilometers, of which almost 70% is agricultural land. Lake Vomb is the main source of drinking water for the city of Malmö, from where it is pumped at an average flow of 1 m3/s. There are three main tributaries to the lake: Borstbäcken river, Björkaån river, and Torpsbäcken river, and there are two mainly outflows: one that is almost constant taken by Sydvatten for supplying water to Malmö (around 25% of its outflow) and the Kävlingeån river (The another 75%).

Source: SMHI

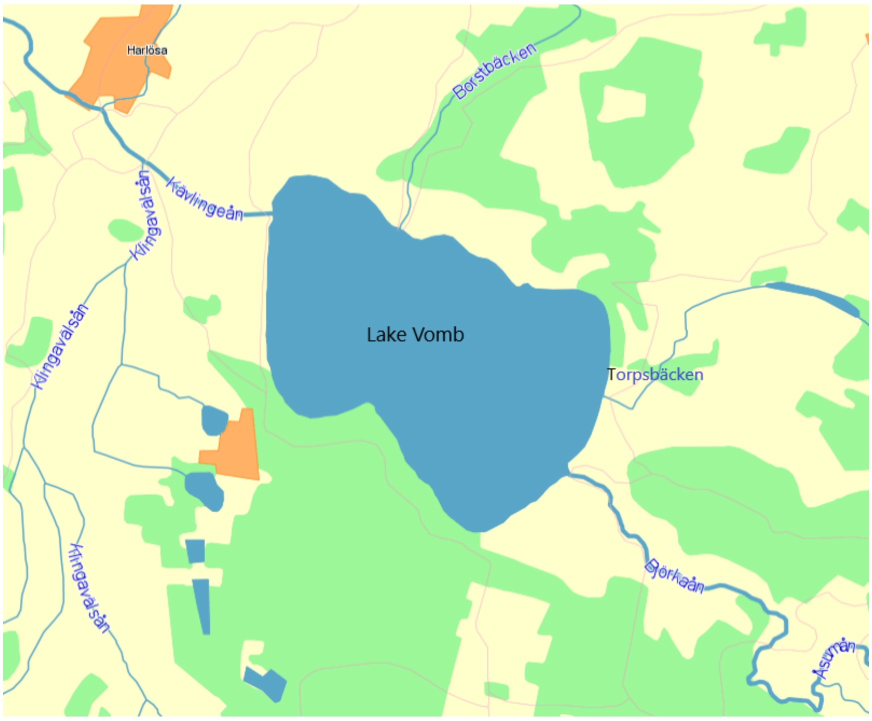


Figure 11 Lake Vomb catchment

This lake has very big issues of eutrophication due to the content of phosphorus in agricultural surrounding lands and disposal of wastewater. According to measures, the lake acts in a variate way either as a source or a tramp for phosphorus despite the inflow of phosphorus has remained at an average of 10 tons/year since the decades between 1960 and 1980 with the improvement of wastewater disposal. The lake is classified as a non-satisfactory situation by the water authority. The quality factor for nutrients (phosphorus) is classified as poor due to the high levels of presence of this element.

It is important to notice that the lake has an approximately 600 tons of phosphorus in the sediment, about 40% is transferable to water (Ekologigruppen Ekoplan AB, 2021). With this value, it's important to consider the stratification of water because, with a lack of oxygen, a bigger quantity of phosphorus could be transferred to water, and the stratification generates conditions for oxygen deficiency. The gradients of temperature influence water circulation, which is directly related to the quantity of oxygen in the water. The less quantity of oxygen, the more phosphorus as sulfates that are released in water. Studies have shown that the release of phosphorus from the sediments into water (internal load) is around 4-10 tons per year (Ekologigruppen Ekoplan AB, 2021)

As a variation of the lake height is regulated to oscillate between 3 meters, the volume of control for the outflow can be estimated as a cube of one side equal to the surface area (12 km). That is the volume that is directly linked to the variation of flow. If this volume is multiplied by the average depth of 6.6 meters is obtained the approximate volume of the lake is about 80 million cubic meters. These assumptions are supported by the statement declared that a variation of 2 meters represents around 20 – 30% of the volume of the lake (Ekologigruppen Ekoplan AB, 2021)

Source: (Ekologigruppen Ekoplan AB, 2021)

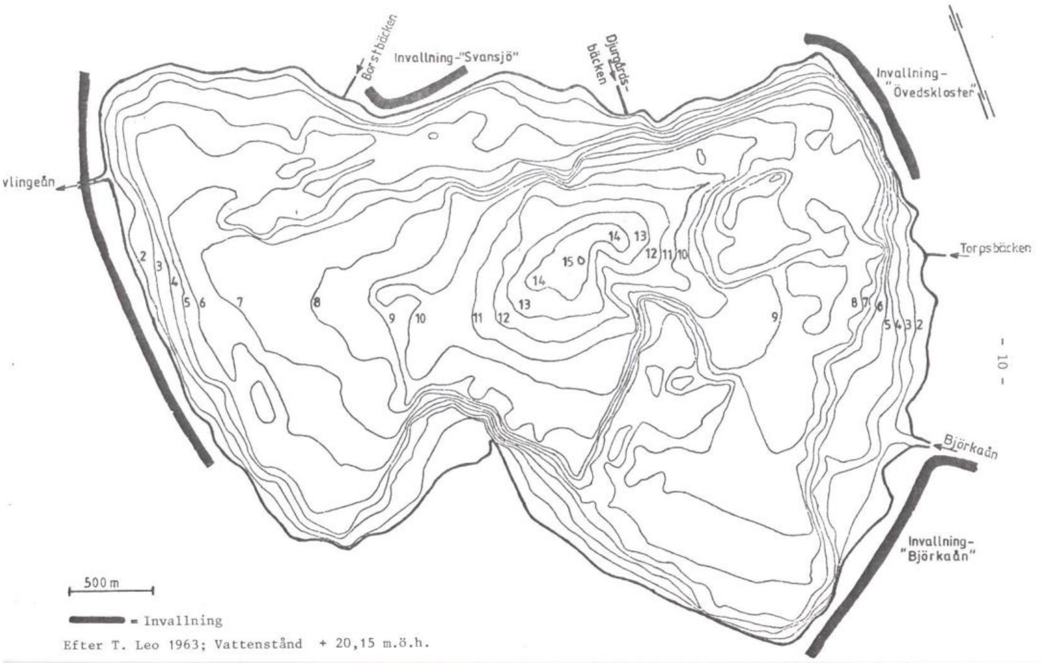


Figure 12 Level curves of Lake Vomb.

The retention time of shallow water is small in relation to the total volume of the lake. That is, the total inflow of the lake can reach all the surface water in about 24 hours, but the total residence of water is about 0.7 years to rotate. This fluctuation is mainly influenced by wind velocity.

It is also remarkable the influence of the regulation on the outflow water since the construction of the gate reduced the variation of minimum values of the lake, but the maximum levels were not altered in big variations.

Source: (Alström et al., 2017)

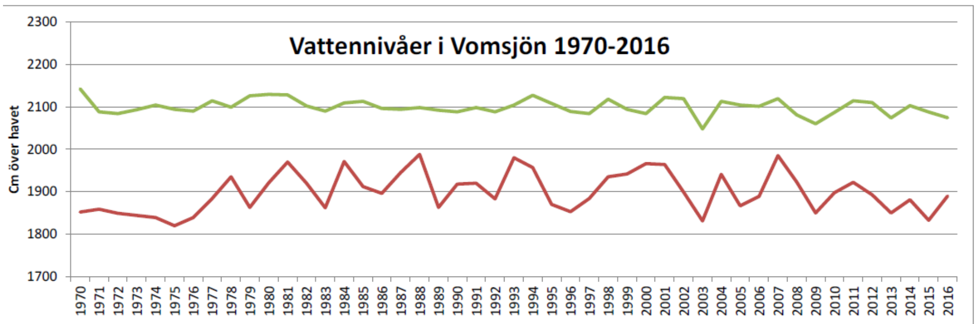


Figure 13 Variations of min and max values of the lake before and after regulations in the 1970´s

Figure 14 Inflow of the gates that regulates the outflow of Lake Vomb

Figure 15 Outflow of Gates that regulate the height level of Lake Vomb

Generally, the bathymetry of a lake is complex, and its bottom profile is variable according to the height of the lake and the behavior of currents and sediments transport at the bottom. In this object to study: Lake Vomb, the historical height variation has remained fluctuating within the interval of three meters. This situation occurs since its controlled outflow was constructed. For the profile varies according to the height, a constant value is assumed, generating that the control volume is estimated as a cube of volume equals to height times the surface area.

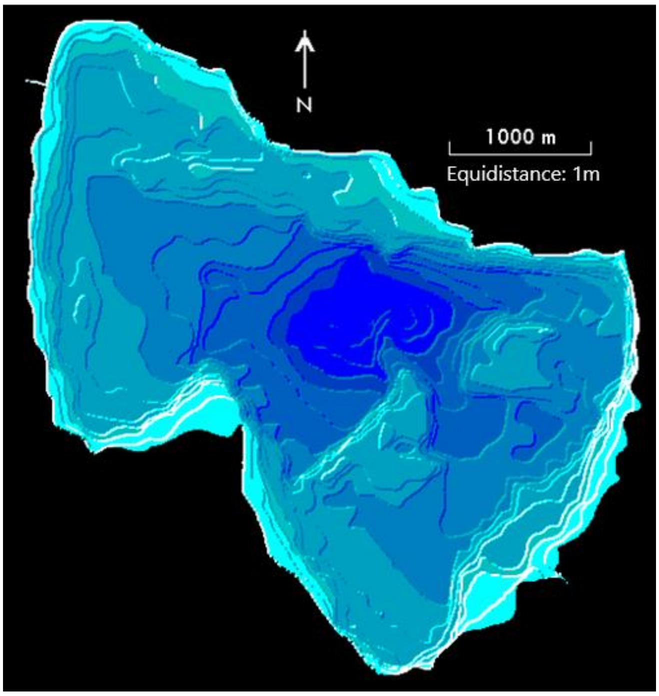


Figure 16 Bathymetry of Lake Vomb

The figure above shows the bathymetric of Lake Vomb, the bedrock profile is variable, with an average depth of 6 meters. An outflow hydraulic structure controls the height level. The variation of height is maintained lower than 3 meters, and the variation of the bedrock profile along this height is almost neglectable. This situation changes dramatically when you go over deeper places in the lake, where it can be found distances of more than 16 meters between the surface and the bedrock. Like in this study, a phosphorus balance is included, and this nutrient is not only in inflow waters but found in sediments at the bottom of the lake and goes again to water for chemical and physical processes. It is important to headlight that the deep in the same point varies in time. This must be noted when measures of oxygen and stratification are made. Deep values for oxygen deficiency and stratification could show different data even if they are taken over the same points

Temperature and Oxygen

Temperature and oxygen concentration in the lake are measured by Sydvatten, and according to the graphics below, it can be seen that there is a link between stratification and oxygen concentration. That confirms the statement made lines above that points out that in many cases, stratification in water bodies generates isolated areas with oxygen concentration deficiency.

Source (Ekologigruppen Ekoplan AB, 2021)

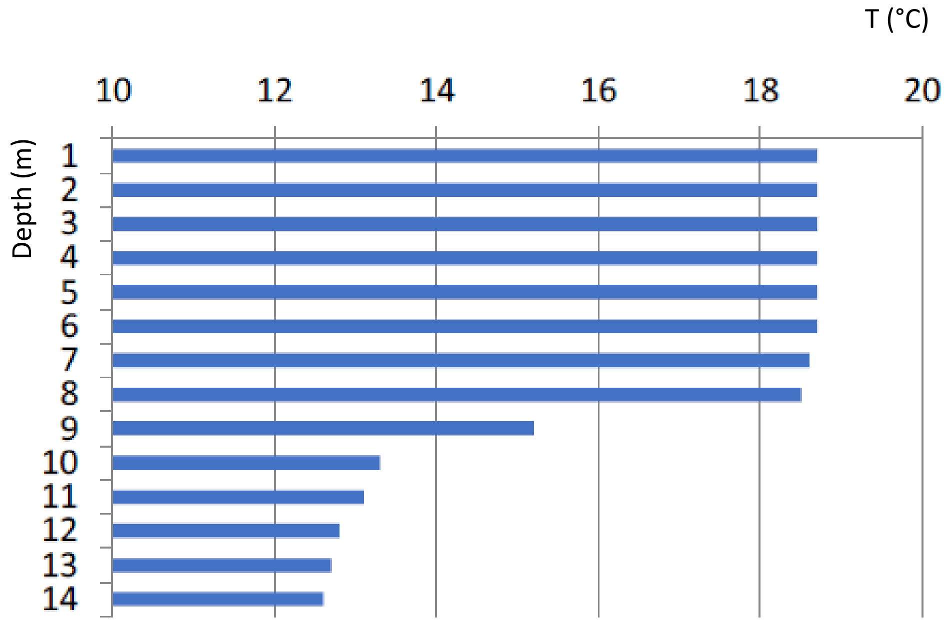


Figure 17 Depth vs. Temperature in Lake Vomb.

Source (Ekologigruppen Ekoplan AB, 2021)

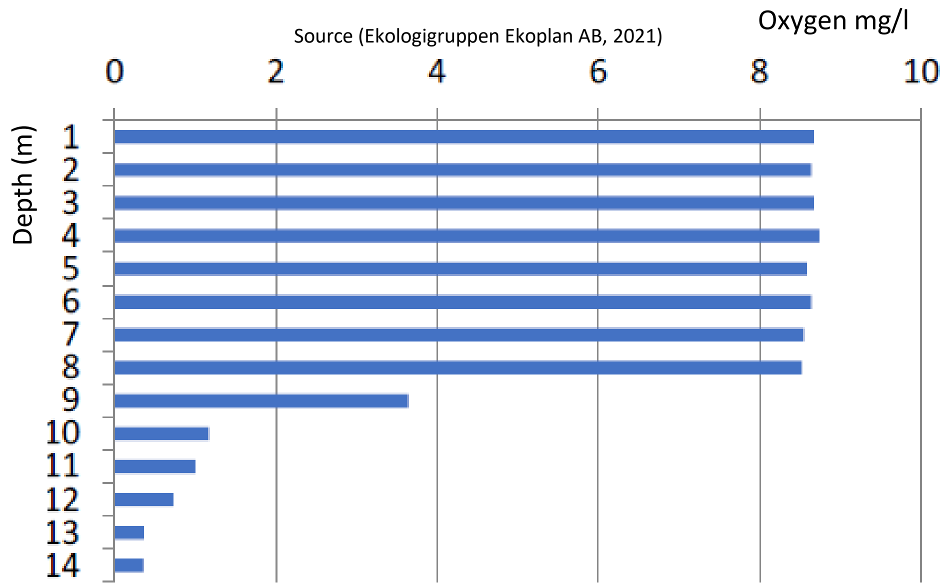


Figure 18 Depth vs. Oxygen concentration in Lake Vomb

Although there is a link between stratification with oxygen deficiency pointed out in the graphics, there are other samples taken in the lake that present some independence among these two phenomena (Ekologigruppen Ekoplan AB, 2021). In that sense, there is no clear trend or correlation between these two processes carried out at Lake Vomb. The temperature in the lake and air temperature are shown in the graphic below. The difference in temperature between air and water can be seen for different periods of the year; when this variation increases, stratification is more feasible to occur.

Source (Ekologigruppen Ekoplan AB, 2021)

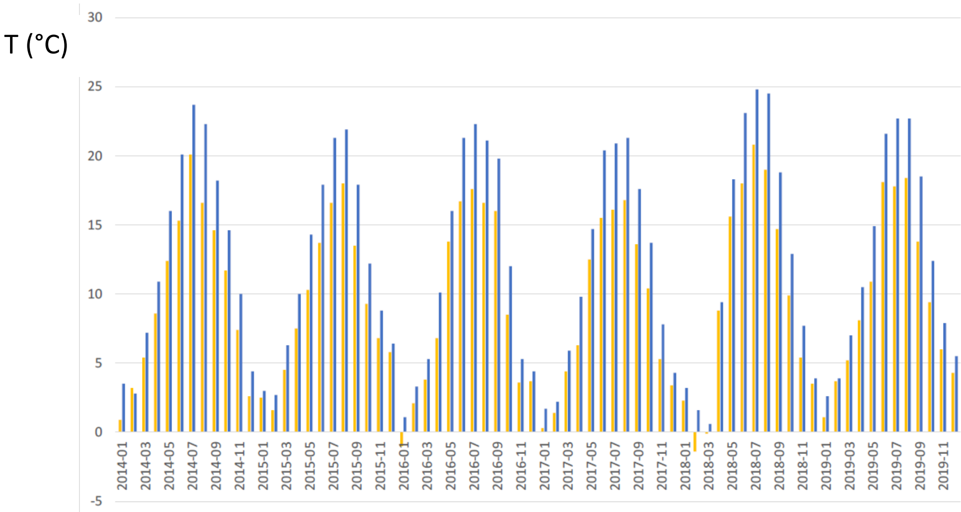


Figure 19 Temp in the lake(blue) and temp in the air(yellow) in Lake Vomb

Also, it can be observed that there are periods when stratification of the lake doesn't occur all year; the different measuring stations at varying depths and temperature gradients influents directly for these phenomena.

Source: (Ekologigruppen Ekoplan AB, 2021)

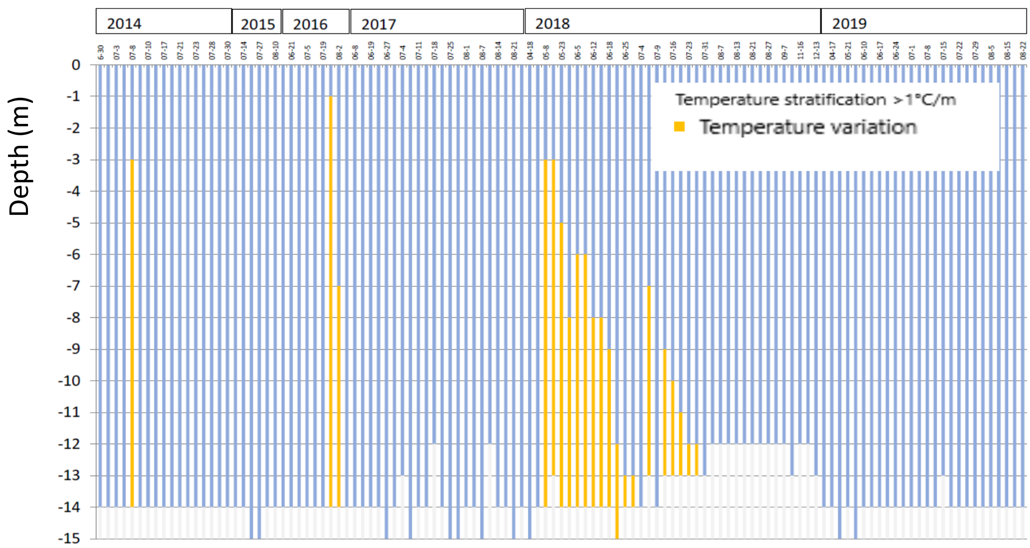


Figure 20 Stratification in different measured station (yellow) over the lake.

Phosphorus

Kävlingeåns Vattenvårdsförbund and SLU (Swedish university of agricultural sciences) take yearly samples of phosphorus concentration in the catchment area of the lake, obtaining the concentrations shown in figures 21 and 22.

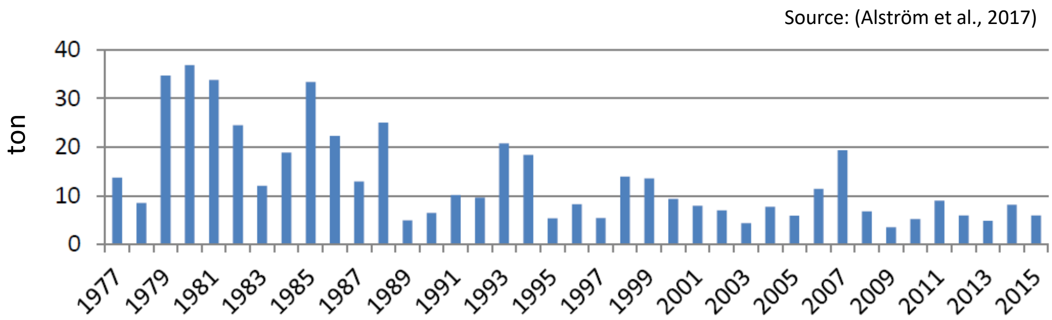


Figure 21 Decrease of the phosphorus inflow from Björkaån to Lake Vomb over the years

The above graphic shows the clear trend of the decrease of the inflow of phosphorus in the main tributary river but in the graphic above, that shows the outflow of phosphorus from Lake Vomb doesn't decrease in the same size.

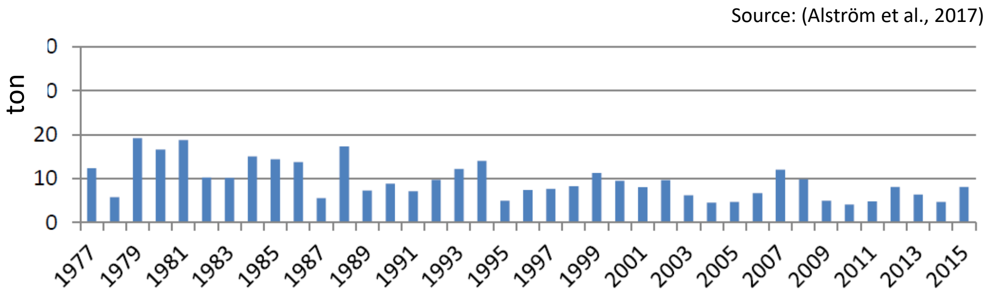


Figure 22 Phosphorus outflow from Lake Vomb

According to the graphic, the outflow has an approximate mean value over the years, and the situation turns to be stranger when the net flow over the lake of total phosphorus is shown in figure 23

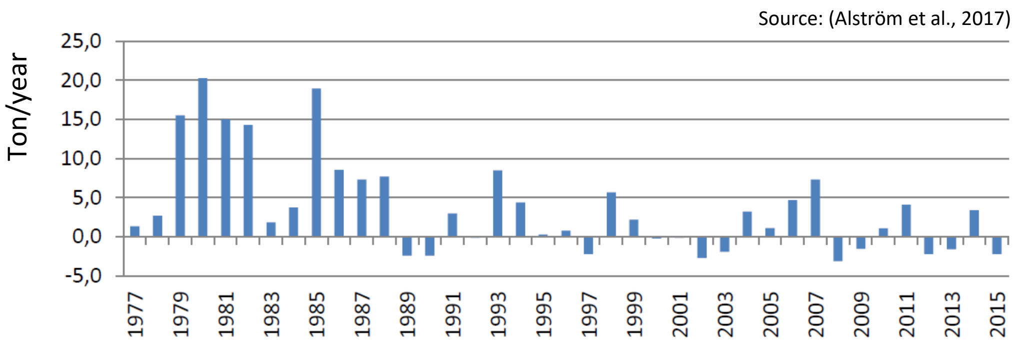


Figure 23 Balance of phosphorus over Lake Vomb

Tributaries

The main tributary river is Björkaån and during the period of study has a mean flow of 3.46 m3/s, and it apports around 77% of the total inflow. The flow of this station is measured in the station number 113. According to field visits realized during the preparation of this study, there was no measuring station in this river close to Lake Vomb, but in the data obtained from SMHI, there is a column of modeled data with a correction factor taken in the field. Also, SMHI specialists confirmed, during the elaboration of this report, that measures were taken in the field in this river to correct the modeled data obtained only through S-HYPE. This is the only inflow that has corrected values with measures taken in the field in data obtained from SMHI.

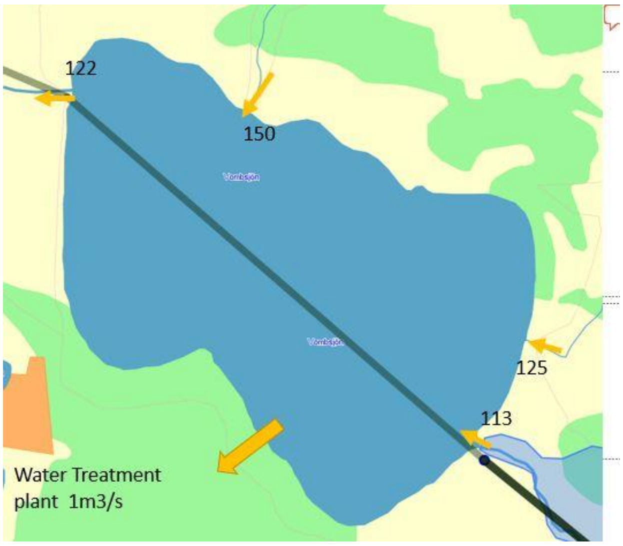


Figure 24 Tributaries and outflow stations of Lake Vomb

Figure 25 Björkaån river

The other two tributary rivers are Torpsbäcken and Borstbäcken. They apport the 8% and 5% respectively, with a mean inflow of 0.38 m3/s and 0.22 m3/s during the period of study. In Torpsbäcken, the point of measurement is number 125. This station has modeled flow obtained from model S-HYPE. Flows in this station represent a fairly small inflow to the lake. The point of measure flows in this zone is named 150. Borstbäcken is the smaller inlet to the lake, which could be a reason that the information of flows in this measuring point is also obtained through S-

HYPE. Furthermore, there are other sources that feed the lake with water. They represent 8% and are about 0.38 m3/s. Precipitation over the lake is taken as a factor obtained from SMHI data-based, and it is explained in more detail later.

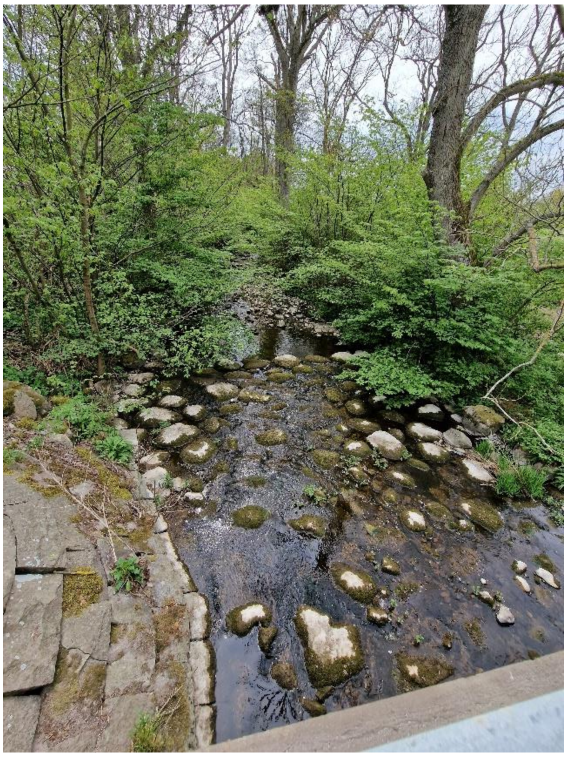


Figure 26 Borstbäcken river

Figure 27 Torpsbäcken river

Lake water quality

According to the Swedish Agency for marine and water management, the classification of Lake Vomb is unsatisfactory, and this characterization is made mainly on the basis of phytoplankton and nutrient quantities (Alström et al., 2017).

Over the years, the phosphorus transport to the lake has decreased. With the improvement of wastewater treatment plants, the less use of detergents, in general, the better management of phosphorus has been achieved to maintain the phosphorus inflow to an average of 10 tons per year.

Chapter 4

Data employed and analysis

Precipitation and evapotranspiration

SMHI offers daily modeled flow from S-HYPE but not the same for precipitation. The input data for the program was the average precipitation and evapotranspiration over the period 1991-2020. There are no values for daily precipitation, and the net flow that turns into runoff is taken from table 1 as net flow

At this point, it's necessary to remark that for the modeling process, the behavior of the height level of the lake was split into two parts. This was done to better analyze the change of trend that occurred since approximately the 3000th day; it means that the analysis period of 17 years is shown in two parts of around 8.5 years (about three thousand days). The change of the trend is going to be analyzed in the modeling part, but it is important to headlight that this process is going to be done in two parts, and that’s the reason why the precipitation is also split into two parts. Appendix 1 it is shown the precipitation obtained from SMHI.

SMHI´s data has measured monthly precipitation and evapotranspiration for the study period, and the average is shown in table 2

Source: SMHI

Period (d)	precipitation (mm/m)	evapotranspiration (mm/m)	net
01 to 3000	67.3	53.8	13.8
30001 to 3200	65	54.4	11

Table 2 Monthly average precipitation

Water level

The water level data was obtained from the SMHI database. In appendix 2, there is the complete database, and in figure 25 it can be seen the behavior of lake height for 17 years which is the total period for this study. It can be seen that the height variation is controlled by gates inside the interval pointed above (3m). It is also important to point out that for the second period (the last 8.5 years or 3200 days) of this study, the actual data wasn’t verified by SMHI, but the height is within the usual data of the behavior of the lake.

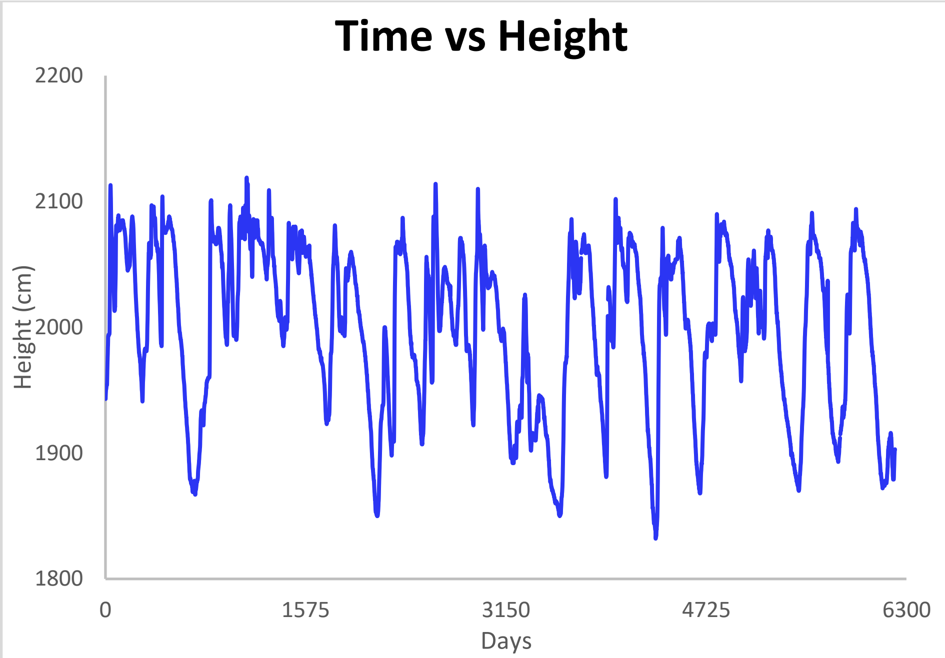


Figure 28 Height variation of Lake Vomb

Flow

Flows data are obtained from the SMHI database. In the SMHI database, there are points or stations of measurement where it can be obtained several types of measures. From all values offered in the files, there are two types that are required for this study: total flow measurements and corrected total flow measurements. The second one is data of flow modeled and corrected with data taken in the field. For this research, the flow needed is the flow with actual measures taken in the field to gain more accuracy, but that data was obtained only in station 122, which is at the outlet of the lake. The inflows data is obtained from a modeling program (HYPE) which SMHI uses to obtain information on flows over Sweden. Data is organized into yearly, monthly, and daily and is taken in cubic meters per second (m3/s).

The analysis of data made for carrying out this study showed that there is a difference in the data model corrected with measures obtained in the field compared with the data obtained only from the modeling software S-HYPE. That difference is clear overall in peak flows; figure 26 shows how the differences are notorious in peak flows.

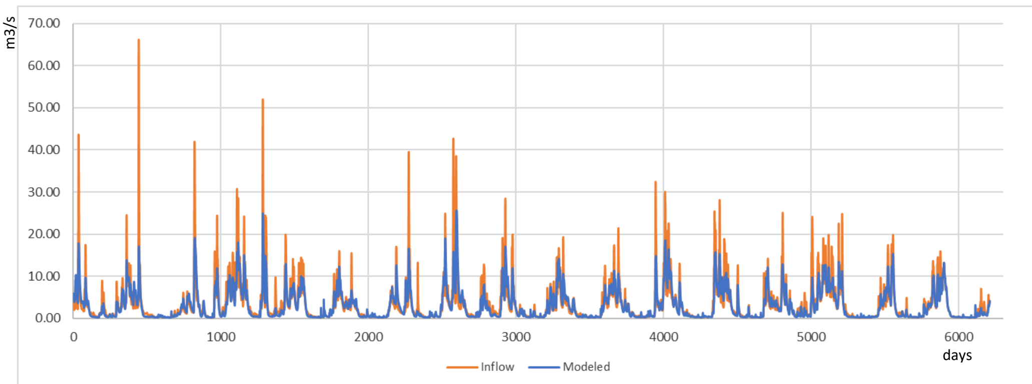


Figure 29 Difference between modeled flow vs flow corrected with measures in field in station 113 (Björkåan)

This information is very relevant at the time of modeling a software for obtaining the lake height with flow information.

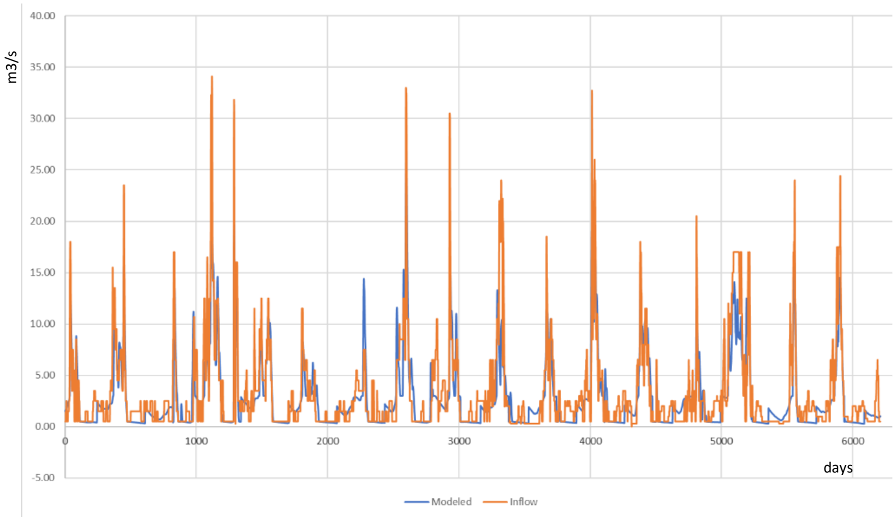


Figure 30 Difference between modeled flow vs flow measured in field in station 122 (Outlet)

This difference gets bigger when peak flows are reached. In figure 27, it's observed that the modeled flows are much lower than actual flows measured in the field. This is a pattern that is clear in station 122 due to the existence of actual measured flows in the sluice gate at the outlet of Lake Vomb. Notice that this information is important for further calculations.

Phosphorus concentration

The concentration or osmolality shows the quantity of a solute present in the solution. Like the three inflow rivers that feed Lake Vomb go through agricultural lands, they all will bring a quantity of phosphorus according to their respective flows (m3/s). This sum of phosphorus and their respective flow goes into the lake that has a different quantity of phosphorus as a result of years and years of receiving different quantities of phosphorus since years where even, because of the bad management of wastewater treatment plants and the agricultural uses a higher amount a difference of nowadays.

As it was observed, the behavior of the lake varies each year. The balance of phosphorus changes according to additional factors besides the inflow concentrations, behavior that would be expected after a full mixing and full circulation of water, and all flow in goes out. For a better understanding of phosphorus behavior, some phenomena are described to explain what internal factors affect the phosphorus concentration over the lake and try to explain why some years the lake acts as a sink and sometimes as a source of phosphorus.

Chapter 5

Water and phosphorus balance models

Water balance model

A model is a representation of reality for a specific objective. This representation must lead to solving any questions that we have from events and situations in reality. The model is made to diminish parameters that, in reality are too complex and can be neglected for a specific topic. For example, if a construction company needs to look for areas where to build new buildings, it could be useful to make a model of the field distribution of Lund city with the objective of looking for free zones; it will be very useful to schematize free green areas in the suburbs from constructed zones. It doesn't matter if there are various types of constructions or different types of soil if only free surfaces are required. More parameters could be added if the requirements increase. For example, if the company not only looks for free areas but also for a specific type of soil, a parameter must be added to the model. The more parameters are included, the more complex is the model, but in the end, it must help to solve the main requirement for what the model is made.

Precipitation is one of the parameters taken into account for modeling. Only the precipitation that goes directly to the lake surface is included for modeling.

The net precipitation is taken over the surface area of the lake and changed to m3/s according to the following equation.

$$Q = CIA$$

Where:

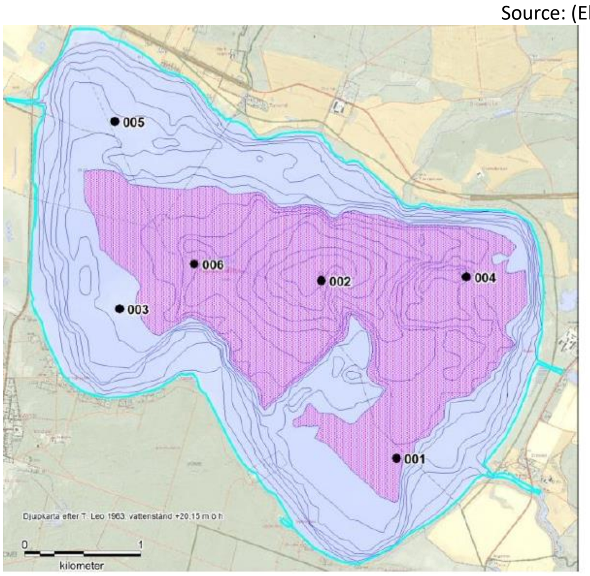
C: Coefficient of runoff is not needed in this case due to the precipitation goes directly over the lake surface
I: Precipitation
A: Surface area

For measuring flow, there are many models that can be used but for a reservoir situation like Lake Vomb a box model approach is a useful tool. The box model, as its name points out, is a model of a water body that works as a box that changes its volume according to the inflow and outflow, simulating the lake as a box that fulfills the equations of a linear reservoir. The continuity equation in fluids is represented by Q=VA, where Q is the flow, V is the velocity of the flow, and A is the cross area of the water conduit. Then, the continuity equation in the box model will be:

$$\frac{dV}{dt} = Qin - Qout$$

As mentioned above, for this model, an approximation of a cube is made in the volume due to the height variation is regulated. The maximum variation is three meters, and within these three meters, the surface area remains at a value that doesn't significantly affect the results.

Source: (Ekologigruppen Ekoplan AB, 2021)



djup, m	km²
0	12
1	12
2	11
3	10
4	9
5	8
6	7
7	5
8	4
9	2,3
10	1,6
11	0,9
12	0,6
13	0,3
14	0,1
15	<0,01

Figure 31 Variation of surface area according to depth

In figure 32, it is shown that the variation of the area within three meters along 3000 thousand days or 8.5 years affects in certain peak points, but the variation for the general volume can be neglected. During the phosphorus concentration modeling, a sensitivity analysis shows that the variation of water surface within 3-meter doesn't affect the results importantly.

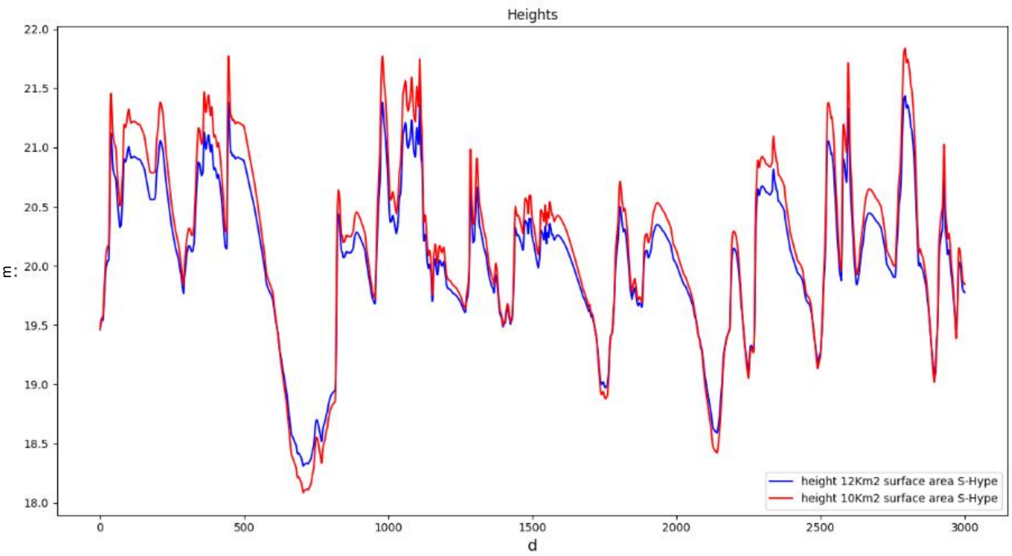


Figure 32 Variation of height with a different surface area

When the volume is obtained with a constant parameter of the area equal to surface area, the above equation turns into:

$$\frac{dh}{dt}.A = Qin - Qout$$

Qin is the sum of the flows of the three tributary rivers, and Qout is the sum of the water taken by Sydvatten for supplying drinking water to Malmo city and the outlet of the lake to the Kävlingeån river. With those equations, a numerical solution is searched and obtained through time steps from the daily data of flows obtained from SMHI. The equation acquires the form of:

$$\frac{h_{k+1} - h_k}{\Delta t} = \frac{1}{A}(Q_{in} - Q_{out})$$

$$h_{k+1} = h_k + \frac{\Delta t}{A}(Q_{in} - Q_{out})$$

The time step is going to be daily because that is the data obtained from SMHI, and the lake heights are obtained from measures in the field. In appendix 2, I it can be found the historical measures of lake heights.

Phosphorus balance model

For the phosphorus model, as the water balance, the input data is the inflow rivers but this time multiplied by their respective concentrations of phosphorus. The data of phosphorus for the 2021 year is limited, and some interpolations were needed in order to get daily data that matches with daily data of inflows. In order to have a more accurate model, the values of phosphorus found were validated with the values of phosphates and such nutrients have a similar behavior over the lake. The interpolated values are close to reality. In figure 33, it can be seen that both values follow the same pattern over the lake.

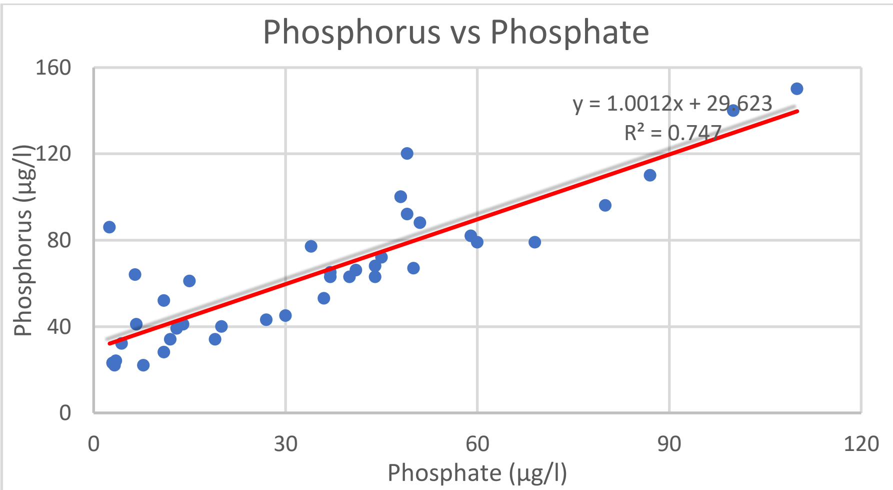


Figure 33 Phosphorus vs phosphate

The concentration values of the three tributary rivers and the concentration of phosphorus are plotted in figure 34. This is the concentration obtained after the interpolation process.

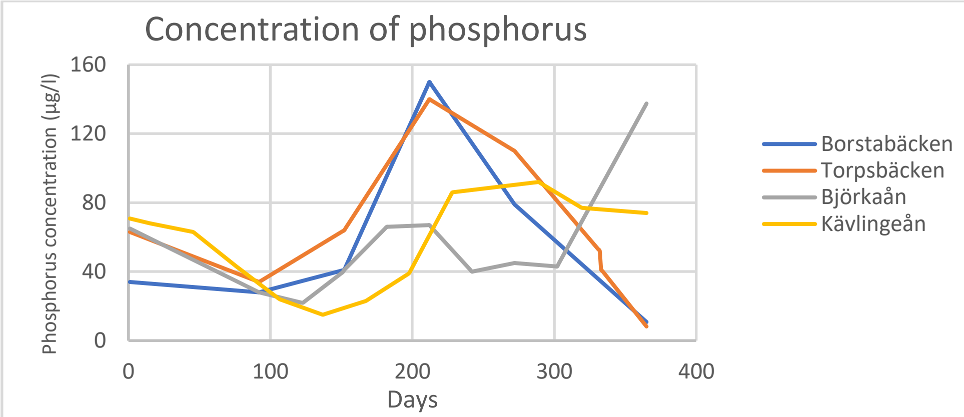


Figure 34 Phosphorus concentration

The concentration of phosphorus in the outflow is the validation for observing how the model is working. It is expected that after the phosphorus balance is done, the obtained phosphorus values are the same as the measured values at the outflow.

To develop the model, the following equation is used.

$$\frac{d}{dt}(VC) = Q_1C_1 + Q_2C_2 + Q_3C_3 - Q_0C - Q_wC + m_{source} - m_{sink}$$

Where Q is the inflow in the "i" tributary. In the case of concentration, four values are included in the equation, the ones corresponding to the river and the concentration in the lake after mixing, this value is the concentration in the outflow, and that's why it multiplies the flow at the outlet (Q_0) and the water taken for Sydvatten (Q_w)

The values $m_{source} and m_{sink}$ are the concentrations of phosphorus that go into the water from sediment and vice versa in processes like leaking, sedimentation, or resuspension that were explained above.

In order to organize equations according to data available:

$$\frac{d}{dt}(hC) = \frac{1}{A}(Q_1C_1 + Q_2C_2 + Q_3C_3 - Q_0C - Q_wC + m_{source} - m_{sink})$$

Where h is de height obtained in the water balance model and A is the area

Then, to get a numerical solution that finds the concentrations in the lake iterating in the program developed for this objective, we got,

$$\frac{h_{k+1}C_{k+1} - h_kC_k}{\Delta t} = \frac{1}{A}(Q_{1k}C_{1k} + Q_{2k}C_{2k} + Q_{3k}C_{3k} - Q_{0k}C_k - Q_wC_k + m_{source} - m_{sink})$$

And lastly, we got

$$C_{k+1} = C_k\frac{h_k}{h_{k+1}} + \frac{\Delta t}{Ah_{k+1}}(Q_{1k}C_{1k} + Q_{2k}C_{2k} + Q_{3k}C_{3k} - Q_{0k}C_k - Q_wC_k + m_{source} - m_{sink})$$

Chapter 6

Model simulations

Water balance model

For finding the height level of the lake using as input data the inflows and outflows, a program in Python is developed according to daily values. The equation shown above for the water balance is introduced in the coding process, and a comparison between actual height and obtained height is made. The calibration is made in the inflows due to this information is data obtained from models from SMHI. In this process, it is necessary to recall the information above about the flow.

1) There are three main tributary rivers to Lake Vomb, and those rivers have their respective measuring point before reaching the lake: Stations 113, 125, and 150. Stations 125 and 150 belong to Torpsbäcken and Borstbäken rivers, respectively, and the station number 113 belongs to Björkaån. The three inflow stations got their values from the modeling program S-HYPE. The station at the outflow of Lake Vomb has both values, modeled and measured in the field.

2) The measurements of height level in Lake Vomb have three characteristics that can be observed in Appendix 2, and there are three kinds of observations for the measures: "Good," "Externally checked," and "Unchecked." In the last 3000 days, most of the values are "Unchecked," so, the measurements entrusted weren't verified by SMHI. Despite this unverified situation, there is a clear trend of a height maintained within a maximum variation of 3 meters along overall years since the gates were constructed. Height variation in the lake can be seen in figure 35.

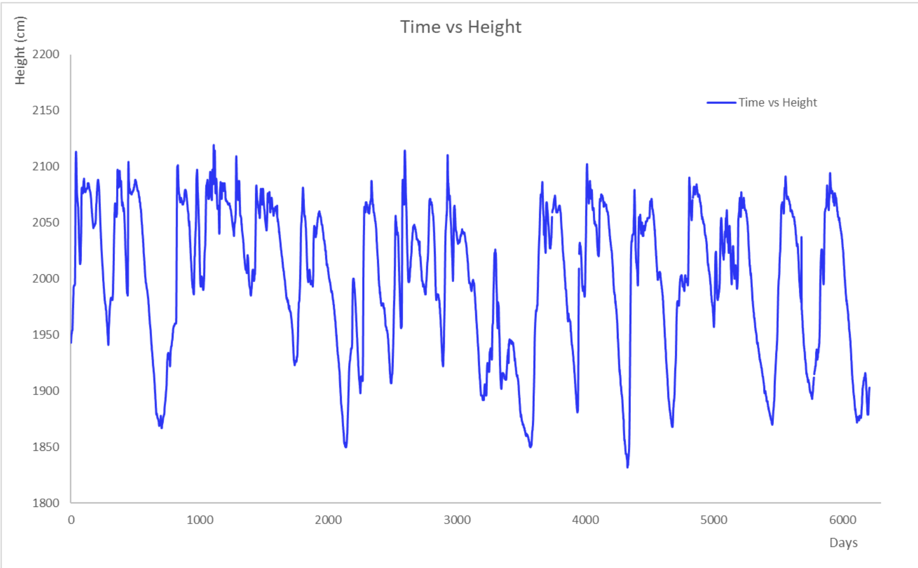


Figure 35 Height measured.

Like it was mentioned above, the hydraulic structure built in the lake maintains the water level variation at less than three meters.

When the program designed for getting the height through flows is used, it can be seen that the height levels change in a dramatic slope. It shows a shrinking in the lake. A trend that seemed to decrease the height level dramatically was shown by graphics that analyzed the height behavior according to the inflow and outflow data. It was necessary to focus on why this trend was occurring, and since that objective, the study period was divided into two periods three thousand days in the first and three thousand two hundred in the second.

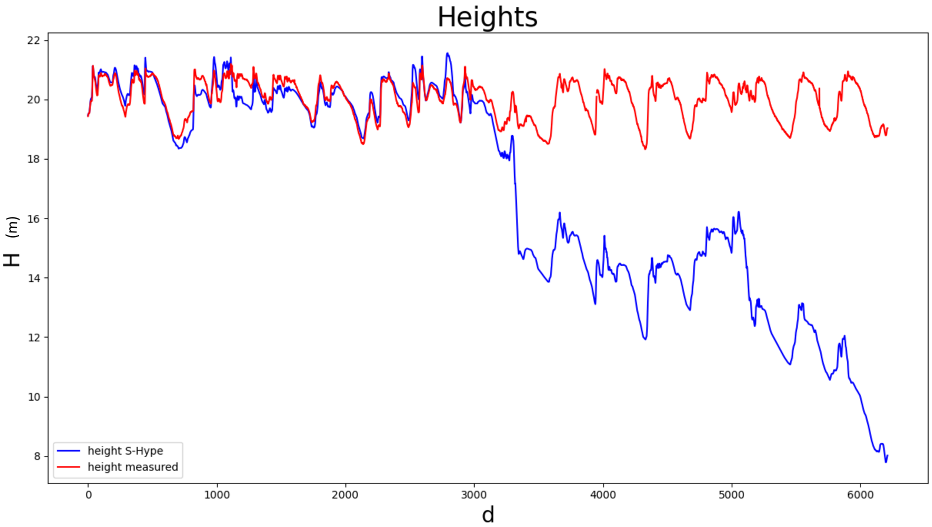


Figure 36 Height measured vs Height modeled.

There is a big difference in heights that appear after three thousand days in the model elaborated on the base of the total inflow and outflow versus the actual measured data. In order to know the origin of this behavior, the model was split into two parts. One model over the first three thousand years and another for the last three thousand and two hundred days.

The graphic shows a good fit for the first period using the net precipitation value as a correction parameter for the difference between inflow and outflow. In this period, peak flows do not reach high levels, and precipitation doesn't vary too much.

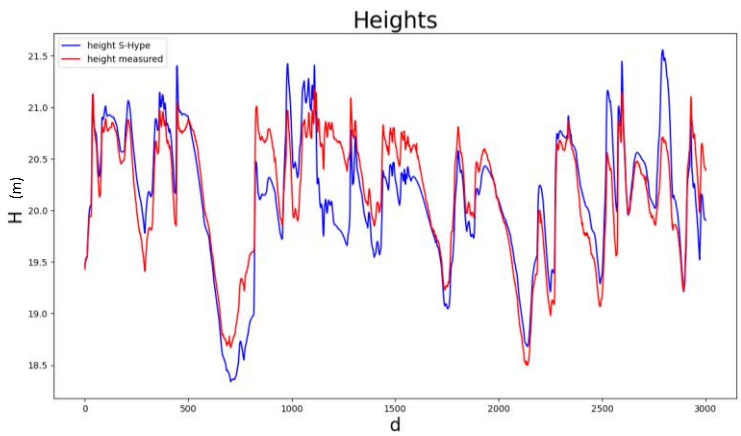


Figure 37 Height measured vs Height modeled for the first 3000 days (80.3 years)

For achieving a similar fit in the second period of the study, precipitation of 0.55 m3/s is required, and also there is a behavior over some periods of time where the graphics show a big difference. That value is unrealistic because it is more than four times the net precipitation over the lake. During this period, there is a need for correction of the input data.

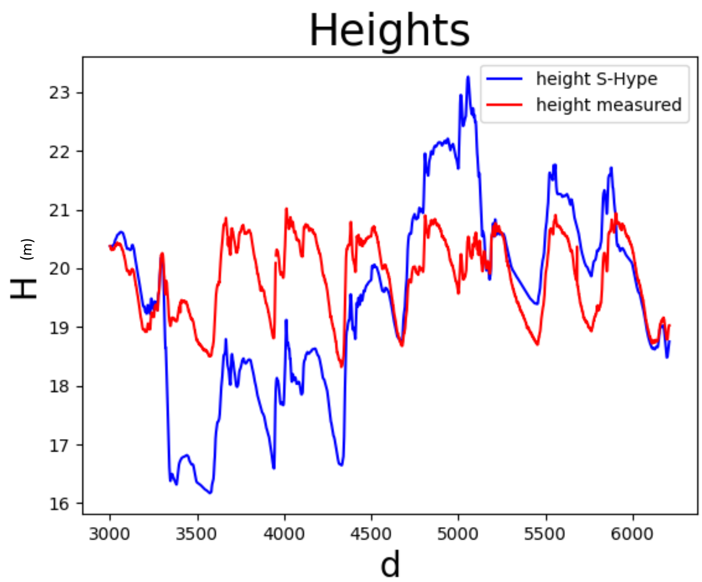


Figure 36 Height measured vs Height modeled.

After the analysis realized with the data of the flow and verifying carefully in what parts there is occurring this strange behavior that is far from the real heights of the lake the observation made above showed that in years where peak flows were with values out of an average quantity there is a difference between the two graphics. That verification was made each year of the present study in each river or outflow that has corrected values of flow taken in the field. It was verified that whether Björkaån or the lake outlet when there were peak flows the curves did not match. Overall, during the period of study, three situations with unusual peak flows were detected. Two in the outlet of the lake and one in Björkaån. After assigning a mean value of peak flows of all periods instead of those unusual values, the graphic began to match but still, there was one more period that did not fit well. Looking carefully at what could happen in this situation, it was noticed that it was a year of really low values. In the dry season, the inflows' flows were lower than usual. So, it was assigned a correction factor of the mean minimum value of all the periods to these unusual values the graphics matched, which can be seen in the picture below.

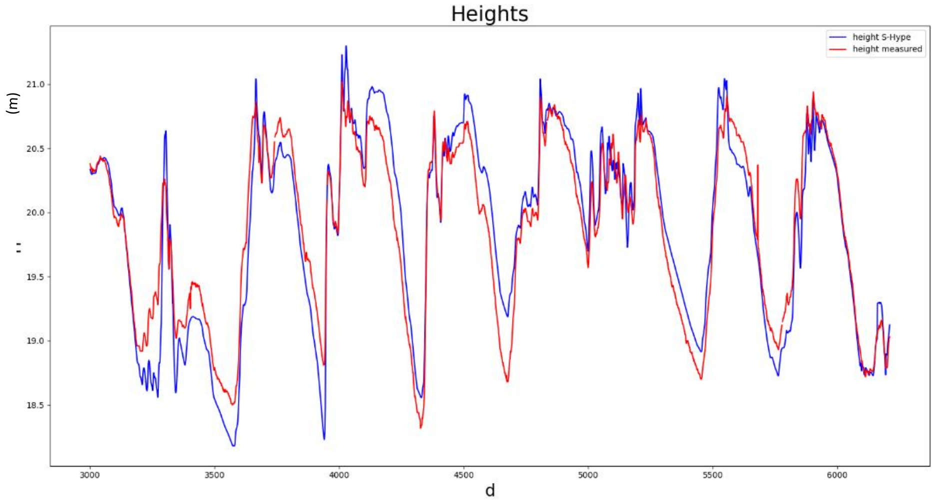
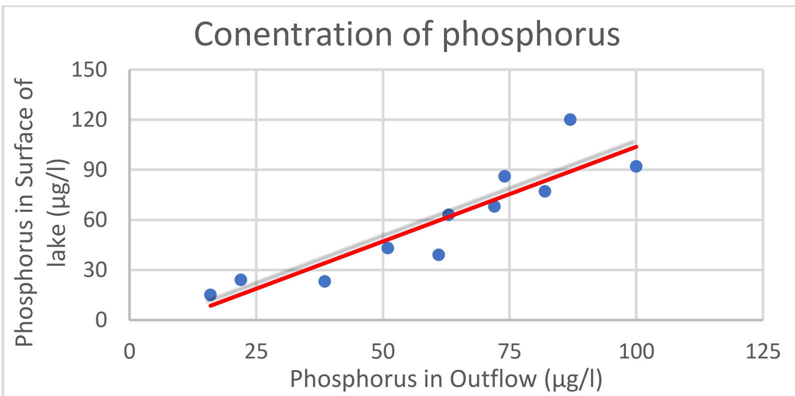


Figure 37 Height measured vs Height modeled.

With these observations and realizing how correcting by factor situations of pick flows, the graphics match well in the height whether measured or obtained through flows. It can be made the statement that there is an extra regulation for the height of the lake. It was also observed that the variance in the difference of the curves is smoothed if a gradual correction is made, so instead of changing a punctual peak flow of 5 m3/s, it can be made 5 changes of 1 m3/s over five days. This correction could be made by Sydvatten to feed Malmo city with drinking water variations over all the seasons and its water requirements for each season.

Phosphorus balance model

The approach of this study is a box model. Based on measurements obtained in the lake surface and outflow of the lake, it can be seen that this is a correct approach due to the almost similar concentration over all the lake like it is shown in figure 40. The data of phosphorus used for this study is from 2021. So, the equation for phosphorus in this year is used with the designed water balance made for 17 years



Also, it seems that there is no big difference in samples taken on the surface and at the bottom of the lake. Figure 41 shows the difference between both parts of the lake.

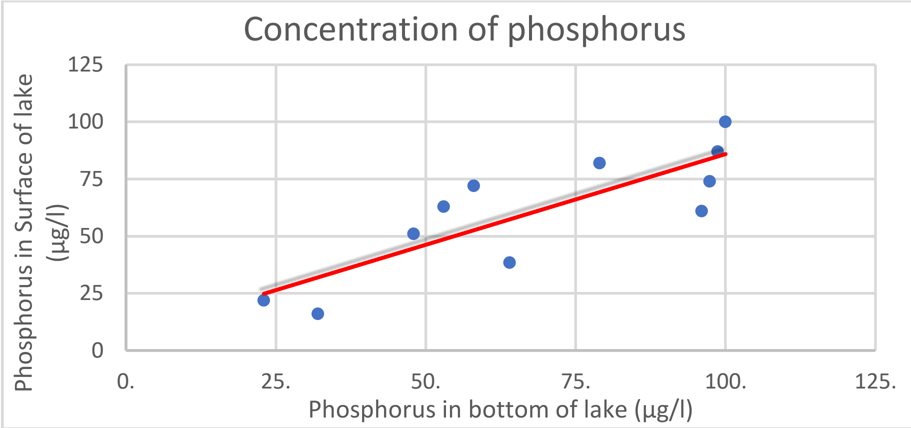


Figure 38 Different phosphorus concentration in samples taken in surface and bottom of the lake

With this data on concentration and the values of mass balance, the program designed in Python for this study shows a variation in phosphorus concentration that can be seen in figure 39.

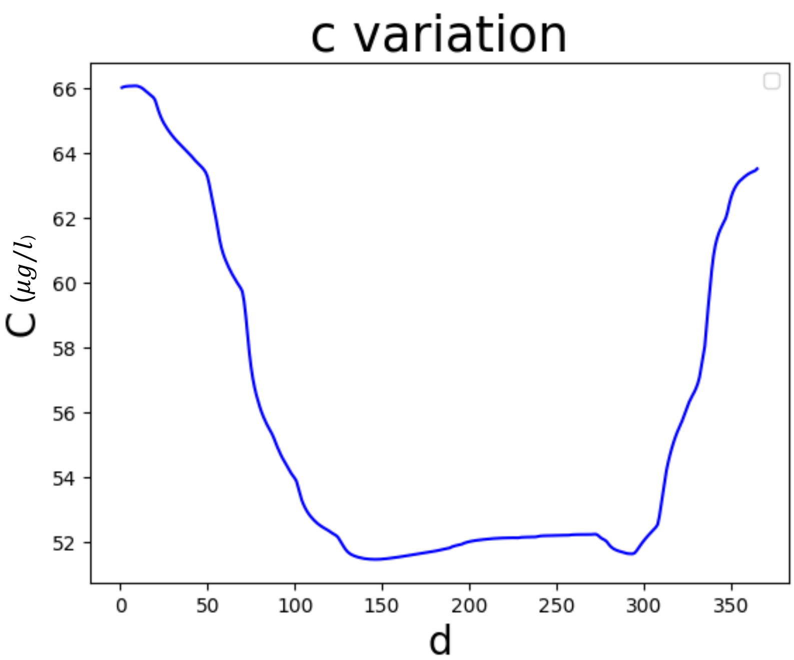


Figure 39 Variation of phosphorus concentration over the period of study (1 year)

The behavior of phosphorus over the entire period seems balanced. All the phosphorus in goes out. But if it is compared over a specific period there is a variation in the measured values at the outflow. The sensitivity analysis is made for three different volumes making an assumption that only a part of the lake is involved in phosphorus behavior, but there is no big difference. In figure 40, it can be seen the variation of phosphorus concentration for the total volume of the lake, half and one-third assuming different volume participation in the phosphorus process.

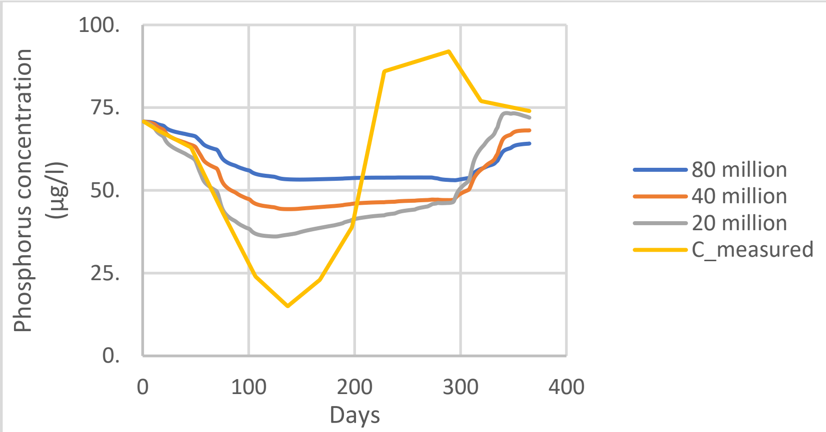


Figure 40 Different phosphorus concentrations

In general, with the water balance, it seems there is a big buffering of phosphorus in water, but actual values reach peaks that cannot be explained in concentration in inflows and outflows. In that sense, if the external load can completely explain the phosphorus behavior, an internal load influences the measured phosphorus concentration values. Internal load is mainly ruled by the following processes:

Sedimentation

The explanation for behaving as a sink could be because of the sedimentation. The equation for the sedimentation of phosphorus may be written:

$$m_s = W_s A C$$

Where: W_s: Settling velocity

Sedimentation is a process by which the particles of a solute present in the solution are deposited at the bottom of the container. In this case, the phosphorus goes to the bottom of the lake, and like it was pointed out before, the lake has a great quantity of phosphorus in its sediments.

Resuspension

An explanation for the lake behaving like a source is the opposite effect: Resuspension. If there is a lot of material available at the bottom of the lake and strong shear forces act over it, precipitated elements that are part of the sediments in the bedrock are suspended again. The main force that alters the sediments are streams at the bottom of the lake; streams are produced by waves that are produced by wind. An approximation for wind energy is:

$$E_w \approx \rho_a x W^3$$

If wind energy is bigger that the energy of consolidation, the resuspension occurs.

$$\rho_a(W^3 - W_{cr}^3) \qquad m_R = A\rho_a\left(W^3 - W_{cr}^3\right)K_R$$

It is essential to point out that if there is stratification in the bottom of the lake, the transfer coefficient is zero, then resuspension is not possible.

Leakage

The last and very important motive for increasing the quantities of phosphorus in the water body is the leakage of this mineral into the water from sediments. That phenomenon depends on the quantity of oxygen at the bottom of the lake. If the oxygen in the bottom of the lake is low, there is more possibility that the phosphorus present in the sediment is transferred to the water body. There must be big quantities of phosphorus in the sediment to reach high levels of leakage.

$$m_L = Aq_B; q_B = C_B K_B; K_B = f(Oxygen_{concentration})$$

These phenomena explain the internal load of phosphorus that occurs over the lake, and some of them will be used in the modeling process. These terms are not going to be used due to the lack of data, but a representation of its total value can be done.

To find the total internal load influence over the lake, equations are reorganized in the python code in order to get the value called "m," which is the sum of sink or source processes. Phenomena like resuspension or sedimentation explained above are included in one parameter m to measure the influence of internal load through the following equation:

$$\frac{d}{dt}(CV) = Q_{in}C_{in} - Q_{out}C + m$$

This "m" parameter is the looked at to measure the internal load then:

$$m = \frac{d}{dt}(CV) + Q_{out}C - Q_{in}C_{in}$$

The numerical solution for that differential equation becomes:

$$m_k = \frac{A(C_{k+1}h_{k+1} - C_k h_k)}{\Delta t} + Q_{out}C - Q_{in}C_{in}$$

Where Qin is the sum of tributaries and Qout is the sum of the outflow plus water taken from Sydavatten. Figure 41 it can be seen the behavior of the "m" parameter.

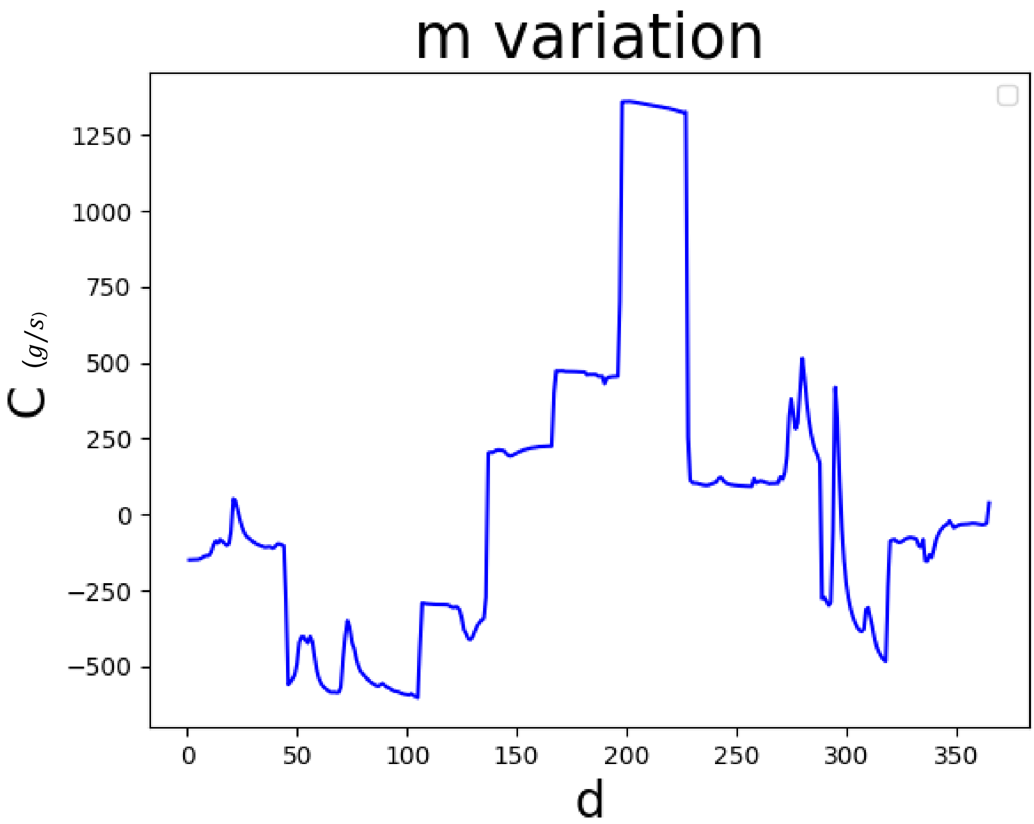


Figure 41 Variation of parameter m

The variation of concentration of the “m” parameter that includes the sink and source phenomena shows a behavior where in the first years of the year it decreases, pointing that in that period of time, the lake is working as a sink of phosphorus. That explains the behavior of measured phosphorus concentration in figure 40, where the measured data is below the level of the data obtained by modeling. The phosphorus of the inflow is precipitating into the bottom of the lake. On the contrary, in the second part of the year, when the temperatures are warmer, the “m” parameter increases, pointing that the lake is behaving as a source of phosphorus, releasing the nutrient from sediments to water, which explains the concentration of measured values above the curve obtained through the modeling process.

Discussion

Using a box model approach for making balances is a powerful tool and, in this case, is consistent with the behavior of phosphorus due to the behavior of phosphorus over the lake. The water balance helps to understand the behavior of the lake as a buffering system in the catchment and also gives an idea of the total inflows and outflows influences over the lake's height. The limitation of the code made for finding the water balance is that it doesn't consider the variation of the area with the increase or decrease of the lake's height, however. It offers a really good accuracy in comparison with measured values. The calibration is very important due to the input for the code in Python is data, the inflow values, which are modeled data that offers values that are below the actual values in the peak flows. For periods where there are several pick flows, the software S-HYPE will not be very accurate in predicting the behavior of flows, and the values are going to be sub-estimated. In normal conditions, the data is optimum, and the calibration is only through precipitation.

For the phosphorus balance, the model designed in this research shows promising results over long periods of time (yearly), but when values over specific variation of phosphorus concentration come, the values are different. The behavior of the concentration of phosphorus is almost constant due to the buffering of the water mass in the model and to explain the actual behavior plotted from samples taken in the field is necessary to find the parameters of internal load. Studies in the field of the data required for solving the equations related to resuspension or leakage of phosphorus in the lake will help to have a more accurate result at the time of following the phosphorus behavior and for taking measures to control or diminish the presence of this nutrient in the lake.

Conclusions

Water balance over Lake Vomb with a box model approach gives really good results, and the accuracy of the model is close to reality. The input data fails when peak flows frequently occur in the period of study due to the sub-estimation of values. It is necessary to focus on peak flows events to calibrate well the model in order to design a water balance that is accurate. Once checked the peak flows, the model obtains results that match the height of the water level in the lake. Then, the water balance and behavior of the lake can be expressed in terms of the three mainly inflows and the two outflows. Other sources for shrinking and flooding the lake are small and can be included in the small parameter as direct precipitation. The results obtained from making a water balance with a box model approach work in an accurate way.

For the phosphorus concentration in the lake, it is important to point out that the box model approach gives good values over long periods of time, with values obtained from modeling close to the actual values measured in the field. However, in short-term periods the internal processes rule the behavior of phosphorus. Internal load phenomena have an active role in the concentration of phosphorus over the lake. These internal load phenomena depend on hydrogeological parameters that, if included in the equations for the box model, the accuracy will be improved.

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Appendix 1:

	Total vattenföring [m³/s]	Total stationskorrigerad vattenföring [m³/s]	Lokal nederbörd [mm]	Lokal evapotranspiration [mm]	Lokal lufttemperatur [°C]	Vattendragstemperatur [°C]
2004-01	2.03	1.18	88.0	17.1	-2.1	0.3
2004-02	7.32	8.93	38.2	12.2	0.8	1.3
2004-03	4.92	3.95	56.7	29.0	3.2	4.2
2004-04	2.48	1.57	28.6	45.8	7.5	10.0
2004-05	0.472	0.500	30.9	68.1	11.4	15.3
2004-06	0.425	1.07	98.8	86.0	13.8	18.4
2004-07	0.431	0.597	120	111	15.4	19.7
2004-08	0.491	2.79	79.4	100	17.9	22.4
2004-09	2.14	1.73	53.7	65.8	13.7	17.8
2004-10	1.73	1.47	80.5	50.2	9.2	12.0
2004-11	1.75	1.17	59.7	26.9	4.1	6.4
2004-12	2.36	5.27	77.3	25.7	3.0	4.1
2005-01	7.99	9.64	69.1	24.7	2.2	3.4
2005-02	6.32	5.68	62.9	13.6	-0.6	1.1
2005-03	8.46	10.5	52.3	17.6	0.2	1.1
2005-04	1.96	1.83	5.91	37.3	7.1	9.0
2005-05	0.466	1.08	53.9	72.8	11.3	14.6
2005-06	0.424	1.50	58.4	88.0	14.6	18.9
2005-07	0.372	1.66	85.0	95.7	18.4	23.1
2005-08	0.338	0.952	68.0	87.8	16.0	20.6
2005-09	1.63	1.70	22.7	52.7	14.5	18.4
2005-10	1.14	1.85	56.0	43.5	10.3	13.1
2005-11	0.848	0.800	50.5	25.7	4.7	7.6
2005-12	0.724	0.694	89.1	23.1	1.4	2.2
2006-01	1.04	1.05	25.7	5.6	-1.9	0.4
2006-02	1.43	2.43	47.8	9.7	-0.9	0
2006-03	1.92	0.952	41.4	11.6	-1.7	0.2
2006-04	7.47	9.21	64.8	43.5	5.6	7.3
2006-05	1.01	0.790	78.5	79.7	11.3	14.6
2006-06	0.892	0.500	31.5	89.6	16.1	19.7
2006-07	0.436	1.34	21.5	85.1	20.8	24.9
2006-08	1.74	0.597	256	134	17.4	22.7
2006-09	5.38	6.85	36.1	73.1	15.9	19.3
2006-10	2.44	1.73	89.3	63.0	11.7	15.3
2006-11	3.05	5.37	88.0	40.1	6.6	8.4
2006-12	6.90	7.98	96.7	39.5	6.0	7.4
2007-01	13.5	19.6	135	42.1	3.9	5.5
2007-02	9.20	10.2	66.3	18.7	1.1	2.6
2007-03	9.14	7.66	46.8	38.1	5.7	6.5
2007-04	0.929	1.93	23.5	49.2	8.6	11.3
2007-05	0.466	0.500	57.7	79.2	12.3	15.8

2007-06	0.432	0.500	143	110	16.7	21.4
2007-07	12.0	13.4	239	140	16.1	20.8
2007-08	3.14	4.90	43.6	94.0	17.1	21.5
2007-09	2.58	2.07	89.9	72.0	12.7	16.7
2007-10	2.12	3.02	31.8	38.3	8.2	11.4
2007-11	1.78	1.47	42.8	22.7	4.0	6.2
2007-12	2.45	4.60	69.8	24.2	3.0	4.0
2008-01	4.39	5.92	83.6	28.5	3.1	3.5
2008-02	5.12	6.50	33.3	23.6	3.9	4.9
2008-03	7.13	7.40	92.9	33.7	3.0	5.7
2008-04	6.70	5.57	48.3	48.3	7.2	9.0
2008-05	0.508	0.500	32.8	71.2	12.4	16.0
2008-06	0.434	0.500	34.3	75.4	15.3	19.9
2008-07	0.384	0.500	51.7	89.7	18.0	22.1
2008-08	0.409	0.823	156	107	16.8	21.8
2008-09	1.86	2.10	39.9	57.7	12.9	17.0
2008-10	1.54	1.02	102	55.2	9.3	12.3
2008-11	1.96	1.37	68.3	32.5	5.2	7.2
2008-12	5.34	7.53	66.9	21.1	2.1	3.6
2009-01	3.23	4.63	27.5	9.1	0	1.0
2009-02	3.62	3.21	46.4	11.3	-0.7	0.9
2009-03	4.19	2.56	38.6	23.1	2.9	4.1
2009-04	1.36	0.500	12.3	48.3	9.0	10.5
2009-05	0.462	0.500	63.7	77.0	11.6	15.6
2009-06	0.428	0.900	73.2	88.3	14.0	18.4
2009-07	0.394	0.500	96.1	114	18.3	23.0
2009-08	0.356	0.758	48.6	86.3	17.8	22.3
2009-09	1.71	1.50	43.9	59.1	14.4	18.6
2009-10	1.25	1.53	69.4	37.5	6.8	10.3
2009-11	1.25	0.700	108	43.3	6.7	7.6
2009-12	2.01	1.37	66.8	18.4	0.5	3.0
2010-01	2.85	3.37	36.5	6.6	-3.9	0
2010-02	2.66	3.93	60.2	11.7	-1.9	0
2010-03	6.80	4.66	30.2	18.7	1.9	1.2
2010-04	3.94	2.57	20.9	41.1	6.9	8.9
2010-05	0.486	1.15	65.6	70.4	9.9	13.8
2010-06	0.463	1.17	47.9	87.9	14.5	18.5
2010-07	0.411	1.31	32.3	87.2	19.9	24.3
2010-08	0.372	0.597	157	109	17.1	22.3
2010-09	1.96	0.933	60.3	64.1	12.7	16.7
2010-10	1.54	1.98	65.7	40.4	7.5	10.4
2010-11	3.05	0.967	140	39.4	3.0	6.1
2010-12	6.20	7.31	84.4	15.2	-5.1	0
2011-01	7.79	9.60	55.5	11.7	-0.9	0.1
2011-02	16.9	15.8	44.6	11.4	-1.3	0.4
2011-03	5.19	3.08	45.9	21.3	2.4	2.1
2011-04	1.79	0.500	15.9	53.1	9.6	11.1

2011-05	0.468	0.500	67.6	76.6	11.6	15.5
2011-06	0.426	1.40	66.9	96.8	16.0	20.4
2011-07	0.414	0.500	182	129	17.2	22.0
2011-08	2.84	1.92	137	113	16.5	21.1
2011-09	3.00	6.17	55.8	73.6	14.1	17.9
2011-10	2.47	4.11	51.4	45.5	9.1	12.5
2011-11	1.95	3.87	14.7	23.3	6.2	8.1
2011-12	2.13	2.40	94.7	31.3	3.8	5.2
2012-01	10.1	12.9	109	27.1	1.2	3.2
2012-02	5.56	6.02	51.0	14.1	-1.8	0.1
2012-03	4.23	3.95	11.4	28.1	5.1	5.8
2012-04	0.468	0.500	50.0	43.3	6.0	9.0
2012-05	0.462	0.500	31.7	73.6	12.3	15.7
2012-06	0.421	1.43	82.2	81.1	13.5	18.2
2012-07	0.393	0.629	85.5	104	16.9	21.4
2012-08	0.412	2.56	52.0	82.4	17.1	21.5
2012-09	1.73	2.13	53.5	59.3	13.5	17.7
2012-10	1.47	2.27	78.0	45.5	8.1	11.5
2012-11	1.80	3.62	75.3	34.2	5.7	7.1
2012-12	2.48	5.06	91.3	20.2	-1.0	0.8
2013-01	9.15	14.2	65.1	17.5	-1.1	1.4
2013-02	7.45	17.8	35.1	7.3	-0.9	0
2013-03	3.59	2.39	17.1	5.1	-1.3	0.6
2013-04	1.49	0.627	19.9	35.7	5.8	5.8
2013-05	0.479	0.306	45.1	78.7	12.8	15.8
2013-06	0.435	0.950	89.4	95.3	15.3	20.2
2013-07	0.391	1.39	33.3	84.9	18.4	22.4
2013-08	0.343	0.300	65.2	86.7	17.4	22.3
2013-09	1.67	0.300	66.0	60.5	12.7	17.3
2013-10	1.29	0.300	101	57.8	10.7	12.6
2013-11	1.68	0.800	76.6	33.9	5.4	8.2
2013-12	2.47	2.40	83.2	31.7	4.4	4.9
2014-01	7.94	9.08	79.9	22.6	0.9	3.5
2014-02	7.45	8.14	49.9	22.3	3.2	2.8
2014-03	3.21	3.40	40.5	35.5	5.4	7.2
2014-04	1.06	1.45	39.6	53.4	8.6	10.9
2014-05	0.488	0.597	67.9	83.8	12.4	16.0
2014-06	0.451	1.98	64.6	88.9	15.3	20.1
2014-07	0.406	1.84	64.7	109	20.1	23.7
2014-08	0.366	1.52	144	106	16.6	22.3
2014-09	1.95	2.37	51.0	70.8	14.6	18.2
2014-10	1.91	1.74	152	73.3	11.7	14.6
2014-11	2.66	4.70	35.9	33.6	7.4	10.0
2014-12	7.95	7.40	131	35.8	2.6	4.4
2015-01	13.8	15.6	109	30.1	2.5	3.0
2015-02	6.71	6.04	22.0	12.4	1.6	2.7
2015-03	3.40	3.34	70.7	35.8	4.5	6.3

2015-04	3.00	1.47	28.8	46.3	7.5	10.0
2015-05	0.491	0.629	68.7	73.7	10.3	14.3
2015-06	0.462	0.950	51.8	84.3	13.7	17.9
2015-07	0.417	1.74	61.5	93.3	16.6	21.3
2015-08	0.371	2.34	53.9	86.6	18.0	21.9
2015-09	1.84	2.32	79.3	68.1	13.5	17.9
2015-10	1.36	1.78	23.1	36.4	9.3	12.2
2015-11	1.27	0.300	178	55.0	6.8	8.8
2015-12	5.69	7.29	99.5	39.4	5.8	6.4
2016-01	8.81	8.60	55.3	15.0	-1.0	1.1
2016-02	9.46	8.83	60.9	20.8	2.1	3.3
2016-03	4.51	2.48	34.3	26.4	3.8	5.3
2016-04	0.555	0.967	72.3	51.1	6.8	10.1
2016-05	1.37	1.60	16.1	75.0	13.8	16.0
2016-06	0.446	1.75	75.0	92.3	16.7	21.3
2016-07	0.419	0.532	86.5	106	17.6	22.3
2016-08	0.434	1.97	66.8	84.1	16.6	21.1
2016-09	1.81	1.55	20.7	58.6	16.0	19.8
2016-10	1.40	0.500	107	50.2	8.5	12.0
2016-11	2.15	0.633	78.6	28.4	3.6	5.3
2016-12	2.82	2.10	44.1	21.8	3.7	4.4
2017-01	2.93	2.89	25.2	9.7	0.3	1.7
2017-02	3.46	2.54	77.2	22.4	1.4	2.2
2017-03	7.30	6.98	50.1	32.6	4.4	5.9
2017-04	2.49	2.27	53.6	44.6	6.3	9.8
2017-05	0.897	0.661	33.2	75.9	12.5	14.7
2017-06	0.467	0.850	131	110	15.5	20.4
2017-07	0.453	2.03	83.6	104	16.1	20.9
2017-08	0.438	2.39	75.8	97.3	16.8	21.3
2017-09	2.70	3.97	124	82.0	13.6	17.6
2017-10	3.42	4.11	114	63.6	10.4	13.7
2017-11	7.66	10.8	90.9	36.1	5.3	7.8
2017-12	11.5	16.5	90.8	29.5	3.4	4.3
2018-01	9.71	15.8	85.5	25.6	2.3	3.2
2018-02	7.07	9.61	39.1	9.5	-1.4	1.6
2018-03	7.57	5.29	65.7	15.7	-0.1	0.6
2018-04	5.09	6.30	45.8	56.1	8.8	9.4
2018-05	0.483	1.08	7.24	76.8	15.6	18.3
2018-06	0.426	2.00	38.4	80.1	18.0	23.1
2018-07	0.371	0.871	22.0	77.9	20.8	24.8
2018-08	0.318	0.500	89.8	85.8	19.0	24.5
2018-09	1.52	0.500	27.2	54.8	14.7	18.8
2018-10	1.08	0.500	74.9	46.2	9.9	12.9
2018-11	0.761	0.427	29.3	23.2	5.4	7.7
2018-12	0.749	0.358	85.6	28.5	3.5	3.9
2019-01	1.38	0.500	56.2	16.4	1.1	2.6
2019-02	2.54	5.70	62.5	26.9	3.7	3.9

2019-03	10.2	12.5	111	47.5	5.2	7.0
2019-04	1.15	1.45	20.0	44.2	8.1	10.5
2019-05	0.469	0.758	55.7	73.7	10.9	14.9
2019-06	0.440	1.88	68.5	107	18.1	21.6
2019-07	0.400	1.87	64.4	96.3	17.8	22.7
2019-08	0.353	1.92	69.8	92.0	18.4	22.7
2019-09	1.75	0.917	95.9	71.1	13.8	18.5
2019-10	1.46	0.742	79.7	51.5	9.4	12.4
2019-11	1.47	1.58	63.0	33.4	6.0	7.9
2019-12	2.15	3.71	68.1	28.8	4.3	5.5
2020-01	4.04	5.56	97.0	37.1	4.9	5.4
2020-02	10.4	16.0	95.4	36.4	4.5	6.2
2020-03	7.08	7.84	30.9	28.3	4.3	6.7
2020-04	0.541	0.950	22.2	45.1	8.2	10.5
2020-05	0.452	0.516	32.6	66.3	10.9	14.6
2020-06	0.404	1.87	52.4	90.5	17.2	21.1
2020-07	0.357	1.32	71.8	91.7	16.1	21.4
2020-08	0.351	2.05	66.5	82.6	19.0	23.2
2020-09	1.45	0.963	68.4	66.6	14.6	18.4
2020-10	1.14	0.500	95.7	56.6	10.4	13.2
2020-11	1.04	1.28	37.2	33.5	7.6	10.0
2020-12	0.915	3.15	56.8	25.8	4.2	5.1

Appendix 2:

```
Station Site:
Station Name:   VOMBSJÖN ÖVRE
Station Number: 2018
LocalX:    1358530,000219
LocalY:    6176650,006744
Datum:     ---
Parameter Name: W
Parameter Type: W
Parameter Type Name:  Water level
Time series Name:     100/2018/W/Day.Mean.Abs
Time series Unit:     cm
GlobalX:   409190,398293
GlobalY:   6173461,738264
Longitude: 13,555142
Latitude:  55,698424

2004-01-01 00:00:00   1943,0     40  (Good)
2004-01-02 00:00:00   1946,0     40  (Good)
2004-01-03 00:00:00   1948,0     40  (Good)
```

```
2004-01-04 00:00:00   1950,0     40  (Good)
2004-01-05 00:00:00   1951,0     40  (Good)
2004-01-06 00:00:00   1951,0     40  (Good)
2004-01-07 00:00:00   1952,0     40  (Good)
2004-01-08 00:00:00   1953,0     40  (Good)
2004-01-09 00:00:00   1954,0     40  (Good)
2004-01-10 00:00:00   1954,0     40  (Good)
2004-01-11 00:00:00   1954,0     40  (Good)
2004-01-12 00:00:00   1954,0     40  (Good)
2004-01-13 00:00:00   1958,0     40  (Good)
2004-01-14 00:00:00   1963,0     40  (Good)
2004-01-15 00:00:00   1968,0     40  (Good)
2004-01-16 00:00:00   1972,0     40  (Good)
2004-01-17 00:00:00   1976,0     40  (Good)
2004-01-18 00:00:00   1979,0     40  (Good)
2004-02-03 00:00:00   2025,0     40  (Good)
2004-02-04 00:00:00   2044,0     40  (Good)
2004-02-05 00:00:00   2073,0     40  (Good)
2004-02-06 00:00:00   2094,0     40  (Good)
2010-01-22 00:00:00   1976,0     90  (Ext. check)
2010-01-23 00:00:00   1973,0     90  (Ext. check)
2010-01-24 00:00:00   1970,0     90  (Ext. check)
2010-01-25 00:00:00   1968,0     90  (Ext. check)
2014-03-22 00:00:00   2034,3     200  (Unchecked)
2014-03-23 00:00:00   2036,5     200  (Unchecked)
2014-03-24 00:00:00   2036,5     200  (Unchecked)
2014-03-25 00:00:00   2039,3     200  (Unchecked)
2014-03-26 00:00:00   2043,2     200  (Unchecked)
2014-03-27 00:00:00   2048,5     200  (Unchecked)
2014-03-28 00:00:00   2052,7     200  (Unchecked)
2014-03-29 00:00:00   2055,5     200  (Unchecked)
2014-03-30 00:00:00   ---   missing (M)
```