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A GIS based approach identifying phosphorus sources within the lake Flaten catchment in Salem, Sweden

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A GIS BASED APPROACH IDENTIFYING PHOSPHORUS SOURCES WITHIN THE LAKE FLATEN CATCHMENT IN SALEM, SWEDEN

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Master thesis, 30 credits, in Geographical Information Sciences

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Abstract

The purpose of this study has been to test if GIS based methods calibrated with limited local data can be used to determine the origin and quantity of phosphorus transport to and within a small eutrophic lake, and to assess the effects of this transport on the lake water quality. The lake studied is Lake Flaten in Salem municipality, Sweden.

The objectives have been achieved by delineating catchment areas from digital elevation data, classifying land cover by manual editing and based on spectral characteristics, and identifying leach from point sources. The geographical data has been complemented with attributes, measured and interpolated, on monthly and annual water flow, lake water phosphorus content, assessed mass transport and estimation on internal load from sediments. Phosphorus load per catchment and subcatchment was quantified by assessing export coefficients per land cover class. Finally future scenarios like changed water flow and urban development as well as some measures of mitigation were simulated.

A comparison of different land cover data, both vector and raster based, show that manually editing data is not necessary, available land cover data is sufficient for estimating phosphorus transport even from small research areas. Moreover a couple of raster-based methods presented in this study might be useful for fast overall estimations on nutrient transport and sources.

Results on TP transport and lake water quality show that Lake Flaten is in a constant eutrophic state with high in-water phosphorus levels. Phosphorus load to the lake mainly origin from urban areas, and the subcatchments with the highest total and area specific contribution have been identified. The substantial internal load from lake sediments must cease, and actions be taken to reduce the external load, if the lake is to meet guidelines stipulated by the Swedish Environmental Protection Agency (the Swedish EPA).

While the GIS based approach is a feasible methodology for overall estimations on phosphorus transport and identifying the origin of phosphorus load, further measurement data than available for this study would make it possible to improve the accuracy of the predictions.

Acknowledgments

I would like to thank my supervisors Harry Lankreijer at Lund University and Clara Neuschütz at NIRAS Stockholm for input, inspiration and support; Roger Huononen at Yoldia Environmental Consulting for sharing the long term data upon which a large part of this study is based, and for explaining and clarifying limnological concepts and Carita Lindqvist at Salem Municipality for geographical data. Last but not least the encouragement and patience of my wife Malin Ericsson has been invaluable during the progress of this work.

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1. Introduction

Despite regulations and monitoring, nutrient leach impact on Swedish waters continue to put stress on ecosystems and cause unwanted effects like algal blooms. Limiting the amount of nitrogen and phosphorus that reaches our fresh water systems and eventually the sea is therefore important (Klintwall et al. 2003). To decide upon appropriate measures in order to mitigate effects from nutrient leach it is vital to identify the pollution sources and quantify the amounts reaching the water of interest. It is also important to know the characteristics of the particular water to calculate how much the nutrient inflow must decrease in order to reach a sustainable system (Naturvårdsverket 2003).

There are several models and applications available to facilitate calculating the amount of pollutants reaching waters and assess the resulting effects (Ekstrand et al. 2009). Many of these models do however require multiple and preferably synchronized measurements over long time periods on parameters like nutrient inflow and content in surface- and bottom waters, local temperature, precipitation and stream and lake areas. Moreover, a relatively high level of expertise is needed to run most models. Another obstacle may be that many models are adjusted to work on regional and national levels, which make them less appropriate to assess nutrient leach within small areas and effects on smaller water bodies (ibid).

In accordance with the EU water framework of 2001 (The European Parliament and the Council of the Union 2000), and its offspring laws and regulations, the quality of European waters must improve within quite a narrow timeframe (Länsstyrelsen i Västmanlands län 2009). There might be hundreds if not thousands of water bodies in Sweden alone that need to be monitored and attended to within the decade in accordance with the time frame stipulated by the water framework (Staaf et al. 2004). This may call for efficient resource-saving methods and models. The executive responsibility to carry out a large part of these improvements often falls on the municipalities where economic resources may vary. Complicated models that require an abundance of data and a high level of expertise may serve as a hindrance; on the other hand models with lower predictive power may produce data of insufficient quality. The challenge in this context is finding straightforward methodologies to monitor and predict nutrient leach and transport that produces sufficient results.

In the best of all possible worlds there is immediate access to accurate high quality data fitting the temporal and spatial resolution of a survey intended. Since this is most often not the case a GIS (Geographic Information System) catchment based approach built on leach or export coefficients (e.g. kg/ha/year) per land cover class, or standard concentrations in water (e.g. µg/l) may be a cost and time saving method to simplify the evaluation process.

1.1. Objectives

The main objectives of this study are to:

1. Elaborate and test a GIS-based methodology for identifying phosphorus origin and calculating phosphorus mass transport, based on the case study of Lake Flaten in Salem, Sweden.
2. Assess the state of Lake Flaten and the total phosphorus (TP) mass transport within the Flaten creek (Flatenån) catchment and further downstream to Lake Uttran.
3. Suggest methods for GIS-based modelling of scenarios and of measures to mitigate the effects of the TP load.

The study will to some extent evaluate and discuss the GIS methods applied. The study will finally provide some recommendations on further surveys regarding Lake Flaten.

2. Theoretical background

This section gives a brief theoretical background with regard to eutrophication and lake modelling as well as to GIS relevant for this study. It also introduces the research area for the study, the Lake Flaten and Flaten Creek (Flatenån) catchments.

2.1 Eutrophication and lake modelling

2.1.1 Phosphorus and lake eutrophication

Phosphorus (P) is one of the elements that serve as an essential nutrient to plants and animals. In most fresh water systems, P is the limiting factor to biota, i.e. the nutrient that steer the biological production and the amount of biomass in the water. P in lakes occurs both as bound to larger particles, and as dissolved (Florida Lakewatch 2000). When quantifying the amounts of phosphorus in water the fractions measured are most often total phosphorus (TP), which includes all forms of phosphorus in a sample. It may also be measured as soluble reactive phosphorus (SRP) (Ruist 2008).

Most Swedish lakes were formed during the end of the last glacial period when the landscape was sculptured by the withdrawing ice-sheet. Since then the lakes have gradually aged i.e. slowly filled up with sediment consisting of silt and decaying organic matter. This natural process may take ages to complete, but eventually the basin will fill up with sediment and vegetation will take over converting the lake into wetland (Addy & Green 1996).

The concept of eutrophication could imply the aging process described above, but also classification into different steps, or trophic states, based on the productivity and nutrient access within the water body. Eutrophication in this sense denotes the gradual development from clear, oxygenated, low nutrient water (oligotrophic) towards increasingly nutrient rich, turbid water with low oxygen levels (mesothrophic to eutrophic). Since the process may be significantly sped up by human influence, so-called cultural eutrophication, these steps also denote the static state of a particular water body within the fields of restoration and water management (Addy & Green 1996).

The usage of fertilizers and the impact of untreated sewage, urban stormwater and industrial wastewater during the past century, have in periods increased P levels far beyond the influence a natural load would have, and thus unset the delicate balance of many lake ecosystems. Even though Sweden is a sparsely populated country mainly covered by forests, eutrophication may still be considered a national problem given the sensitivity to added nutrients, of many lake systems. Regionally, especially in areas dominated by agriculture and densely populated urban areas, the impact is severe (Staaf et al. 2004).

Apart from anthropogenic point sources, P is leaching from different types of land cover to a varying degree. According to figures presented by the Swedish Environmental Emission Data (SMED), the TP span stretches from 1 µg/l for forest with low emissions (Nisell et al. 2012) to 300 µg/l for dense urban areas and roads with heavy traffic (Ryegård et al. 2007).

In order to estimate the effects of pollutant influx, it is important to have some knowledge on the hydrological, morphological, and biological parameters that influence a lake.

2.1.2 Lake hydrology and morphology

Evapotranspiration denotes the water that is returned to the atmosphere, both directly from evaporation and as water absorbed by plants and transpired mainly from leaf stomata. The amount of water transported through this process varies depending on e.g. temperature, air humidity and vegetation type and density (USGS 2013a).

The precipitation that does not return to the atmosphere as evaporation or plant transpiration reaches streams and lakes directly as surface runoff, or percolates into the ground. During heavy rainfall, pores and small cavities fill up with water until no more can infiltrate. As a result, water washes over the surface as runoff. The amount of runoff depends mainly on surface characteristics, slope and precipitation intensity. Tilted hard surfaces give off a larger relative amount of surface runoff than a flat porous one (Östlind 2012).

Most of the water that percolates is returned to streams and lakes as base flow or ground water discharge. The time for the water infiltrating the ground to reach creeks and lakes varies significantly depending on distance to the water body, permeability of the soil layers and the depth and slope of the bedrock below; it may take anything from days to thousands of years (USGS 2013b).

Lake morphology is an important concept when estimating the overall status and understanding the sensitivity to nutrient load of a particular lake. Basically, lake morphology denotes how the shape, volume, structure etc. of a water body influence internal processes within the lake. Important parameters linked to lake morphology are e.g. mean depth (volume/surface area), relative depth (maximum depth as percentage of mean diameter), shoreline development (length of shoreline in relation to a circle with the same area as the lake surface), and maximum length and mean width (surface area divided by maximum length) (Florida Lakewatch 2001). In the case of Lake Flaten, studied here, the fact that the lake is small and shallow with a round, smooth shape is important when trying to estimate and understand the state of the lake and processes involved.

2.1.3 Lake status indicators

Carlson’s Trophic State Index (TSI) (table 2.1) is an indicator to the trophic state of lakes originally developed by Dr Robert Carlson of Kent State University (Carlson 1977). The index is originally based on the assumption that the clarity of water is negatively correlated to the biota production level or trophic state of a water body and the level of total phosphorus. I.e., a rise in total phosphorus lead to a rise in chlorophyll production levels that in turn causes a decline in water clarity (United States Environmental Protection Agency (EPA) 2010). By lowering a so-called secchi disc into the lake and note when it is no longer visible the secchi depth is measured. A low secchi value denotes a more eutrophic state while a high value denotes a more oligotrophic state. Since secchi depth, chlorophyll production and TP are correlated according to Carlson; all three may serve as indicators to the Trophic State and thus may be translated to a common TSI value using the following equations (eq 2.1):

$$TSI = 60 - 14.41(ln\,Sd) = 9.81(ln\,Cha) + 30.6 = 14.42(ln\,TP) + 4.15 \qquad [Eq\ 2.1]$$

Sd= secchi depth metres
Cha=chlorophyll a µg/l;
TP=total phosphorus µg/l

In the case of Lake Flaten Secchi depth may not be used as an indicator since the lake is very shallow, but the other two estimators should apply to the lake.

Table 2.1: Carlson's Trophic state index (TSI) value and estimator spans (adapted from Addy & Green 1996).

	TSI Value	Secchi Depth (m)	Chlorophyll A (µg/l)	Total Phosphorus (µg/l)
Oligotrophic	<39	>4	>2.6	<12
Mesothrophic	40-50	2-4	2.6-7.2	12-24
Eutrophic	50-110	<2	>7.2	>24

The Swedish Environmental Protection Agency (Swedish EPA) classifies phosphorus levels in lakes according to a 5-step scale from Poor to High status. Based on lake mean depth, altitude above sea level, lake water absorbance coefficient and measured TP level, a lake specific ecological status value and class thresholds in µg/l are calculated (eq 2.2) (Naturvårdsverket 2007).

$$log_{10}(refTP) = 1.627 + 0.246 * log_{10}(Abs) - 0.139 * log_{10}(Alt) - 0.197 * log_{10}(Md)$$
[eq 2.2]

refTP = TP reference value
Abs = Lake water absorption at 420 nm measured with a 5 centimetre cuvette
Alt = Lake surface altitude above sea level m
Md = Lake mean depth m

The TP reference value is divided with the measured lake water TP content in µg/l for the ecological status value. The status of the lake considering TP content in water may now be classified according to table 2.2. Lake specific classification TP spans in µg/l may be determined by dividing the TP reference value with ecological status thresholds.

Table 2.2: Swedish EPA ecological status classification thresholds for lake water TP.

Class	Ecological status thresholds
Poor	< 0.2
Unsatisfactory	0.2
Average	0.3
Good	0.5
High	0.7

The Swedish EPA also suggests that a general threshold value of 25 µg/l may be used in order to determine if a lake is in a eutrophic state or not. The ecosystems in lakes with TP content above this value are at risk of alternations that may lead to accelerating eutrophication. If sufficient data is available, the Swedish EPA recommend high sample frequency over at least three consecutive years, the lake specific estimation method above is to be used since there may be lakes where high phosphorus levels is a natural state (ibid). Given the rather low number of lake samples available in this study, 25 µg/l will serve as target value; an attempt to assess the state of Lake Flaten with the method above will however also be made.

2.1.4 Predicting phosphorus load and impact on lakes

In order to understand the impact of phosphorus and the mechanisms of eutrophication on a specific water body, several parameters like lake morphology, climate, water detention time and the phosphorus and nitrogen cycles must be considered. In order to facilitate predictions on water quality various methodologies and equations, so-called lake models, have been elaborated. Different models display different degrees of complexity and are hence able to consider these parameters to a varying degree. Simple models based on less data and relationships are less accurate, but more user friendly and demand lower level of technical expertise. Lake models may be divided into two subgroups: Static and dynamic models (Bryhn 2008).

Presuming that the lake is in a long term steady-state, i.e. with no significant fluctuations over shorter time periods, limnologist Richard Vollenweider came up with a simplified static model based on TP load and a regression parameter for water residence (eq 2.3):

$$TP_l = L_{ext}/\left(1 + {T_w}^{0.5}\right) \qquad \text{[Eq 2.3]}$$

TP(l)= Lake water TP content (mg/m³)
L(ext)= External TP load(mg/m³)
T(w)= Water detention time (years)

The original Vollenweider model was constructed in the late 1960s and has since been altered into several similar offspring models, e.g. Ostrofsky, L&M, OECD, Walker etc., adjusted to fit various lake types and climatological conditions (Håkansson 1999). The Vollenweider model and similar are based on annual total load of phosphorus. The simplistic character of the model makes it accessible but limits the predictive accuracy. The OECD model is an empirical development of the original equation with two regression-based adjustable calibration constants (C1 and C2 below) that makes it possible to adapt the model to different lake types and climatic conditions (Alanärä 2006) (eq 2.4 and 2.5).

OECD model:

$$TP_l = C1\left[L_{ext}/(1 + \sqrt{T_w})\right]^{C2} \qquad \text{[Eq 2.4]}$$

Original calibration constants[1]:

$$TP_l = 1.55\left[L_{ext}/\left(1+\sqrt{T_w}\right)\right]^{0.82} \qquad \text{[Eq 2.5]}$$

Dynamic models carry more predictive power but demand a higher degree of understanding and generally more input data, considering both quantity and diversity, since they are based on several more of the parameters that steer the flux of nutrients. Additional input compared to static models could be e.g. water temperature, sediment content of phosphorus, and more precise morphometric data (Håkansson 1999). If sufficient data are available dynamic models produce more detailed predictions on nutrient fluxes over shorter time spans, e.g. monthly dynamics on leach from bottom sediments and how long it will take to reach an acceptable water quality when measures to mitigate the external load to a water body have been implemented (J. Jensen et al. 2006).

2.1.5 TP leach coefficients

In order to quantify land cover specific leach or export[2] of phosphorus and other pollutants, standardized coefficients per land cover class are often used. These coefficients are either adapted to calculations based on content per volume unit of water, e.g. µg/l, or directly on a surface unit, e.g. kg/ha/year of the specific land cover class. The coefficients calculated on volume, in this study referred to as “standard concentration values”, permit a more dynamic approach e.g. modelling based on monthly changes in water flow. The latter often called “export coefficient” appeal to a more static long term approach.

2.2 GIS and its application on this study

The definitions of a Geographic Information System (GIS) are many, but may be concluded as a computerized information system for storing, handling and performing analysis on data connected to geographical positions.

There are four basic cornerstones defining the required functionality of a GIS. The system must be able to (Eklundh 2003):

- Handle data originating from different sources and in different formats. A GIS must be able to import and digitize data as e.g. keyboard inserted information, edited from paper maps and from digital sources like satellite data and aerial photographs.
- Facilitate overall handling of data, i.e. the system must be searchable and updateable and hold functions for standardizing geometrical properties. There should also be facilities for handling metadata included.
- Analyse attribute and spatial data, i.e. overlay analysis containing several map layers, spatial searches, measurements of geometrical entities, etc. More advanced functions like statistical analysis of data and modelling may also be included.
- Present data as maps, tables and graphs.

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[1] Calibration constants based on data from 87 lakes with different characteristics.

[2] In this study “Leach” denotes diffuse contribution of TP *from* a land cover class, “Export” signifies TP *from* an entity like a point source or a defined geographic area and the term “Transport” signifies the overall movement of TP within a system, while finally “Load” denotes leach, export or transport *to* an entity e.g. a water body.

Building a GIS including several geographic parameters and large amounts of attribute data is complex. Since geographical data are often found from numerous and various sources and in different formats, both digital and analogue, editing, digitizing and transforming these data is usually a sizeable task before they are compatible and may be linked to different attributes (Burrough & McDonnell 2006).

In this study, GIS in relation to hydrology and land cover classification is of particular relevance. To be able to perform hydrological modelling, a raster Digital Elevation Model (DEM) of sufficient quality is required. The DEM must be of a resolution high enough and sinks and terraces, often anomalies caused by interpolation, need to be levelled (Pilesjö 2006). A common method for determining flow direction based on a grid DEM is called the D8, or eight-point pour algorithm. By moving a 3x3 cell window over the original DEM, the algorithm calculates flow from each cell towards the neighbouring cell with the lowest relative altitude value. This determines flow direction from each cell in 45-degree units, thus, eight possible flow directions (Burrough & McDonnell 2006, pp. 193-194). From the resulting flow direction grid, new layers like stream network raster and catchment demarcations may be derived. Since the D8 approach is simplified, in the sense that all water seldom drains in only one direction from a given location, several more advanced versions of the algorithm have been suggested over the years (Pilesjö et al. 1998). One way is to use so-called multiple-flow algorithms, which distributes flow proportionally based on slope in all eight directions (*ibid.*).

Choosing data format for land cover classification is important. If data is digitized manually from scratch, it is most likely initially processed into vector format. Depending on the complexity of the feature being digitized, automatic, semi-automatic or manual methods may be used. Vectorization (digitizing of vector data) of complex base data, like large scale and detailed maps and aerial photographs, are preferably done manually (Georgiadou et al. 2001) .

Manual editing is, however, a time consuming process that demands exactitude and a systematic approach. Nonetheless, it does, when accurately performed, produce data of high quality. The editing may be performed on a so called digitizing tablet or on a computer screen (Hauska 2006). It is first of all, as with all data selection, important to find an original or basemap of sufficient quality, e.g. aerial photographs of highest possible resolution and dated as recently as possible. Apart from the value of input data, other factors important for the quality of the spatial data produced are the resolution of the digitizer and the skill of the operator.

Land cover may be classified using the spectral characteristics of aerial photographs or satellite images as well. Surfaces on the ground reflect different amounts and wavelengths of electromagnetic energy depending on their features. The energy is recorded by satellite or aerial camera in different ways depending on the sensitivity and settings of the sensor. Each pixel of the resulting image is assigned a value depending on the energy recorded. E.g., in an 8-bit image the digital number value span is 0-255 (Janssen & Bakker 2001).

Using these images, a computer driven automatic or semi-automatic classification method assigns the pixels to different land cover classes by cell value. When the area at hand and the land cover classes are known to the editor a supervised method may be used. So-called training areas representing each land cover class of the image are assigned and the typical pixel value range of these areas is saved as the signature of the land cover class (Janssen & Gorte 2001).

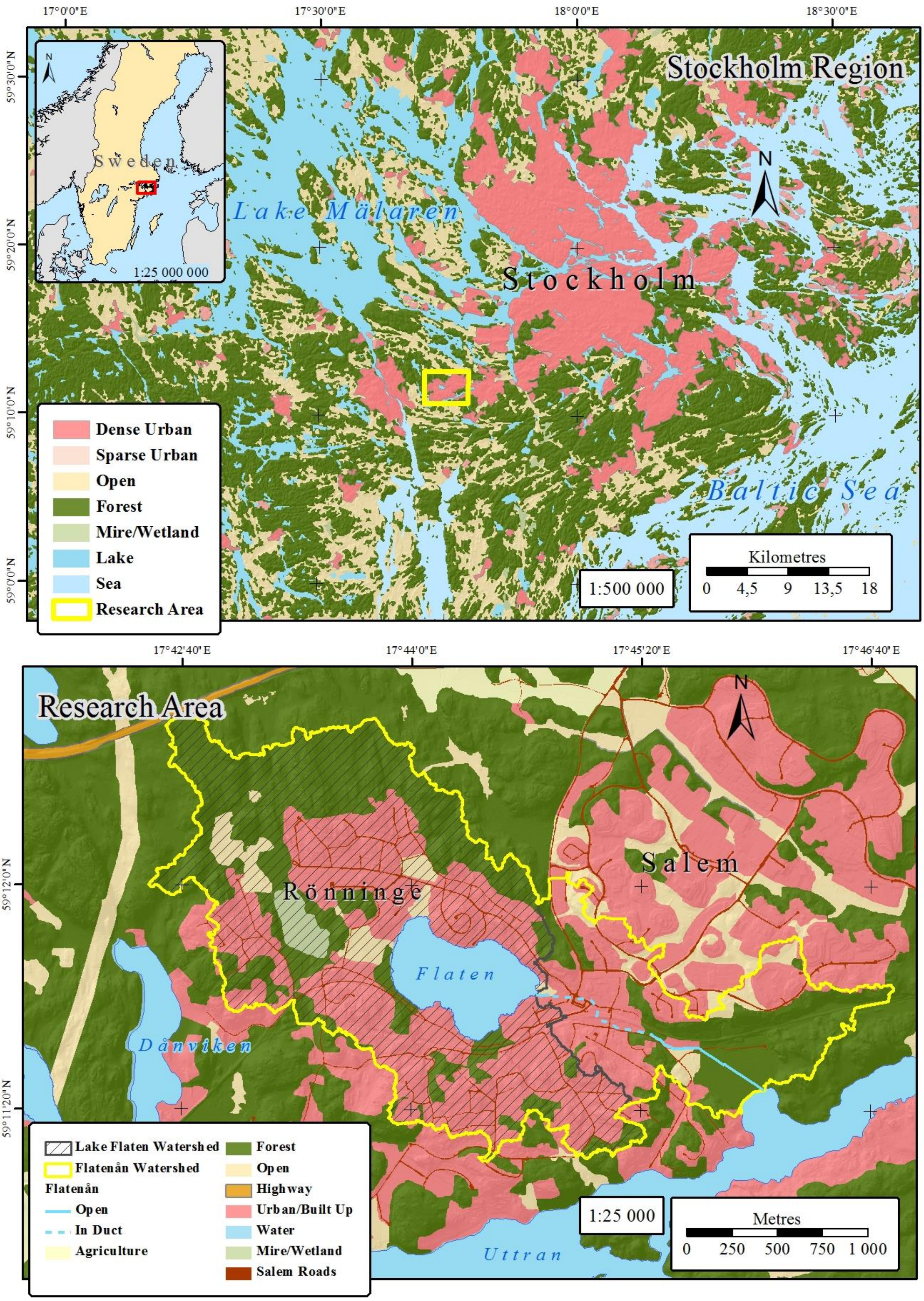
A continuous raster field is an excellent base for mathematical operations and, thus, analysis. These operations include e.g. math algebra, spatial analysis operations and overlays. Since each attribute is recorded in a separate grid, layers may be combined for different analytical purposes, e.g. arithmetic, relational and conditional operators (Burrough & McDonnell 2006; Sun et al. 2001)

2.3 The research area

2.3.1 Lake Flaten

Lake Flaten is completely contained within the boundaries of the Salem Municipality approximately 25 km southwest of the Stockholm city centre (fig 2.1). The north-western part of the roughly 300 ha catchment area consists mainly of coniferous forest, while the rest is suburban dominated by detached houses. The altitude difference within the basin is approximately 50 metres and the terrain is broken (fig 2.2). There is a small wetland to the west connecting with the lake by a short ditch. Water from the Lake Flaten basin drains to the large Lake Mälaren via a system of downstream creeks and lakes (the Tumbaån catchment), and eventually into the Baltic Sea.

Lake Flaten is a small shallow lake (table 2.3). There is no major inlet and no daughter subcatchment areas above the lake. A larger ditch enters the lake to the west and several smaller stormwater drains and small inlets surround it. Lake Flaten is connected to the larger Lake Uttran via the roughly 1.5 kilometre long Flatenån of which approximately half is led through a duct under a small commercial centre.



SWEREF99 - Transverse Mercator

Fig 2.1: Stockholm region and the research area of the study.

Table 2.3: Lake Flaten morphometric data.

Lake Flaten[3]	
Lake Area (m²)	316 367
Catchment Area (ha)	306.28
Mean depth (m)	1.80
Max depth (m)	2.50
Water Detention Time years	0.78
Lake Perimeter (m)	3 029
Lake Volume (m³)	569 460
Annual water Flow (m³)	730 077

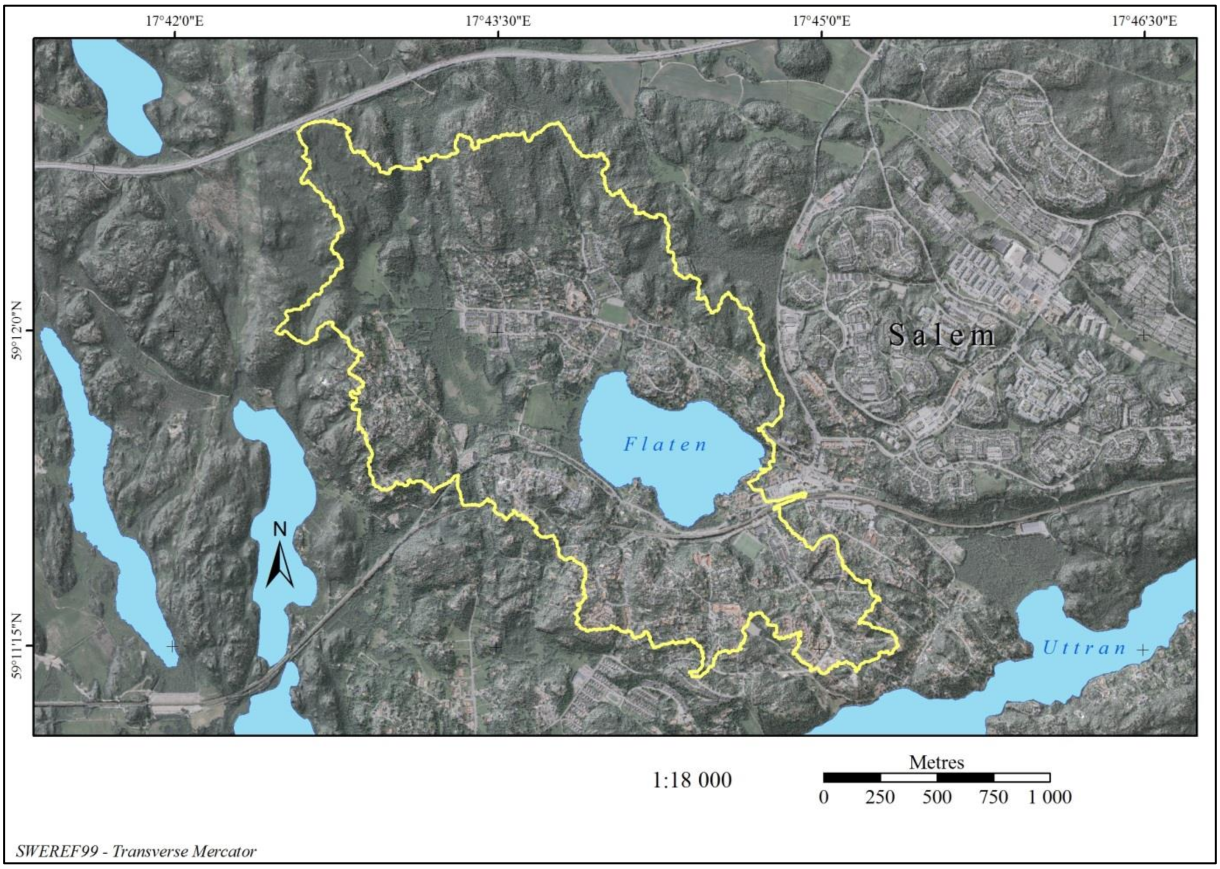


Fig 2.2: Lake Flaten catchment on hill shaded digital elevation model (DEM) and transparent aerial photograph.

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[3] Mean/max depth and water detention time figures from Huononen (2000).

2.3.2 Previous studies

In 2000, Yoldia Environmental Consulting AB (Yoldia) conducted a survey to estimate the state of Lake Flaten in order to suggest actions to reverse eutrophication (Huononen 2000). The survey focuses on P, and is based on standard concentration values in order to estimate the external load to the lake.

In the report (ibid.), the total TP load is estimated to 44-62 kg/year and a Vollenweider diagram is used to determine whether the load is severe or not. Given the rather small volume of the lake and the fairly long water detention time, the report proposes that the external phosphorus load may be too high if the eutrophication process is to be reversed.

Despite Lake Flaten’s possible internal load of nutrients, the report suggests that the external load is attended to first, so that these sources of pollution may be minimized before addressing the internal load. This is the general recommendation of the Swedish EPA as well (Naturvårdsverket 2003).

In 2001, another survey was conducted by the Swedish company SWECO in order to determine the state of Lake Flaten as a recipient of nutrients and other pollutants, and to suggest actions to improve the state of the lake (Larm et al. 2001). The survey was based on both short term field measurements and standard concentration values. The report includes calculations on diffuse leakage from different land-cover classes, measurements in storm drains (three main outlets) and atmospheric deposition directly on the lake surface. The TP load to the lake is estimated to 48 kg per year in this report.

The result of the survey shows that while the amounts of pollutants as a whole may not be very high, Lake Flaten as a recipient may still be sensitive to nutrients since the volume of the lake is small. The result also points to that the standard concentration values initially used is exaggerating the TP load to the lake. A possible explanation presented is that the value for attached houses (the dominant urban land use class around the lake) was initially designed for denser housing areas.

From October 2007 until September 2008, Yoldia (Huononen 2008) conducted tests and measurements with the objective of evaluating the efficiency of two water retention ponds, which of one is situated within the Flaten catchment area on the northern perimeter of the lake. The purpose of these ponds, and the dams attached, is to slow down the water flow so that there is time for pollutants to settle in the sediment. The results show that while the retention ponds were quite efficient in reducing metals like lead and chromium, the reduction of phosphorus was negligible, around 1 %. The author (ibid.) concludes that there is a possibility that the detected reduction of some pollutants may partly be caused by unpolluted ground water leaking into the dam. This dilution makes it difficult to draw conclusions on the efficiency of the dams’ capability of retaining phosphorus.

Yoldia has also carried out long term monitoring on TP and other substances in both Lake Flaten and Flatenån resulting in annual reports (Huononen 2011). This study will to a large extent be based on these reports and measurements. Previous studies will also be used to verify the total TP load to Lake Flaten assessed here. This study will additionally include more thoroughly elaborated geographical data, both considering catchment and land cover delineations. Point source load on subcatchment level, lake water TP content on monthly basis and internal load in the lake, not previously assessed, will also be predicted and taken into account.

3. Methodology

This chapter presents the methodology used to assess TP transport within the research area and the effects of this transport. It further presents methods to model scenarios.

The process has entailed eight consecutive steps; each necessary in order to produce sufficient data for coming steps and for a final assessment on TP transport and Lake Flaten water quality considering phosphorus levels:

1. Generating catchments and sub-catchments
2. Producing land cover classes
3. Estimating lake water TP content
4. Assessing water flow and mass transport
5. Assessing external TP load to Lake Flaten
6. Estimating load from point sources
7. Estimating internal TP load in the lake
8. Modelling scenarios

Steps 1 and 2 include producing necessary geographical data. Steps 4 to 7 are about processing attribute data to assess parameters like water flow, lake water quality, internal load from bottom sediments and finally, together with geographical data, TP load per subcatchment within the Lake Flaten and Flatenån catchments. Scenarios modelled in step 8 simulate the effects of some possible future measures of mitigation, changed water flow and urban development on the TP transport to Lake Flaten and the lake water quality.

Sub-results necessary for coming steps of the methodology are reported in this chapter, while overall results are presented in chapter 4.

3.1 Input data and applications

The following data, applications and hardware have been used in the study:

Base map data

- Colour aerial photographs. Swedish Mapping, Cadastre and Land Registration Authority (Lantmäteriet). Date of Capture 2011-06-27. Spatial resolution 1 metre. Provided by Salem Municipality. Tiff.
- Elevation data contour lines. Salem Municipality. 1 metre contour interval.
- Digital elevation data. 2 metre spatial resolution. Vertical accuracy < 0.5 m. (Lantmäteriet).
- Storm water drains and points feature. Salem Municipality.
- Cadastre map. Salem municipality 2005. Pdf.

Base attribute data

- Measurements from Lake Flaten and Flatenån. Water samples. Yoldia Environmental Consulting 1997-2012. Sampling points: see fig 3.1.
- Precipitation and water discharge 1997-2010. Swedish Meteorological and Hydrological Institute.
- Standard in water concentration values per land cover class, Standard Runoff coefficients, etc. Swedish University of Agricultural Sciences (SLU) (Ekstrand et al. 2003) and StormTac (StormTac 2012).
- Survey on private sewage systems and pollution sources. Salem Municipality 2008 (Bygg-och Miljöenheten 2008)

All spatial data were re-projected (if demanded) to SWEREF 99 Transverse Mercator with a central meridian of 18 degrees east in order to ensure best possible fit to the research area.

Applications and software used

- *ArcMap, ArcView license* (2009)
- *Arc Catalog* (2009)
- *ArcHydro plugin* (2011)
- *MS Excel* (2010).

Hardware used

- GPS receiver Garmin GPSmap 60Csx.

3.2 Generating catchments and sub-catchments

An initial reflection was that catchment and land cover delineations used in previous studies and those available from e.g. SMHI and Lantmäteriet were too crude given the small size of the research area. A decision was made to produce all geographical data needed for this study.

In order to estimate the origin and size of the TP load to Lake Flaten, as well as the transport below the lake, catchments had to be delineated. Lake Flaten and Flatenån catchment demarcations were generated with a Digital Elevation Model (DEM) from laser scanned elevation data (Lantmäteriet 2012). Another DEM for comparison was produced from a contour line feature with one metre vertical resolution provided by Salem municipality. Both DEMs underwent the same processing.

First depressions were burnt into the raw DEM, where water pass man-made structures like roads and railway embankments. These passages were easily recognisable thanks to the high resolution of the DEM.

The new manipulated DEM was treated in accordance with the ArcHydro workflow (Djokic et al. 2011). The resulting catchment area polygon feature (Catchment_raw) was used with the ArcHydro “point delineation” application to define catchments based on Lake Flaten and Lake Uttran inlets and the Yoldia control point in Flatenån. The inlets had previously been identified from the DEM, maps and a field survey.

Because surface runoff in some areas was largely brought to the lake via storm water drains, ducts and ditches, the Flatenån catchment feature (fig 3.1) was finally examined and demarcations adjusted manually based on a storm water drain feature, in order to better fit the subcatchment demarcations to true conditions. The adjustments were small.

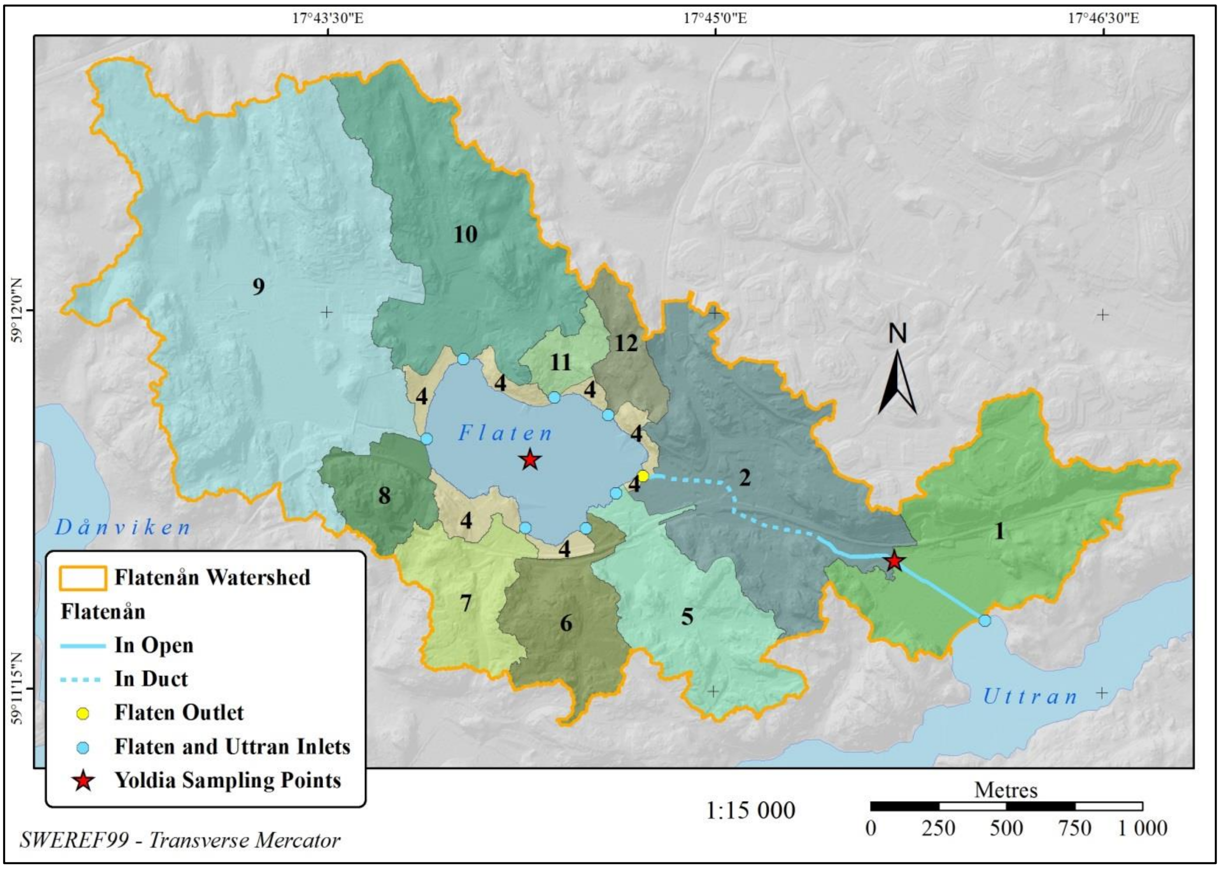

Fig 3.1: Flatenån catchment area with subcatchments. Subcatchments 4-12 form the Lake Flaten catchment area.

Subcatchments 4-12 water Lake Flaten, while “1” and “2” are situated below the lake.

“4” represent areas on the lake perimeter without point inlets. Subcatchment 8 has no specific catchment point or inlet either, but was treated as a separate catchment area due to its size.

3.3 Producing land cover classes

Having generated a catchment layer, the next step would be to produce the land cover features necessary to calculate TP leach per land cover class. In the process, two methods were used: Manual editing (vector) and remote sensing (raster) approaches.

The manual editing aimed at receiving high detail in order to generate divisions suitable to urban and suburban conditions, and the large mapping scale of the survey. The features were later dissolved to fit applications used.

Editing was performed on aerial photographs provided by Salem Municipality. An editing scale of 1:1200 offered a good compromise between detail level and oversight.

To check accuracy of the manually edited map (fig 3.3), 50 points were randomly generated within two designated polygons (fig 3.2). Conformity between mapped points and ground truth was checked in the field with a GPS receiver. Some points were not directly reachable due to reasons of difficult terrain (mire) or trespassing (detached houses), but were within eyesight.

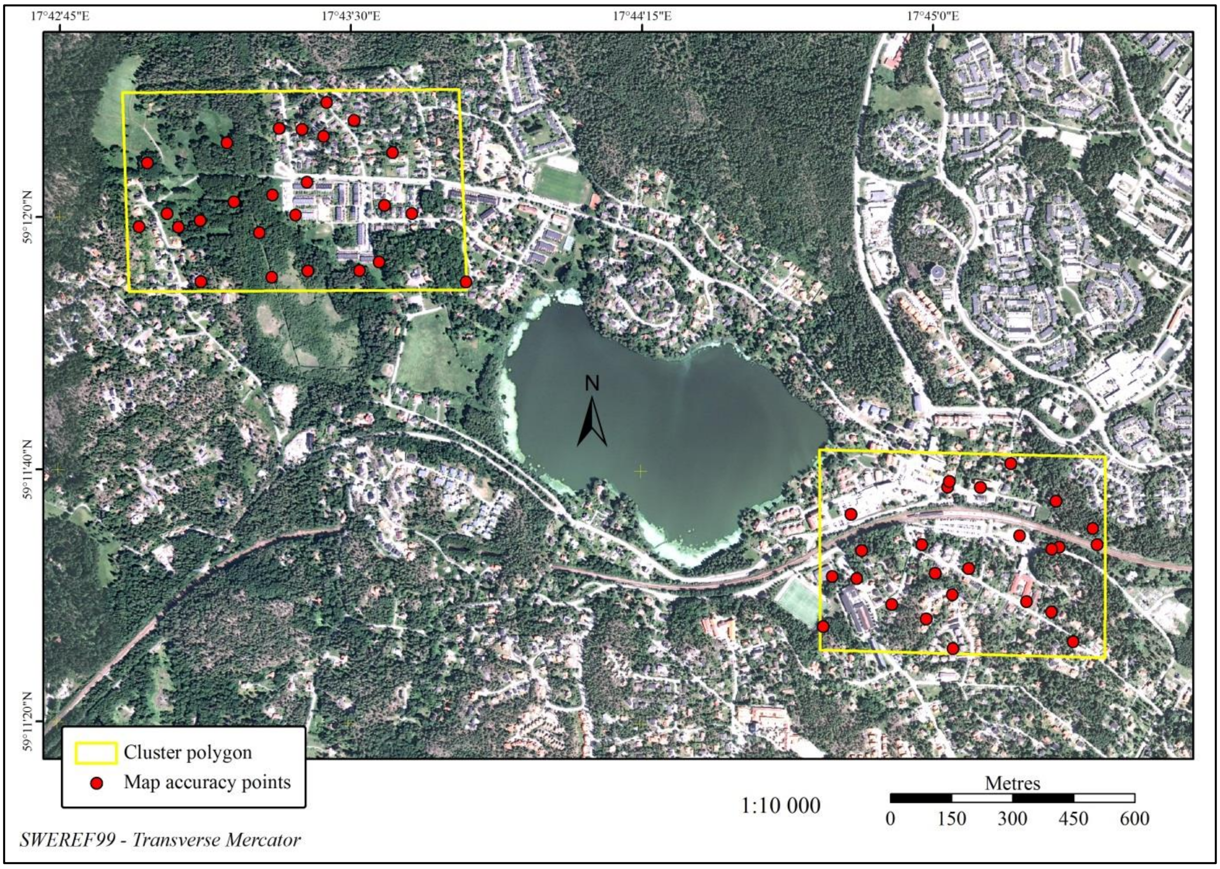

Fig 3.2: Points for checking map accuracy generated within two separate clusters polygons on an aerial photograph of Lake Flaten surroundings.

Results were inserted in a confusion matric table, overall accuracy and coefficient of agreement (kappa) was calculated.

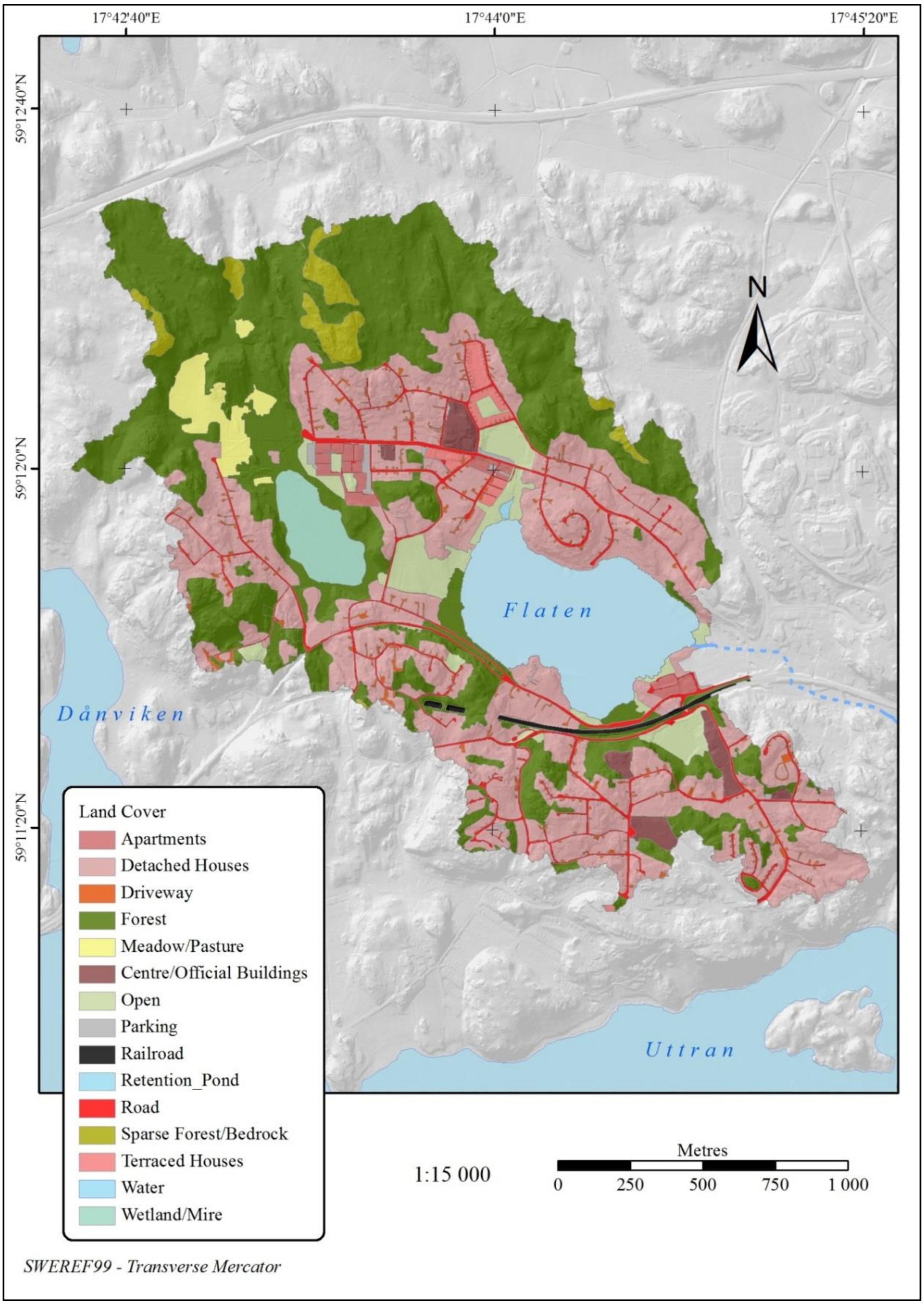

Fig 3.3: Land cover classification from manual editing (LC_raw) clipped with Lake Flaten catchment area demarcation.

In order to present an alternative to time-consuming manual editing, another land cover layer was produced using a remote sensing raster based method.

The 3-band true-colour aerial photograph from the summer of 2011 previously used for editing land cover was used. The red band, which depicts distinctive contrast between urban land cover and vegetation, was converted to grey scale, with pixel DN-values from 0 to 255.

A decision to use three land cover classes only (1= Forest; 2=Open; 3=Urban) was made given the limited band-width and the fact that there were no agricultural land or larger grazing pastures within the research area.

A feature of polygons (20 for each class) covering class specific areas, so-called training or sample areas, was used to edit signatures for each class. Using a maximum likelihood classifier, a land cover grid was created (LCgrid_1).

Since LCgrid_1 was not found accurate enough considering urban land cover, the original monochrome red band image was reclassified with a supervised approach, using different manually edited DN-value ranges for the three classes and comparing them to the original image, until a satisfactory result was accomplished, thus producing a second grid (LCgrid_2).

The final DN-value ranges were:

Forest= 0-79

Open= 80-123

Urban= 124-255

A majority filter[4] (5 by 5 cell rectangular window) was run repeatedly over both land cover grids (all in all 10 runs) until images with clear boundaries between classes and more homogenous surfaces was achieved and comparably few pixels were shifting class with each run.

The resulting land cover grids were compared and evaluated against the original aerial photograph. LCgrid_1 had higher accuracy considering forest delineation, while LCgrid_2 was more true to the boundaries of urban areas. A new grid based on the two approaches would better delineate the land cover classes.

The two grids were now combined by first reclassifying one to values 5, 7 and 9, while keeping the original 1, 2 and 3 for the other. When multiplying the grids together with an overlay operation, a new raster of 9 unique classes was obtained. This new raster was made transparent, each of the 9 classes were carefully examined with the aerial photograph as background, and reassigned the values 1, 2 or 3 (Forest; Open or Urban) depending on assessed best fit class alignment. The resulting raster (LC_RS) seemed to separate the classes well in accordance to the aerial photograph (fig 3.4).

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[4] Assigns class alignment to the centre cell of the filter window according to the majority value of the other cells within the window. The filter window is systematically moved over the raster surface.

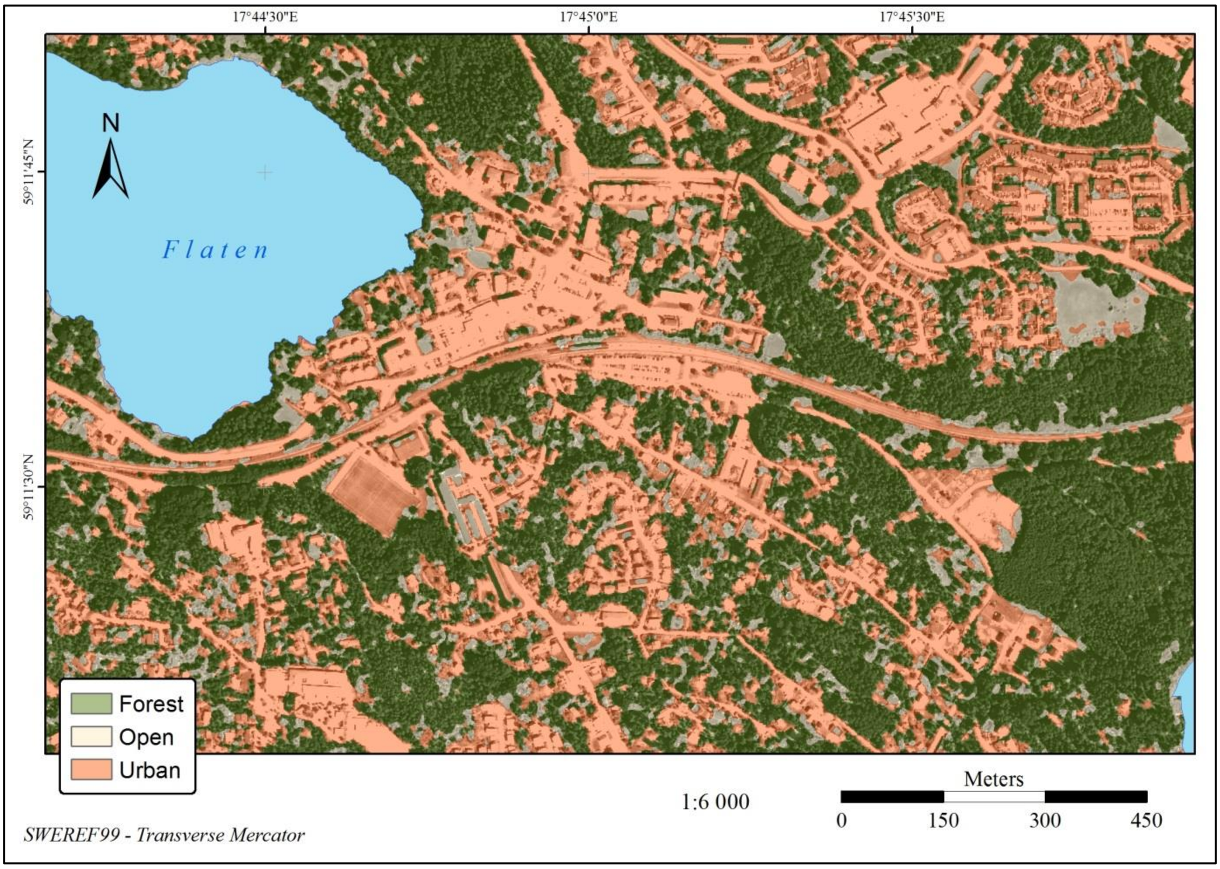

Fig 3.4: Land cover classification as result of remote sensing approach (LC_RS) transparent on aerial photograph, area east of Lake Flaten.

3.4 Estimating lake water TP content

Before the geographical data and layers produced above could be used to calculate export coefficients per land cover class and TP load per catchment area, assessments on mass transport from the lake and in the creek was needed. Estimating mass transport at the sampling point in Flatenån and from the Lake Flaten outlet would make it possible to get an estimation on the TP export from catchment 2 (see fig 3.1). This export estimation would in turn calibrate export coefficients per land cover class within the catchment. Finally the calibrated coefficients would be used to predict load from other catchments in the research area.

A first step in order to quantify the transport was to predict the TP content fluctuations in the lake water over the year. Such a prediction was also necessary in order to estimate the internal TP load in the lake.

All in all, 23 February and August samples on water TP content from Lake Flaten and 187 monthly samples from Flatenån over the 1997-2012 research period were available. If there was a correlation strong enough between collateral samples from the lake and the creek, interpolated Flatenån values could represent Lake Flaten and thus provide monthly assessments on lake water content.

Since samples for each month were few, extreme values would bias estimations on water content. It was thus decided to remove outliers as a first step. Outliers from the Lake Flaten and Flatenån sampling series were detected using an interquartile range (IQR) method (eq 3.1). The method was chosen since it is less sensitive to outliers, and thus more robust than a method based on standard deviation; outliers influence and alter the standard deviation (Seo 2006).

$$IQR = Quartile\ 3 - Quartile\ 1 \qquad \text{[Eq 3.1]}$$

Values more than 3 interquartile ranges below the first quartile and above the third, were considered outliers. Based on the assumption that sample peak values might represent fluctuations important to the result this conservative approach was chosen; values outside 3 interquartile ranges are generally considered as extreme (ibid). Two samples in the lake and three in the creek were detected as outliers and removed.

There was a strong statistically significant correlation as well as equality in values (residuals clustered along the trend line) between surface and bottom waters in the lake (fig 3.5). Since this connection was valid for both February and August measurements, and given the shallow mean depth, the conclusion was that the lake is more or less mixed all year round.

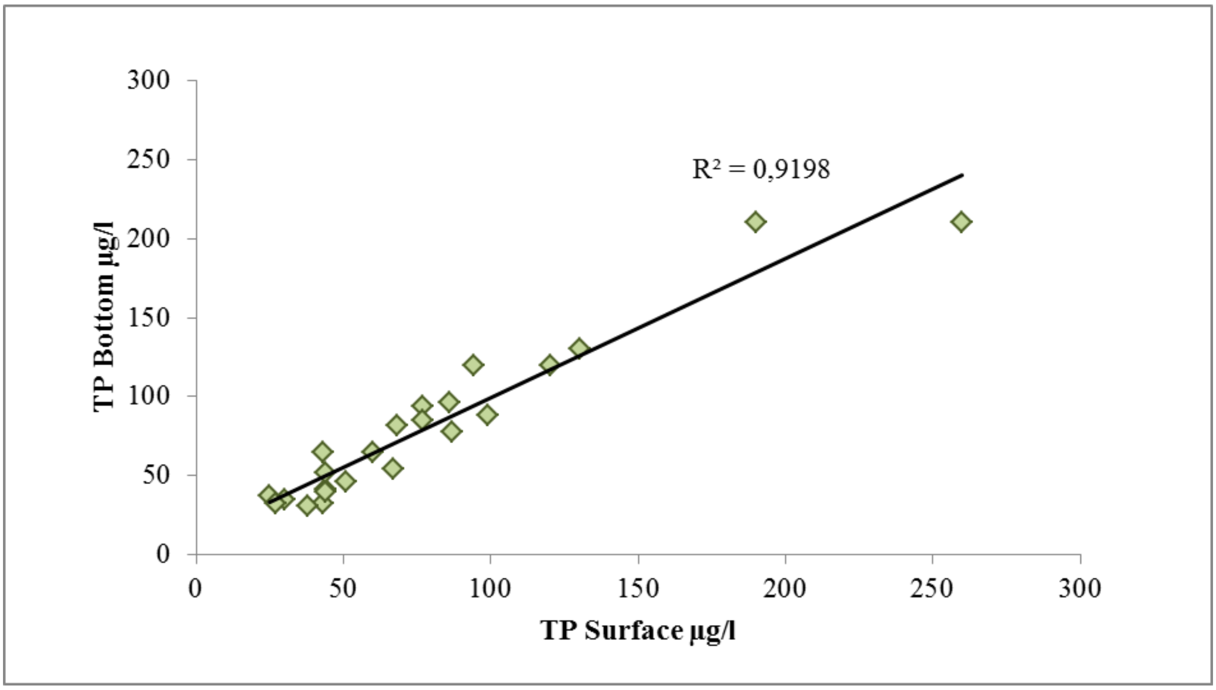

Fig 3.5: Correlation TP content Lake Flaten surface and bottom waters, February and August samples collected 1997-2012.

Surface water values were used for further estimations since the lake outlet is shallow, and these values were thus estimated to more directly relate to the mass transport from the lake. Furthermore the Swedish EPA recommends surface water samples for classifying lake status considering nutrients (Naturvårdsverket 2007).

Creek TP measurements (fig 3.6) show no significant trend over the research period even though fluctuations are large. It was estimated that data from the entire period may be used.

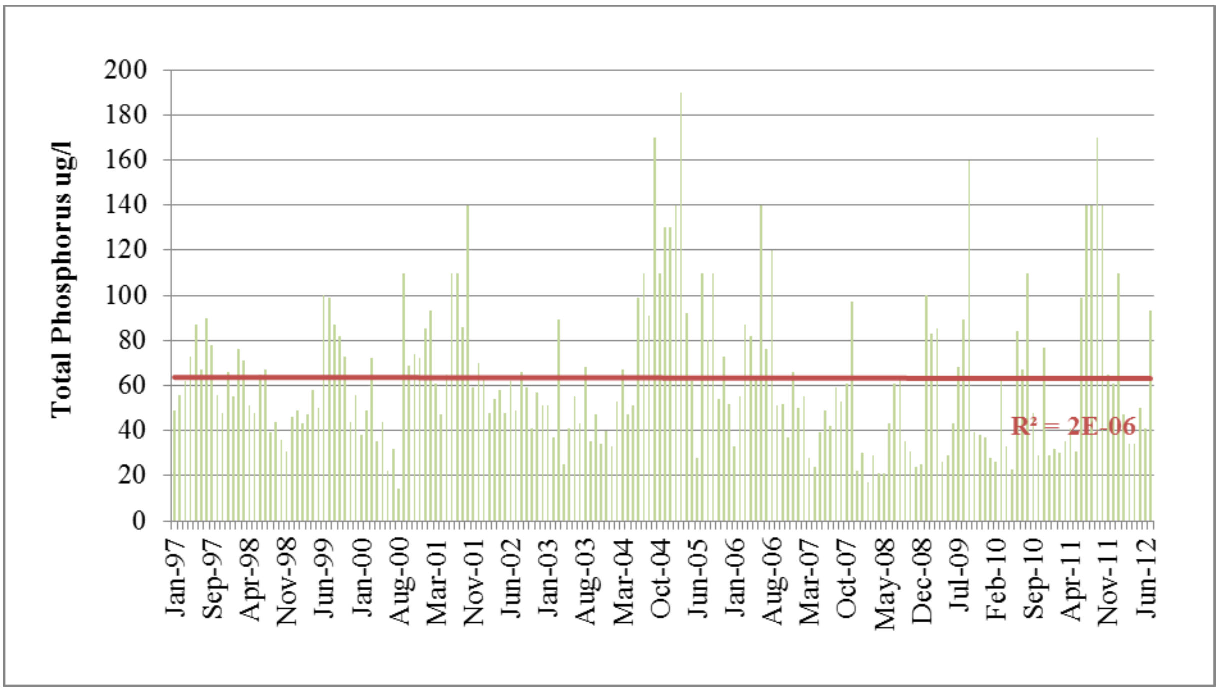

Fig 3.6: Trend Flatenån, monthly water TP content 1997-2012.

Corresponding samples from Lake Flaten and Flatenån were compared in a residual scatter plot in order to find pairs with large residuals. One such sample pair was found and removed. A linear regression analysis (tables 3.1-3.3), was performed on the now prepared data set.

Tables 3.1, 3.2 and 3.3: Regression analysis output, dependence of Flatenån on Lake Flaten TP measurements 1997-2012.

Regression Statistics	
R	0.87
R Square	**0.76**
Adjusted R Square	**0.75**
Standard Error	13.7
Observations	19

ANOVA					
	df	*SS*	*MS*	*F*	*Signif F*
Regression	1	10229.84	10229,84	54.45	**1.08E-06**
Residual	17	3193.84	187.87		
Total	18	13423.68			

	Coefficients	*St. error*	*t Stat*	*P-value*
Intercept	18.75	7.66	2.45	**0.025**
TP Flaten	0.78	0.11	7.38	**1.08E-06**

The “R-square” and “Adjusted R-square” values show how much of the dependent variable that is explained by the independent variable. The ANOVA table “F significance” value shows that the overall regression is significant and validates the output. The value indicates that there is just a 0,0001% probability that the output is merely a chance occurrence. Table 3.3 P-values show the probability that the coefficient and Y-intercept would be obtained from a random distribution; both display P-values beyond the generally accepted 5% (0.05) confidence level, which means that both variables are statistically significant.

A residual plot indicated that the residuals were spread without any obvious pattern, apart from the wanted roughly horizontal band around zero. This points towards a constant variance and makes it reasonable to assume a linear relationship between TP in the creek and the lake.

It was finally concluded that a linear trend equation is appropriate for estimating average monthly TP levels in Lake Flaten, over the sixteen-year research period, based on Flatenån figures (fig 3.7).

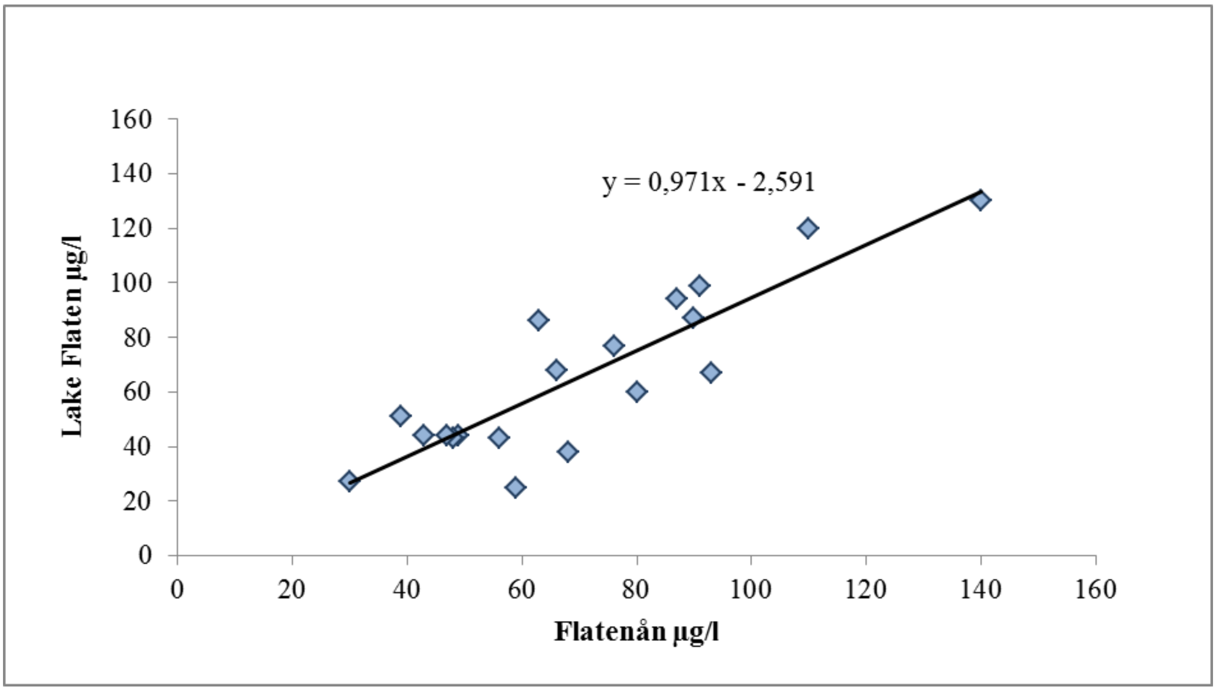

Fig 3.7: TP correlation Flatenån and Lake Flaten, trend line and linear trend equation; February and August samples 1997-2012.

184 TP content values from Flatenån were used to interpolate monthly content in the lake. There were 14-16 values for each month of the year. Median values were considered appropriate when estimating monthly in-water content. Since the values for each month are few, peak values have a strong influence on the sample mean. Median values return estimations approximately 10% lower than mean values on both annual mean TP content in lake water and export from the lake.

Against the calculations and conclusions above, interpolated averages in Lake Flaten based on monthly samples collected during 16 years from Flatenån show that TP values fluctuate over the year (fig 3.8). There is a significant summer increase and a less pronounced one in winter. As a comparison the mean and median (no outliers) of measured August values were 78 and 86 µg/l. The measured mean and median for February were 49 and 44 µg/l. Since measured and interpolated values for these months coincided it was decided to use the latter since these were more comparable to the interpolated values of other months.

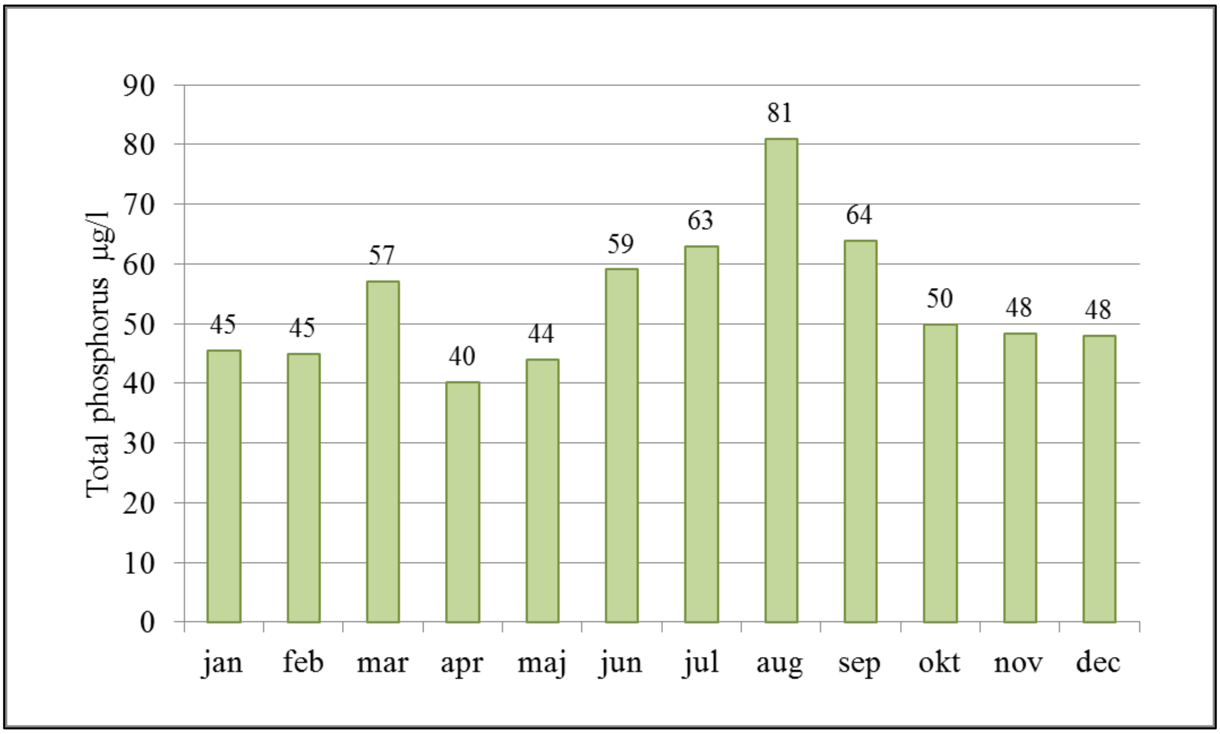

Fig 3.8: Lake Flaten interpolated monthly TP averages 1997-2012 µg/l, based on concurrent samples from Flatenån.

Having estimated monthly median water content values, the current state of Lake Flaten could now be assessed with Carlson's Trophic State Index and Swedish EPA guidelines.

3.5 Assessing water flow and mass transport

With estimated monthly TP water content in Lake Flaten it would be possible to estimate the mass transport from the lake if monthly flow could be predicted. A prediction on the annual mass transport at the sampling point in Flatenån was also needed in order to quantify the load from catchment 2. Monthly flow estimations from the point would make the prediction more exact.

3.5.1 Estimating annual and monthly water flow

Concurrent with TP measurements from January of 1997 until December of 2004 flow at the sampling point in Flatenån (see fig 3.1) was modelled (SMHI PULS) monthly by Yoldia. The median value of these 96 estimations calculates the average annual flow to 909 814 m³.

The SMHI S-HYPE hydrology model is a Swedish adaption of the high resolution HYPE model designed to calculate water discharge and nutrient transport in accordance with the EU water framework directive (SMHI 2012a). The model processes data from the Swedish Water Archive (SVAR) and operates on subcatchment scale from one square kilometre and up. The typical error on flow estimations is ± 10%. The S-HYPE estimation, obtained from the SMHI service "Vattenweb" (SMHI 2013), of annual discharge at the Lake Uttran inlet from Flatenån[5] (fig 3.1) is 1 003 295 m³ . Given the assumption that flow per area unit within the

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[5] S-HYPE 2010 version 1.0.2. Subcatchment id: 656495-161193. Outlet point RT90 1612160, 6564810.

catchment is fairly uniform, the annual discharge from above the sampling point in Flatenån would be 873 551 m³.

The third method of estimating the flow at the sampling point was to use the water detention time and calculated volume of Lake Flaten, to estimate annual water discharge at the lake outlet (730 077 m³/y) and the surface specific water flow of the Lake Flaten catchment area. Applying this surface specific flow on the area above the sampling point, calculates the annual flow to 865 779 m³.

Since all estimators returned similar results and an evaluation on the qualities of the specific method will not be made within this study, a decision was made to hereafter use a rounded average of all three, i.e. 880 000 m³ as the annual flow value at the control point in Flatenån . Assuming that the same 10% uncertainty level reported for the S-Hype model would apply to the other estimators as well the uncertainty span for this estimation stretches from 792 000 to 968 000 m³ annually.

In order to verify the variations in water flow over the months the Yoldia flow predictions were compared with SMHI flow data. At the SMHI site “Vattenwebb” flow results from multiple research stations all over Sweden are available. Monthly averages are based on daily observations, i.e. close to 500 for each month during the 16 year research period. The monthly proportion of annual water flow from six stations in the Lake Mälaren region reveals a general pattern (fig 3.9).

The catchment areas above the stations vary from approximately 6 to 22 000 square kilometres. All seven stations display typical low discharge during the summer caused by high evapotranspiration, the same increase during autumn and winter dip, followed by a snow melt peak in April.

When comparing the curve of monthly predicted water flow in Flatenån, to the curves of other catchments in the region (fig 3.9), it was concluded that the flow predictions from the creek were not accurate or numerous enough for monthly assessments.

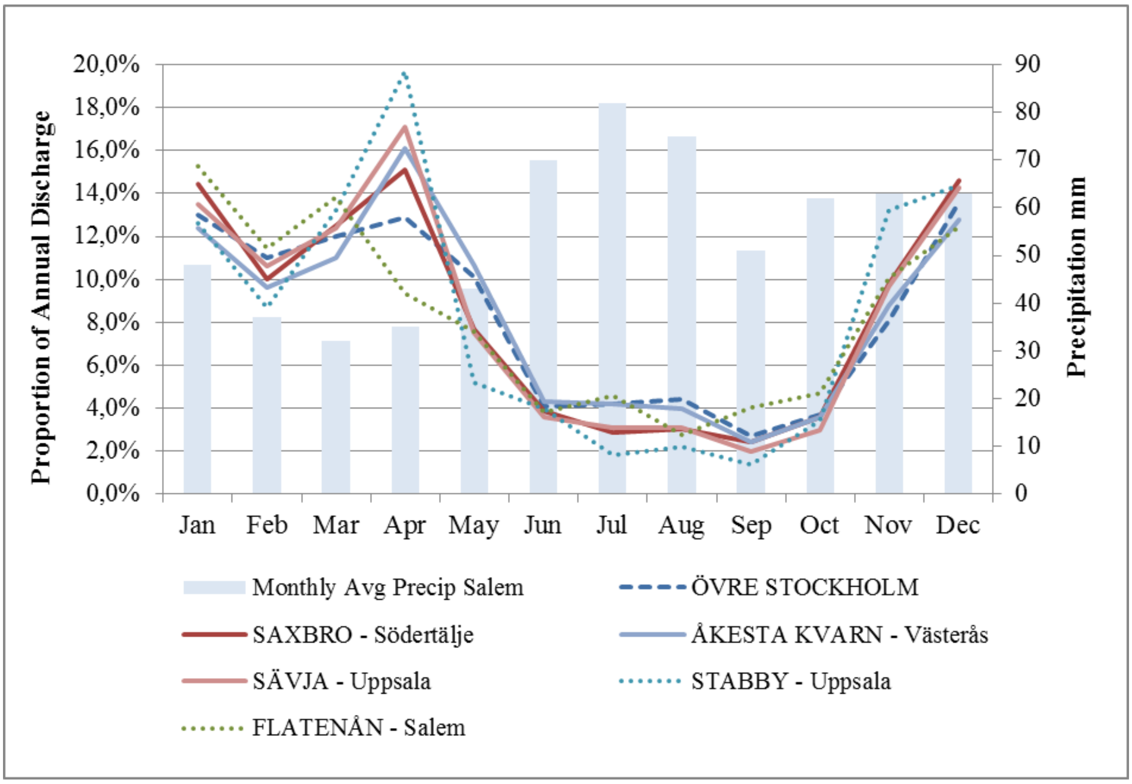

Fig 3.9: Measured (daily observations) monthly proportions of annual discharge at five Lake Mälaren region stations 1997-2012. Flatenån monthly fractions based on modelled values 1997-2004. Interpolated average monthly precipitation Salem 1997-2010 (SMHI).

The two stations closest to the Flatenån catchment area are Saxbro and Övre Stockholm. The centre of the Saxbro catchment is situated just five kilometres from Lake Flaten. Both stations display an area specific discharge comparable to the Flatenån figures, but the lake surface percentage of the Saxbro catchment is lower than Stockholm and Flatenån. Like Övre Stockholm, the Flatenån catchment contains a relatively large water body that may mitigate flow fluctuations. Given these characteristics and the short distance from Flatenån to the Saxbro catchment (uniform precipitation and land cover characteristics), mean monthly fractions of annual totals from the Saxbro and Övre Stockholm stations were applied on the Flatenån catchment to interpolate the monthly water flow (table 3.4).

Table 3.4: Monthly interpolated water flow and proportion of annual total at the Flatenån sampling point and the Lake Flaten outlet, based on monthly fractions of annual flow from adjacent catchments.

Month	Monthly fraction of annual total	Monthly interpolated flow Flatenån m³	Monthly interpolated discharge Lake Flaten outlet m³
Jan	13.7%	120 740	100 311
Feb	10.5%	92 456	76 813
Mar	12.2%	107 798	89 559
Apr	14.0%	123 212	102 365
May	8.9%	78 191	64 962
Jun	4.0%	35 096	29 158
Jul	3.5%	31 222	25 940
Aug	3.7%	32 631	27 110
Sep	2.6%	22 606	18 781
Oct	3.6%	32 018	26 601
Nov	8.9%	78 751	65 426
Dec	14.1%	124 037	103 050
Annual Total	100%	880 000	730 077

3.5.2 Quantifying mass transport

With estimated lake water TP content, assessed monthly water flow and TP measurements from Flatenån it would be possible to quantify mass transport below the lake.

Average monthly mass transport of TP from the Lake Flaten outlet was calculated by multiplying predicted monthly water discharge (see table 3.4) with assessed monthly in-lake TP averages (fig 3.8) . The annual TP export from Lake Flaten was estimated to 36.3 kg (table 3.5).

Table 3.5: Estimated discharge and TP mass transport at the Lake Flaten outlet.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Monthly Discharge m³/10^3	100.3	76.8	89.6	102.4	65.0	29.2	25.9	27.1	18.8	26.6	65.4	103.1	730.1
In-lake average TP µg/l	45.4	45.0	57.1	40.1	44.0	59.1	63.0	80.9	63.9	49.8	48.4	47.9	53.7
TP Mass transport kg	4.6	3.5	5.1	4.1	2.9	1.7	1.6	2.2	1.2	1.3	3.2	4.9	36.3

Combined monthly flow estimations and TP samples from Flatenån existed for eight out of the sixteen years of the survey period. The data was handled with the flow weighted average method recommended by Swedish EPA (Naturvårdsverket 2005) for estimating mass transport in running water (eq 3.2).

$$T = Q_A * \left(\sum_{i=1}^{n} C_i * Q_i\right) / \sum_{i=1}^{n} Q_i \qquad \text{[Eq 3.2]}$$

T= Total monthly mass transport
Q(A)= Total monthly discharge (m³)
C(i)= Concentration at the specific occasion (g/m³)
Q(i)= Discharge at the specific occasion (m³/s)

The sum of resulting monthly transport estimations quantified annual TP transport to 53.8 kg using this method.

Mass transport in Flatenån was also calculated as monthly mean TP content values (all 187 values included) for the entire survey period times monthly flow estimations (see table 3.4). The calculation returned a total TP transport of 53.9 kg at the sampling point.

The conclusion was that approximately 54 kg of TP is transported by the sampling point in Flatenån annually. The export from catchment 2 was hence estimated to 17.5 kg. Since the uncertainty regarding annual water flow influence mass transport to a similar extent the uncertainty span for this estimation was also predicted to approximately ± 10%.

3.6 Assessing external TP load to Lake Flaten

With the estimated total TP export from catchment 2 (17.5 kg ± 10%), it would be possible to calibrate the area specific load per land cover class, export coefficients (kg/ha/y), within the area. These could in turn be used to estimate the external load to Lake Flaten, since all land cover types except one within catchment 2 were present within the lake catchment as well. The land cover class not present in catchment 2 was wetland/mire. The characteristics of this land cover class considering area specific load was however found to be similar to forest.

Since export coefficients were not available, these had to be calculated from land cover class specific parameters like standard TP concentration values (mg/l) in surface runoff and baseflow (dry weather discharge), runoff coefficients (fraction of precipitation discharged as surface runoff) and assessed evapotranspiration.

Standard concentration values and runoff coefficients differ depending on source. Finding values that fit the conditions of the particular research area is important. Standard values may be based on many case studies and thus represent a span; it is therefore important to calibrate them if possible. The following data were used to calculate land cover class specific runoff coefficients:

- Urban surface runoff concentrations and runoff coefficients (all classes except forest an meadow), adapted to Stockholm conditions, SMED/SLU (Ekstrand et al. 2003).
- Rural surface runoff concentrations and runoff coefficients SMED (Ryegård et al. 2007).
- Baseflow (dry weather discharge) concentrations elaborated from StormTac standard values (Larm 2013) to fit SMED/SLU values. They were found to be approximately a

third of the surface runoff concentrations for urban land cover and 85% for rural land cover.

Land cover features of both the Flaten catchment and catchment 2 (fig 3.10) were adapted to fit the new land cover classification. The mire in the Flaten catchment was reclassified to forest.

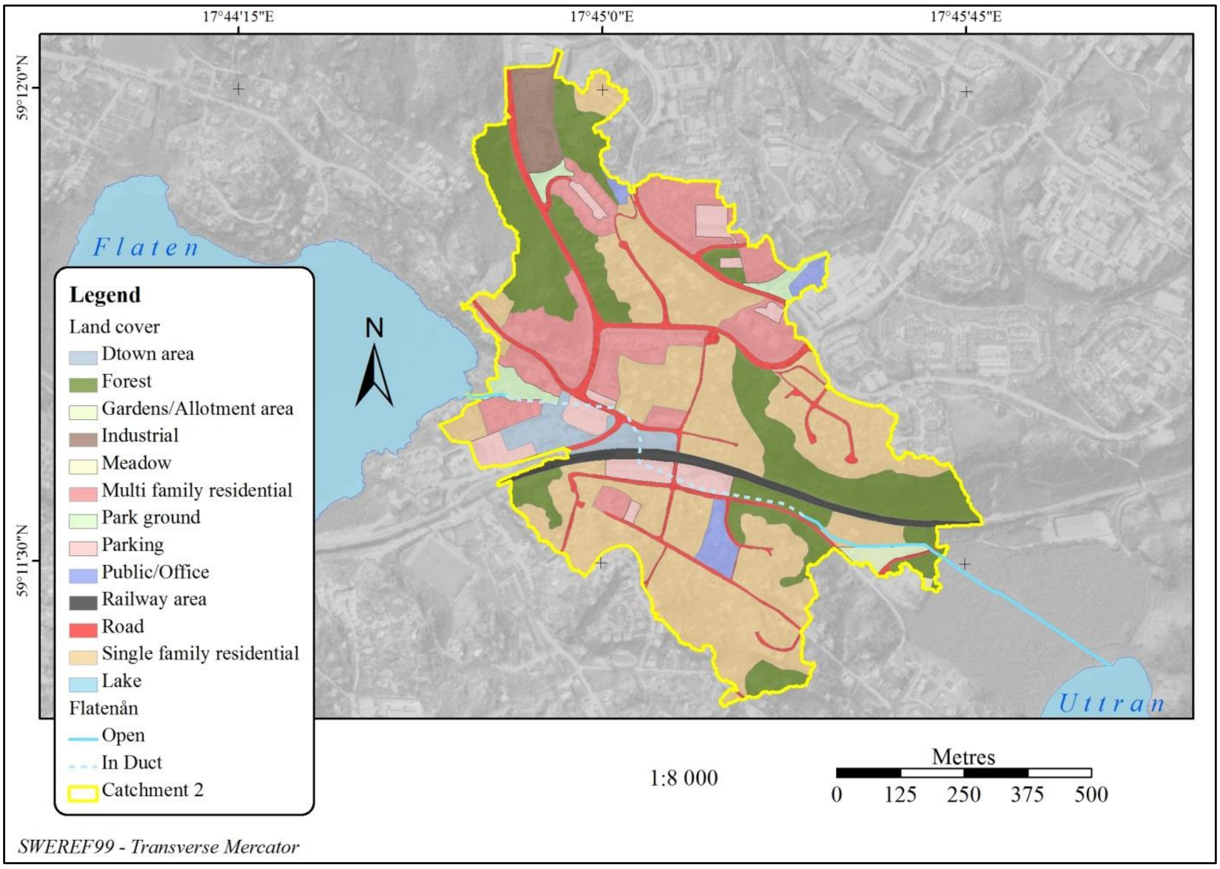

Fig 3.10: Land cover classes adapted to SMED/SLU TP standard concentrations per land cover class within catchment 2, vector approach.

The proportion of precipitation per land cover class released as stormwater or surface runoff is determined by the runoff coefficient (0 – 1); the rest infiltrates or is returned to the atmosphere as evapotranspiration.

One of the equations of the pollutant transport model StormTac calculates annual land cover class specific evapotranspiration (Larm 2000). The equation (eq 3.3) applies to all land cover classes in this study except “forest”, where a constant of 445 mm/year is used (Stenvall 2004).

$$E = 1000(0.5 - 0.55 * Coeff_R) \qquad \text{[Eq 3.3]}$$

E = Evapotranspiration intensity mm
Coeff(R) = Runoff coefficient

Not all water that infiltrates reaches a recipient. In an evaluation of the StormTac model based on case studies (Arwidsson 2011), it was found that the percolated fraction has to be multiplied with a constant of 0.7 to fit measured values.

In order to quantify the proportion of water reaching a recipient as baseflow, precipitation had to be known. Average annual precipitation from 1997-2010 (2011 and 2012 not yet available in database) was calculated by first establishing the centre of gravity for the research area and downloading the precipitation value for the coordinates from the SMHI service “luftwebb”, where monthly corrected[6] precipitation values, for any given point in Sweden, interpolated from surrounding climate stations are available (SMHI 2012b). Corrected average precipitation for the Flatenån catchment area was found to be 661 mm/ year. The proportion of precipitation per land cover class discharged from Catchment 2 as baseflow, hereafter called the “baseflow coefficient”, could now be calculated as (eq 3.4):

$$Coeff_{Bf} = (1 - Coeff_R) * (1 - (E/661)) * 0.7 \quad \text{[Eq 3.4]}$$

Coeff(Bf) = Baseflow coefficient; proportion of precipitation reaching recipient as baseflow
Coeff(R) = Runoff coefficient
E = Land cover class specific evaporation intensity (mm)

Assuming uniform long term precipitation over catchment 2, the variables deciding the difference between the land cover classes within the research area are standard concentrations, coefficients and the specific area of each land cover class. Multiplying these variables gave land cover class specific “load parameters” (eq 3.5):

$$L_p = \left[(Coeff_R * SC_R) + \left(Coeff_{Bf} * SC_{Bf}\right)\right] * A \quad \text{[Eq 3.5]}$$

L(p) = Class specific load parameter
Coeff(R) = Runoff coefficient
SC(R)= TP standard concentration values surface runoff (mg/l)
Coeff(Bf) = Baseflow coefficient
SC(Bf)= TP standard concentration values baseflow (mg/l)
A = Land cover class specific area (m²)

By dividing the class specific load parameter with the sum of all load parameters the fraction of the load from each land cover class is determined (eq 3.6). This fraction is finally multiplied with the annual total load (17.5 kg) and divided with the class specific area, resulting in export coefficients for each land cover class.

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[6] Measured precipitation is rectified to compensate for e.g. wind loss, water adhesion in measurement vessel and evaporation.

$$L_{AS} = (L_p / L_{pTot}) * 17.5 / A_{ha} \qquad \text{[Eq 3.6]}$$

L(AS) = Class area specific TP load (kg/ha/y)
L(pTot) = Sum of all L(p) within catchment
A(ha) = Area (ha)

Example forest:

Baseflow coefficient:

$$(1 - 0.05) * [1 - (445mm/661mm)] * 0.7 = 0.217$$

Load parameter:

$$[(0.05 * 0.035\ mg/l) + (0.217 * 0.030\ mg/l)] * 134\ 267\ m^2 = \ 1109.0$$

Area specific TP load:

$$[(1109.0/52820.6) * 17.5\ kg/y]/13.43\ ha = 0.027\ kg/ha/y$$

As a comparison the estimated export coefficients were also used on a national 25 metre resolution land cover grid from Lantmäteriet (Lantmäteriet 2013) produced in the year 2000, clipped with the Flatenån subcatchment feature. This was done in order to determine if available land cover data produces similar results as the manually edited data of this study.

An attempt to estimate the uncertainty span was made by testing different combinations of standard concentration values and surface runoff coefficients. At the StormTac homepage minimum, maximum and standard values for each land cover class considering standard concentration values and runoff coefficients, based on case studies (Larm 2013), are available. Using these values in different combinations (min, max or std values for concentrations and min, max or std values for surface runoff; 9 different combinations) with the methodology presented above and calibrated to the extremes (10% uncertainty) of estimated export from catchment 2 (15.75 and 19.25 kg), produced different runoff coefficients (kg/ha/y) per land cover class. While the total (15.75 or 19.25 kg) was the same for all combinations, the proportion between land cover classes varied. Using the runoff coefficients resulting from the different combinations on land cover specific areas of the Lake Flaten catchment, produced a rough estimation on the uncertainty span when using calibrated standard values in this study.

From the export coefficients retrieved with the vector approach above it was found that the area specific load from urban land cover is approximately 15 times higher and the load from “open” land cover (no grazing pastures or agricultural areas) about 3 times higher than the area specific load from forested areas. These proportions between the classes were supported by a review on studies of export coefficients in the US (Lin 2004). The raster land cover layer (LC_RS) was reclassified according to the proportion of the phosphorus load between the classes (Forest = 1, Open = 3 Urban = 15). The sum of all cell values within each subcatchment were calibrated to the estimated export from catchment 2 (eq 3.7) for estimations on the annual TP export from each catchment:

$$\frac{17.5}{sum\ catchment\ 2} * sum\ catchment\ x \qquad \text{[Eq 3.7]}$$

Another "quick as possible" approach to determine the origin of phosphorus load, independent of export coefficients, was also used with the automatically retrieved land cover grid (LCgrid_1). Since the absolute bulk of the TP load within the Flatenån catchment origin from urban areas, cells representing urban areas were reclassified to "1" while all other areas were reclassified to "0". The sum of all cells within each catchment was calibrated to the load from catchment 2 as above.

Because of the low number of land cover classes, resulting recalculation of driving variables and the fact that standard concentration values used were designed for use with homogenous vector surfaces (Ekstrand et al. 2003) the raster approaches were considered less reliable. All further calculations and scenario modelling was based on the vector land cover feature.

3.7 Estimating load from point sources

With the diffuse TP load estimated it was important to assess the contribution from point sources in order to get an overall quantification of the external load to Lake Flaten.

A Pdf cadastre map covering the research area, provided by Salem municipality, was first converted to Jpeg and then georeferenced to the aerial photograph of the area, i.e. recognizable points on the map were connected to corresponding points in the photograph which had coordinates.

Using the parcel codes of the cadastre map and corresponding codes from a survey conducted by Salem Municipality in 2008 (Bygg-och Miljöenheten 2008), sites with private sanitation systems were identified and edited as a new point feature, which in turn was clipped with the Lake Flaten catchment area to extract private sewage systems affecting the lake. According to the same survey the private sewage solutions in the area are of simpler older types (septic tanks with or without attached absorption fields), i.e. with lower reduction efficiency than more up to date facilities. All in all seven sites containing private sewage solutions were identified within the catchment (fig 3.11).

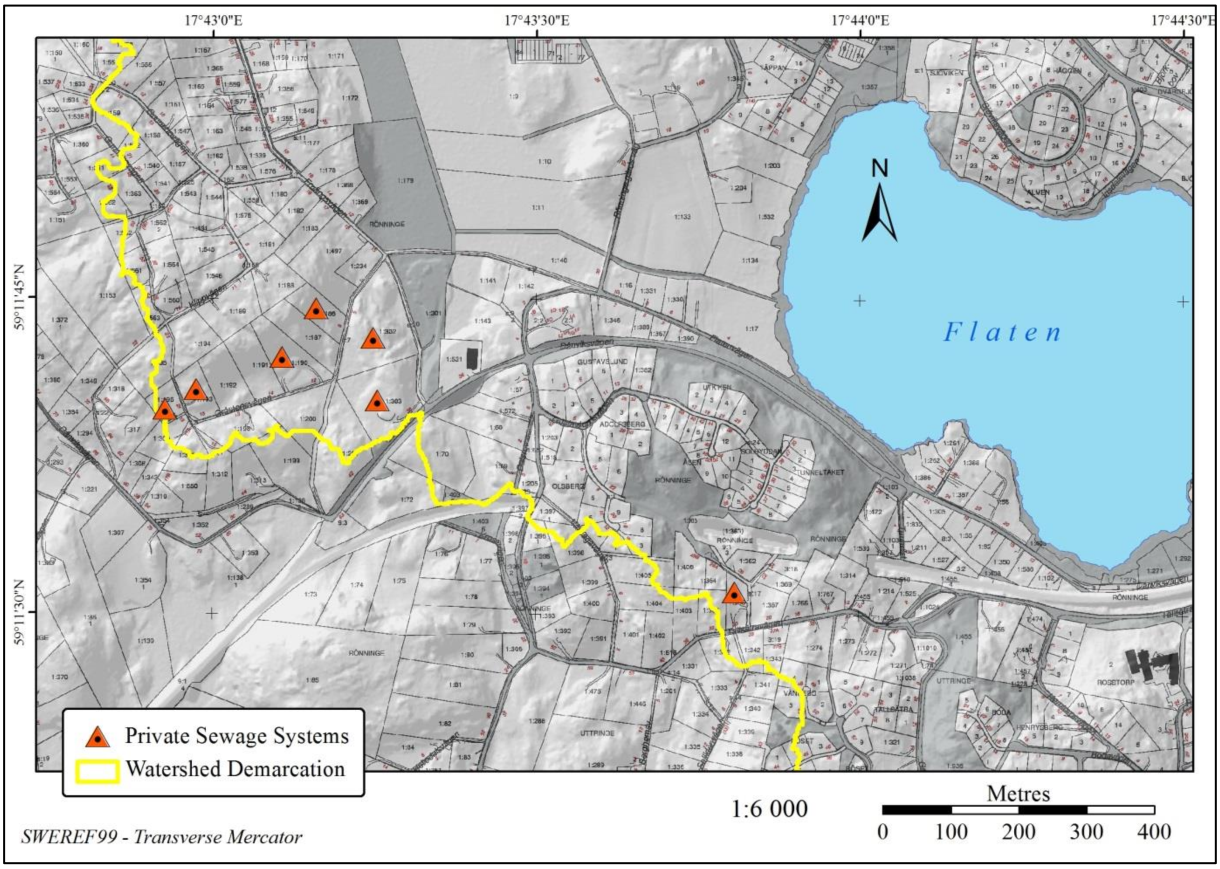

Fig 3.11: Private Sewage Systems within the Lake Flaten catchment identified from a 2008 survey, on a Salem Municipality cadastre map from 2005.

In 2010, a survey on the status of private sewage systems in Sweden was conducted by the Swedish EPA, Statistics Sweden (SCB) and the Swedish Environmental Research Institute (IVL). A poll was sent out to all municipalities in the country with the purpose of gathering information on the frequency of different types of private sewage solutions, rates of usage and update standard emission values (Ek et al. 2011). The resulting median values on the degree of rectification for different system types were complemented and calibrated with previous studies and used as standard values. According to the survey the span of TP reduction depending on type of treatment facility differs from 15 to 85 % or 15 to 50% for simpler types of facilities. Finally, the standard value for how much phosphorus every person in a household emits each day, based on the assumption that 65 % of the time is spent at home, is determined to 1.1 g (ibid.).

Most of the nutrients from private sewage systems are discharged through pipes into ditches that will eventually lead to water systems. The retention in ditches is difficult to estimate. According to a report from SLU with the objective of calculating retention in small agricultural areas without lakes, the overall retention value for phosphorus in ditches, from source to lake, is around 30%. The survey includes both emissions from point sources and diffuse leach from agricultural areas (Orback et al. 2010). According to Ekstrand et al. (2003), retention values for nutrients discharged from agriculture may apply on sewage systems as well.

Without more precise information on types of sewage facilities, all private sewage systems within the Lake Flaten Catchment were given the average retention value of the span 15-50%, i.e. 32.5% reduction.

Load per point source was calculated as:

*1.1g P per person and day * 2.6 persons per household*[7] ** 365 days * 0.675 (32.5% reduction in sewage facility) * 0.7 (30 % retention in ditches)*

3.8 Estimating internal TP load in the lake

Assessing the internal load from lake bottom sediments is important in order to fully invent the TP fluxes in Lake Flaten and to be able to predict the influence from changes in TP load on the water quality in the lake. The internal load in Lake Flaten was estimated by a mass balance approach and with a summer TP increase method.

Internal load in lakes is often associated with hypoxia (low oxygen conditions) in bottom waters (Bryhn 2008). Lake Flaten bottom oxygen levels fluctuate (fig 3.12) and there is no direct correlation between low oxygen levels and high TP levels in the water. This does not mean that hypoxia may be ruled out as a cause of internal load in the lake; many of the samples display low oxygen levels. Since Lake Flaten is a shallow round lake, oxidized water may easily be brought down to the bottom by mixing during windy conditions, which may explain the high oxygen saturation of some samples.

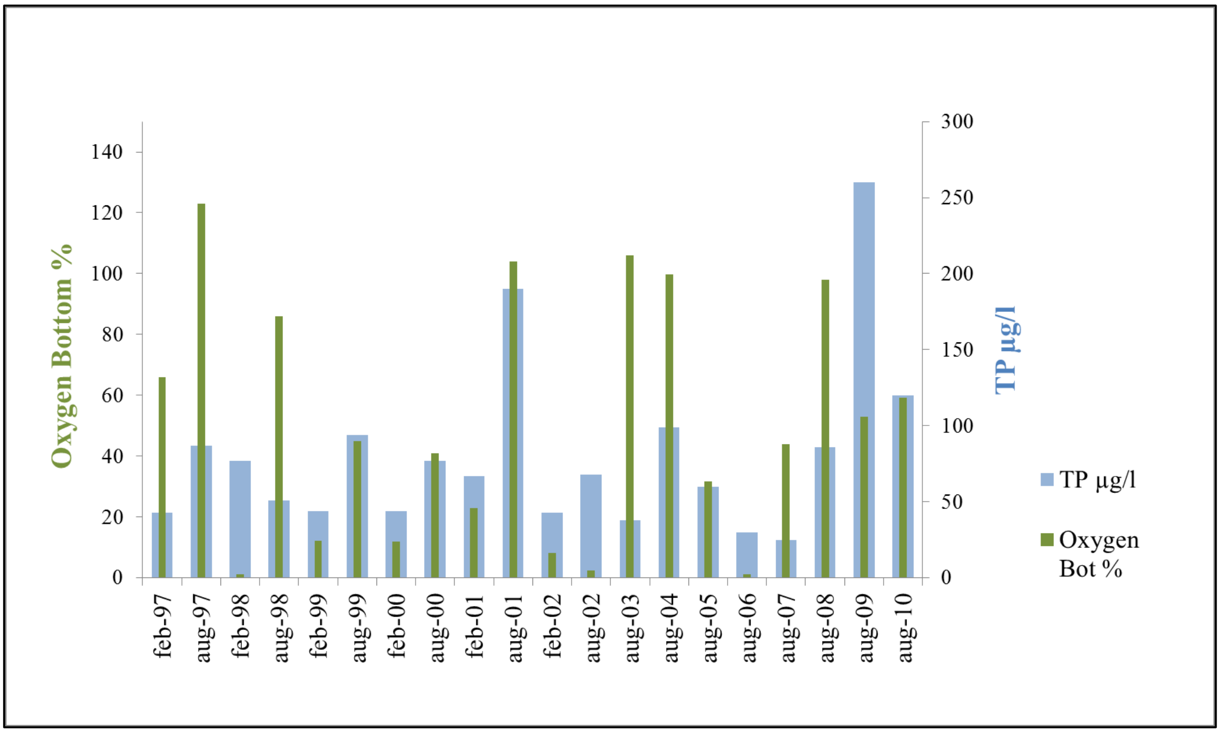

Fig 3.12: Concurrent oxygen and TP levels in the Lake Flaten bottom water, February and August samples 1997-2010.

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[7] 56% of 9.4 million citizens (Dec 2010) live in 2 million detached or terraced houses (Statistics Sweden 2012).

Summer measurements from bottom waters did however show high pH values (fig 3.13), which may cause phosphorus release from bottom sediments. This release is due to the fact that the phosphorus binding to oxidised iron common in lake sediment decreases when pH levels increase. In shallow lakes the entire water column is warmed up during summer; this triggers raised photosynthesis activity which in turn cause water pH values to increase. If the bottom sediment is loose with high water content, pH values in sediment consequently increases as well (Søndergaard 2007; Gröterud & Haaland 2007).

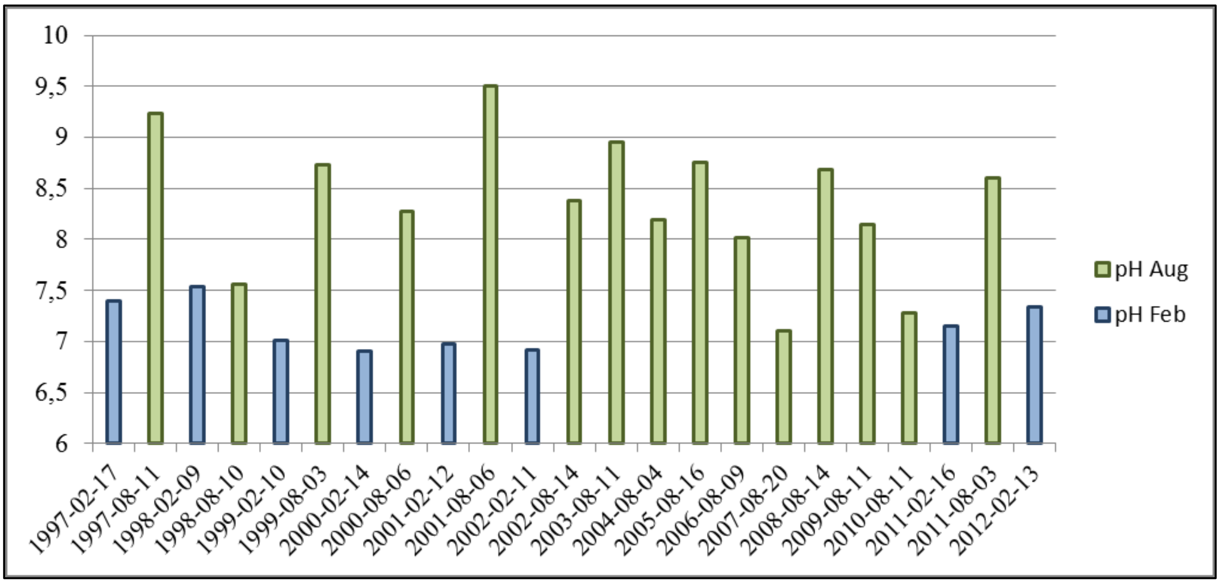


Fig 3.13: Lake Flaten bottom water pH levels, February and August samples 1997-2012.

3.7.1 Estimating the internal load with a mass balance approach

The annual external TP load and the transport from the lake had previously been estimated. In order to assess the internal load with a steady-state mass balance approach the retention capacity of the lake has to be predicted as well. This so-called retention coefficient (R) denotes the fraction of the external TP load retained in the lake through settling.

Larsen and Mercier (1976) suggests an approach (eq 3.8) for determining R with the water detention time (T(w)) as driving variable.

$$R = \frac{\sqrt{T_w}}{1+\sqrt{T_w}} \quad \text{[Eq 3.8]}$$

In the case of Lake Flaten R was estimated to 0.47 with this method.

Based on calibration of data from 93 natural lakes and 119 reservoirs in the temperate zone Hejzlar et al. (2006) suggest an optimization of the OECD lake model equation (eq 3.9)(see section 2.1.4) to determine R:

$$R = 1 - \frac{1.43}{L_{ext}}\left(\frac{L_{ext}}{1+\sqrt{T_w}}\right)^{0.88} \quad \text{[Eq 3.9]}$$

L(ext) = external load as mg/m³ of annual water flow to the lake

Using this equation R was estimated to 0.53. In the same study several R models and approaches were evaluated and tested against measured values. The two mentioned above displayed the best and similar predictive power (ibid). Given the uniformity of the results of the two estimators it was decided to use the latter since it represent newer findings and is based on a more advanced lake model.

Gertrud Nürnberg (1998) suggests two different mass balance equations (eq 3.10 and 3.11) for predicting annual TP average lake water content in shallow non-stratified lakes. Depending on if the internal load estimation is based on methods resulting in gross (measured or modelled release from sediments) or net (annual budget, i.e. gross release with resettling fraction R excluded) predictions, either of the two equations below may be used:

$$TP_l = (L_{ext} + grossL_{int}) * (1 - R) \qquad \text{[Eq 3.10]}$$

$$TP_l = L_{ext} * (1 - R) + net\ L_{int} \qquad \text{[Eq 3.11]}$$

TP(l) = Annual average lake water TP content mg/m²
L(ext) = external load as mg/m² of lake surface
grossL(int) and netL(int) = internal load from sediments mg/m²

Since all other variables are calculated, the equations may be used to predict the internal load in Lake Flaten.

The OECD lake model with calibration constants set to the same values as the Hejzlar et al. retention model (eq 3.12), treating the annual gross internal TP load as an external source, was also used to estimate the internal load in the lake:

$$TP_l = 1.43 \left[\frac{(L_{ext} + grossL_{int})}{(1 + \sqrt{T_w})}\right]^{0.88} \quad \text{[Eq 3.12]}$$

L(ext) and grossL(int) as mg/m³ of annual water flow to the lake

3.7.2 Estimating the internal load with in situ increase method

Another approach to assessing the internal load is to measure the relative increase of phosphorus from spring to summer peak. Even though measured rainfall is higher during summer months than the rest of the year, the net contribution is lower because evapotranspiration is on par of or even exceeds precipitation (see fig 3.6). Summer TP increase in water bodies without any major inlets mainly derive from internal load since overall inflow and external load is low (Nürnberg 2009).

The method for estimating internal TP load in shallow lakes comparing summer peak values (August) with beginning of high-production period (May) is referred to as the “in situ increase method” (ibid).

Assuming small differences of lake volume and surface over the period, internal load may be estimated as (all variables in mg/m² of lake surface) (eq 3.13):

$$L_{int} = (TPl_{t2} - TPl_{t1}) - L_{ext} * (1 - R) + L_{out} \qquad \text{[Eq 3.13]}$$

L(int)= Internal load
TPl= Lake water TP content
t1and t2 denotes sampling occasions 1 (May) and 2 (August)
L(ext)= Estimated period external TP load
L(out)= Estimated period TP export from lake

The mid-May to mid-August water discharge from Lake Flaten was estimated to approximately 101 000 m³ (see table 3.4). The external load from May to August was estimated as annual total load divided with annual water flow times estimated period flow (49.8 kg / 730 077 m³ * 101 000 m³); the export from the lake as average period lake water content times period discharge (61.5 mg/m³ * 101 000 m³). The external load was equivalent to 21.8 mg/m² and the export to 19.6 mg/m² of TP.

The TP increase over the period was 37 mg/m³ of lake volume or 66.6 mg/m² of lake surface.

The full equation for calculating summer internal load in Lake Flaten was:

$$L_{int} = 66.6 - 21.8 * (1 - 0.53) + 19.6$$

The summer internal load in Lake Flaten was estimated to 76.0 mg/m² or 24 kg. The estimation is partially net, i.e. the TP released from the sediment has partially resettled during the period of calculation (Nürnberg 1998).

Nürnberg suggests an average of her two mass balance equations above (eq 3.14) when a method returning a partially net estimation is used (ibid.):

$$TP_l = [(L_{ext} + partnetL_{int} * (1 - R)) + (L_{ext} * (1 - R) + partnetL_{int})]/2 \qquad \text{[Eq 3.14]}$$

3.9 Modelling scenarios

The vector land cover classification was used for modelling scenarios. All scenarios were modelled with raster overlay and zonal statistics operations. The base layers for all operations were a rasterized Lake Flaten land cover feature (diffuse load grid) and the Lake Flaten subcatchment delineation feature. The analysis extent for all operations was the Lake Flaten catchment area (lake excluded). Cell size was set to 1 metre to facilitate calculations. All resulting grids were run in a zonal statistics operation to produce tables with statistics per subcatchment.

With an estimation of the internal load it would now be possible to assess effects on water quality from different scenarios. For these estimations both the Hejzlar et al. OECD (H_OECD) and Nürnberg gross load (Ngross) equations were used (see eq 3.9 and 3.11). Since the purpose of scenario modelling was to predict the effects on lake water quality from changed external TP load, the internal load was to be kept constant during simulation. The values were set to the output of internal load prediction for each model, so that both models would be calibrated to the current annual average lake water content of 53.7 µg/l (see fig 3.8).

3.9.1 No anthropogenic impact

Forest was assumed to be the dominant land cover type of the area before human influence. By first multiplying the assessed TP export coefficient of "Forest" (0.027 kg/ha/y) with the lake catchment area of 306 ha, an estimation on the external load to the lake without anthropogenic factors was made. Secondly the estimated gross internal load was excluded when estimating lake water TP content.

3.9.2 Increased or decreased discharge

In a report on assignment for the Stockholm County administrative board a ± 15% increase of discharge is to be expected in the region before the year 2100 (Stensen et al. 2010). Assuming long term correlation and causality between flow and TP transport, the change was represented by grids with values 0.85 and 1.15, that when multiplied with the diffuse load grid made it possible to calculate TP transport changes. Effects on water quality were estimated with mass balance equations. Since the overall effects of changed discharge is predicted to be small before the year 2050 and local differences are unpredictable (ibid), this factor was ruled out when combining scenarios further below.

3.9.3 Developing wetland and removing private sewage systems

The mire to the west of the lake covers approximately seven hectares. All water from the northern part of sub-catchment 9 today passes the wetland through a ditch, but it may have a potential of retaining phosphorus if the flow might be mitigated and controlled.

The capability of retaining phosphorus in wetlands varies depending on many factors e.g. water detention time, vegetation type, water depth, area of wetland versus area of catchment etc. In a report from SMED on assignment by Swedish EPA a standard value for potential Phosphorus retention in wetlands of 45% is mentioned (Ryegård et al. 2007).

With the "Catchment_raw" feature, and an attribute search operation, the part of sub-catchment 9 above the wetland was delimited. The area was converted to a grid, and reclassified to the value "0.55", while the rest of the catchment was given the value "1", thus producing a 45% wetland retention grid.

The diffuse load grid was multiplied with the retention grid and finally summed with a zonal statistics operation.

3.9.4 Larger urban areas

Areas designated for development were checked at the Salem municipality homepage (Olsson 2012). The planned development mainly consists of detached houses and claim approximately

15 ha, which of 4 on the expense of “Meadow” areas and 11 from “Forest” areas. The development designated areas were edited and reclassified with the land cover map as a base, producing an “urban development” feature (fig 3.14) that was converted to raster. The new grid was subtracted from the diffuse load grid, producing an estimation of the size of increased TP impact due to urban development.

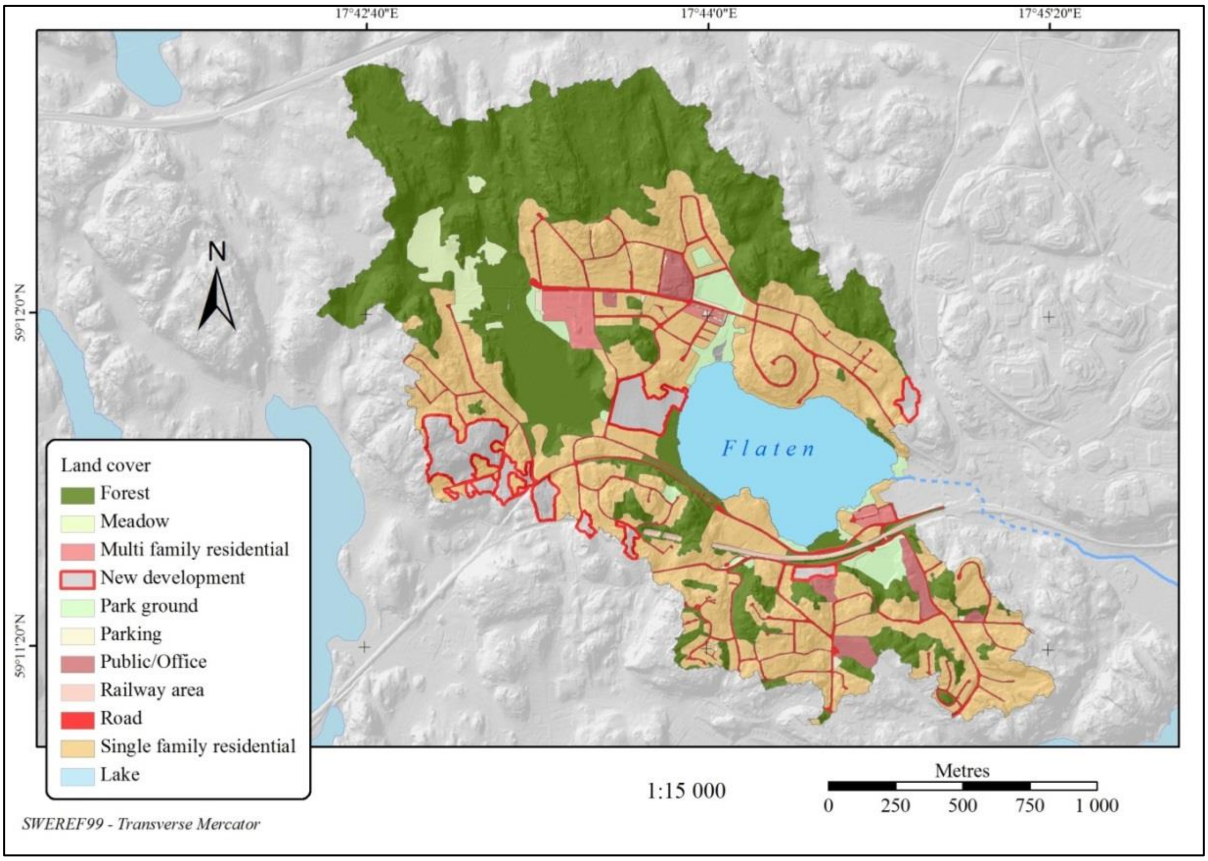


Fig 3.14: Land cover map with areas designated for urban development, Lake Flaten catchment.

3.9.5 Combination of scenarios

Since SMHI predicts that changes considering water discharge will not be dramatic the coming century this modelling parameter was disregarded. The factors included were retention in a developed wetland, removal of private sewage systems and 15 hectares of housing development. The wetland retention grid was combined with the new development grid in an overlay operation (fig 3.15).

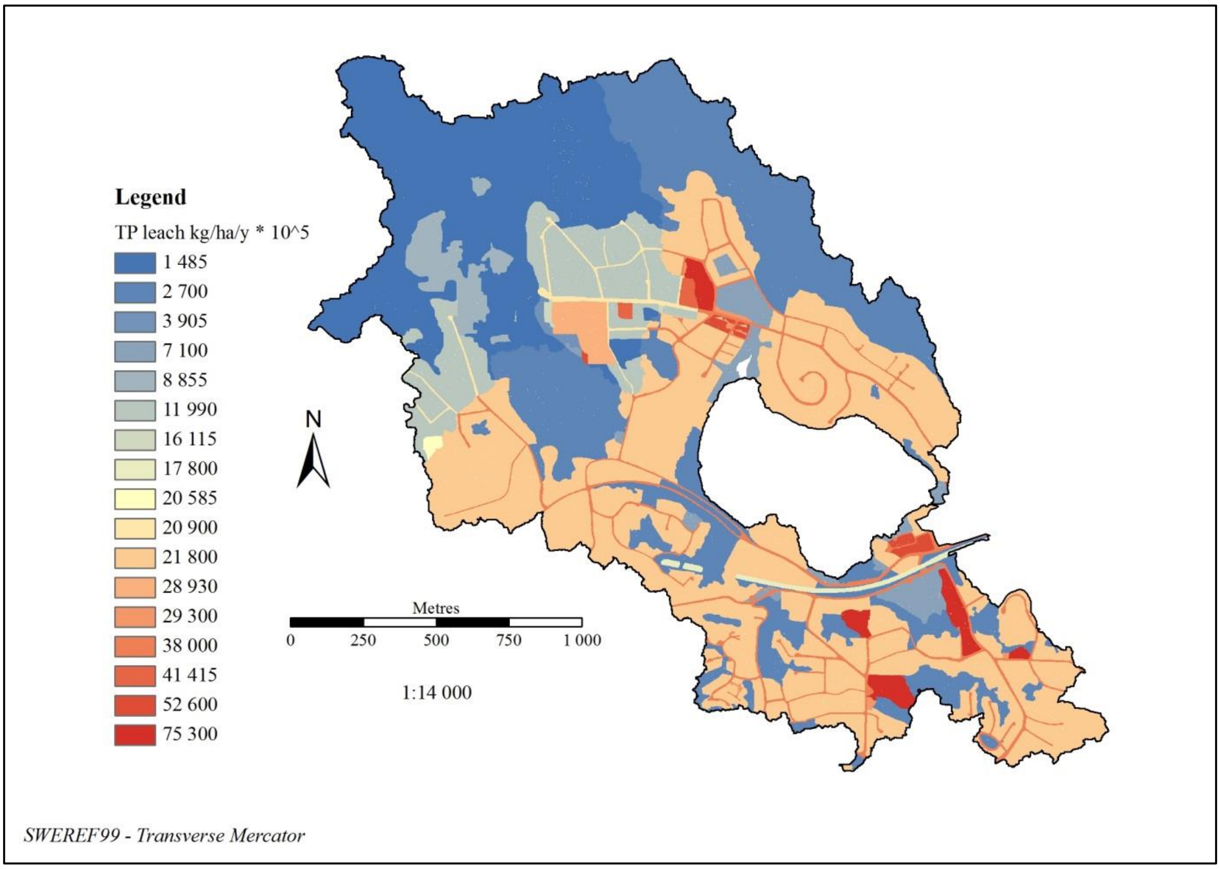


Fig 3.15: Simulation no private sewages, retention in modified wetland and new urban development; TP leach (kg/ha/y) Lake Flaten catchment.

4. Results

In this section the more important overall results of this study will be presented.

4.1 Results geographic data

The two Lake Flaten catchment demarcations were produced by exactly the same methodology but with different source material. A comparison shows overall uniformity and the area is similar (lake included): 338 ha derived from the laser-scanned DEM and 343 ha interpolated from contour lines. The major difference is the large bulge in the south-western part of the catchment (fig 4.1).

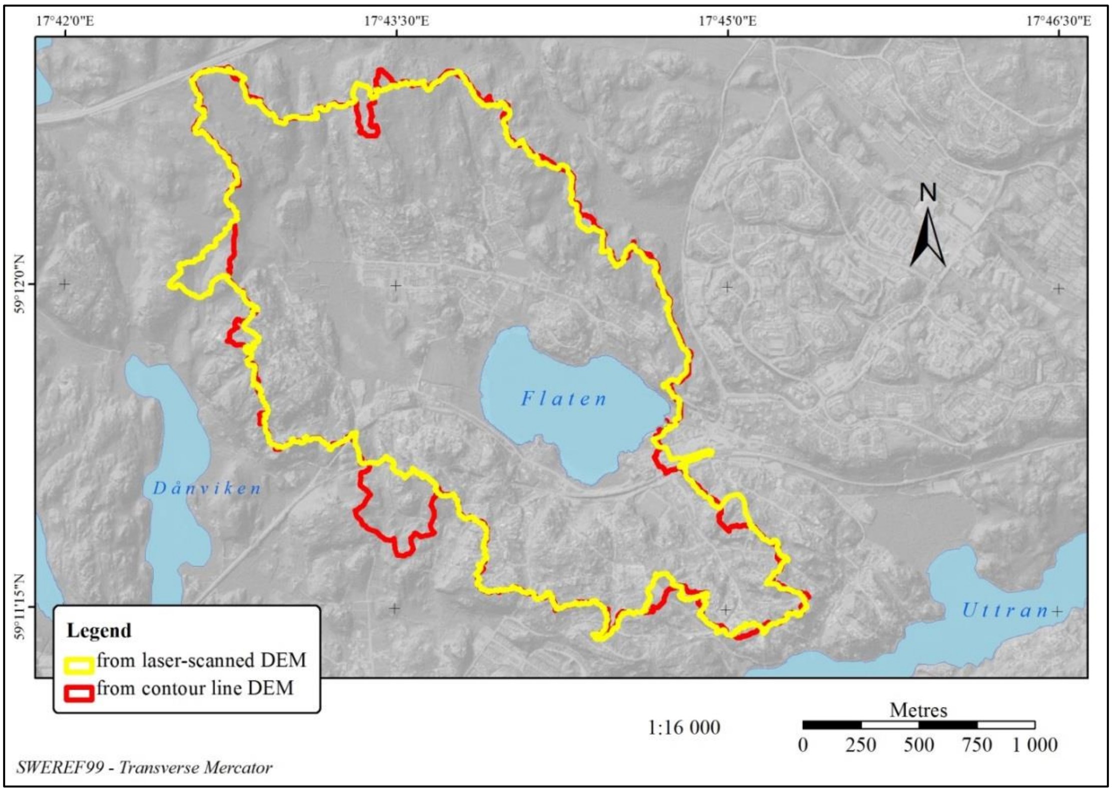


Fig 4.1: Comparison Lake Flaten catchment boundaries derived from digital elevation models based on laser scanned data and contour lines.

The quality of the vector based land cover classification was checked with a map accuracy assessment. After evaluating mapped points versus control (ground truth) in a confusion matrix overall accuracy and coefficient of agreement (Kappa) was calculated. The overall accuracy shows the probability that any given point on the map is correctly classified:

$$\frac{\sum A}{N} = \frac{45}{50} = 90\%$$

Where A= Correctly mapped points
N= Total number of mapped points

The coefficient of agreement, or Kappa, indicates the map quality in relation to chance, i.e. how much better or worse the map is than complete random mapping/assigning of land cover classes. The value span is "-1" to "1", where "0" denotes random agreement," -1" no correspondence at all, and "1" perfect correspondence between map and ground truth points.

$$\kappa = \frac{Nd - q}{N^2 - q} =$$

$$\frac{\left(50 * 45 - \left((3 * 4) + (19 * 19) + (9 * 12) + (3 * 1) + (2 * 2) + (3 * 3) + (1 * 1) + (6 * 6) + (3 * 3)\right)\right)}{\left(50^2 - \left((3 * 4) + (19 * 19) + (9 * 12) + (3 * 1) + (2 * 2) + (3 * 3) + (1 * 1) + (6 * 6) + (3 * 3)\right)\right)} =$$

$$\frac{(2250-543)}{(2500-543)} = 0.87$$

N= Total number of mapped points,

$$d = \sum A$$

$$q = \sum B * C$$

A= Correctly mapped points within each class
B= Ground truth points within each class
C= Mapped points within each class

Both the estimations on overall accuracy and kappa show high (good) results.

4.2 State of the lake indications and mass transport results

4.2.1 Estimations on the current water quality of Lake Flaten

The research period (1997-2012) estimated monthly water TP content in Lake Flaten span from 40µg/l (Apr) to 81µg/l (Aug). The annual mean content was estimated to 53.7 µg/l, and the high production season (May-Oct) mean to 60.2 µg/l.

Monthly TP averages recalculated to TSI index (fig 4.2) thus show that the lake is in a constant eutrophic state.

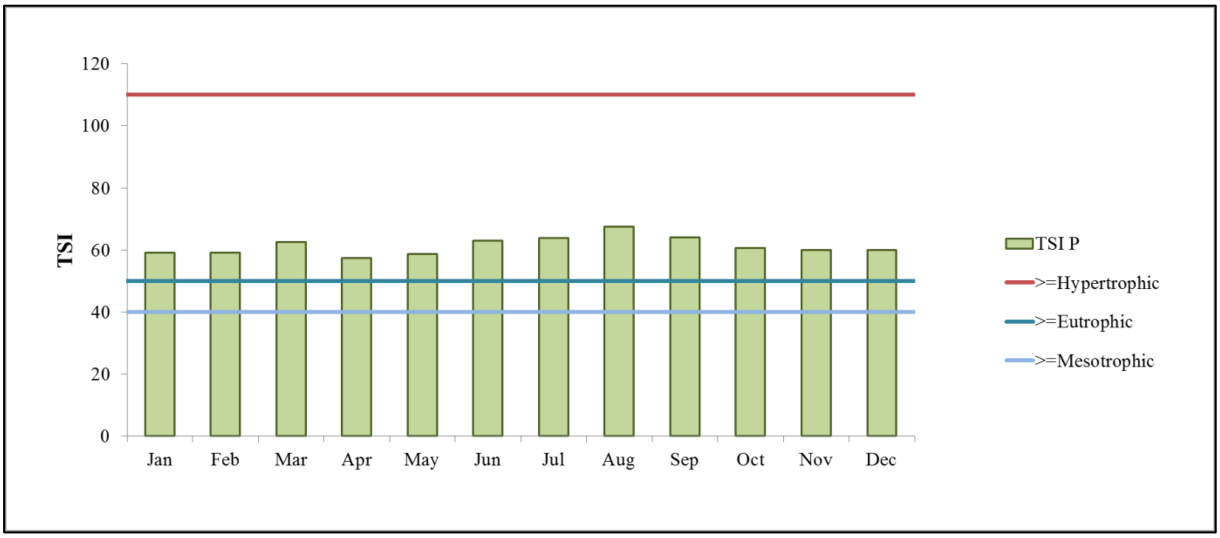


Fig 4.2: Monthly TP levels Lake Flaten recalculated to Carlson's Trophic State Index (TSI).

The ecological status value according to the Swedish EPA methodology was also calculated (see eq 2.2):

$$log_{10}(refTP) = 1.627 + 0.246 * log_{10}(0.153) - 0.139 * log_{10}(19.5) - 0.197 * log_{10}(1.8)$$

ref-TP = TP reference value
Abs = Lake water absorption 420/5 (mean of 9 Yoldia values sampled in Lake Flaten 2005-2012)
Alt = Lake surface altitude above sea level m
MD = Lake mean depth m

The reference value for Lake Flaten was calculated to 15.74.

Dividing the reference value with the measured annual average TP value (53.7 µg/l) returned the ecological status value, which was estimated to 0.29 for Lake Flaten. According to the Swedish EPA classification table (see table 2.2) the lake is in an “Unsatisfactory” state concerning in-lake phosphorus.

Lake Flaten specific threshold values (table 4.1) show that TP levels must decrease substantially in order to reach more healthy levels (“Good” or “High”).

Table 4.1: Lake Flaten specific TP level in water classification ranges, calculated with Swedish EPA classification methodology.

Class	Class threshold µg/l
High	< 22
Good	22 - 31
Average	31 - 52
Unsatisfactory	52 - 79
Poor	> 79

The average productive season water TP content in Lake Flaten was found to be high (60 µg/l). According to the Swedish EPA lakes with a summer TP average of more than 50 µg/l need “powerful measurements” in order to decrease the content to acceptable levels (Naturvårdsverket 2003).

4.2.2 Results phosphorus load to Lake Flaten and Lake Uttran

Table 4.2 show standard concentration values, runoff/baseflow coefficients and results on TP export per land cover class calibrated to an annual export of 17.5 kg from catchment 2.

Table 4.2: Land cover class specific standard concentrations, coefficients and area specific load catchment 2.

Land use	Area m²	Standard konc surface runoff SMED/SLU mg/l	Estimated standard konc baseflow mg/l	Runoff coefficient SMED/SLU	Calculated baseflow coefficient	Calibrated area specific export kg/ha/y
Forest	134 267	0.035	0.030	0.050	0.217	0.027
Meadow	570	0.200	0.170	0.075	0.198	0.161
Park grounds	11 334	0.120	0.040	0.110	0.209	0.071
Gardens/al lotment	4 652	0.120	0.040	0.110	0.209	0.071
Multi-family residential	92 094	0.300	0.100	0.450	0.238	0.526
Single family residential	246 136	0.200	0.067	0.250	0.237	0.218
Down-town area	16 558	0.350	0.117	0.700	0.173	0.879
Industrial area	16 300	0.400	0.133	0.600	0.208	0.887
Roads	48 663	0.130	0.043	0.850	0.100	0.380
Railway area	15 657	0.300	0.100	0.110	0.209	0.178
Parking	30 039	0.100	0.033	0.850	0.100	0.293
Public buildings/ offices	11 805	0.300	0.100	0.700	0.173	0.753

Multiplying area specific load values from catchment 2 with land cover areas within the Lake Flaten catchment, quantified the diffuse external TP load to the lake to 45 kg annually, based on the manually edited vector land cover data. The uncertainty span for calibrated standard concentration values and runoff coefficients, assuming a ±10% uncertainty on flow estimations, was estimated to roughly ±20%.

Using the standard concentration values and coefficients in table 4.2 without calibration returns an annual TP export from catchment 2 of 33 kg. This would mean a diffuse load to Lake Flaten of approximately 85 kg annually.

Regarding private sewage systems the result was 493g TP per source and year or an approximate 3.5 kg total load per year to Lake Flaten. Given the uncertainty on types of sewage solutions the span stretches from 2.6 to 4.4 kg annually.

Two of the Lake Flaten subcatchments previously edited contained households with private sewage treatment solutions (table 4.3).

Table 4.3: Private sewage systems (PS) per subcatchment Lake Flaten catchment.

Subcatchment	No of PS	Annual load kg	Average monthly load kg
7	1	0.493	0.041
9	6	2.958	0.246

In a report from Swedish EPA atmospheric phosphorus deposition of TP averages 4 kg per km² and year (Brandt et al. 2009). The annual deposition on the surface of Lake Flaten was thus quantified to approximately 1.3 kg. With diffuse TP load and the contribution from point sources added, total annual TP load to Lake Flaten is estimated to approximately 50 kg (table 4.4).

Table 4.4: TP load to Lake Flaten all external sources.

Load sources	Load kg
Diffuse	45.0
Atmospheric deposition	1.3
Point sources (private sewages)	3.5
Total	**49.8**

The gross internal load was calculated to 34 kg and the net to 16 kg with the Nürnberg equations (see eq 3.10 and 3.11) and a mass balance approach.

Using the OECD lake model with calibration constants set to the same values as the Hejzlar et al. retention model (see eq 3.9), treating the annual gross internal TP load as an external source, return an estimation of 40 kg (see eq 3.12).

The in situ increase method (see eq 3.13 and 3.14) estimates the gross internal load to 38 kg annually.

Based on an average of the results of the three approaches, it was concluded that the gross internal TP load in Lake Flaten is approximately 37 kg annually.

According to findings in this study the annual gross TP load to Lake Flaten is 87 (±14) kg, with 45 (±9) kg as diffuse external load, 37 (±3) kg as internal load, 1.3 kg as atmospheric deposition on the lake surface and approximately 3.5 (±2) kg as load from point sources. The TP export from Lake Flaten has been quantified to approximately 36 kg.

Approximately 60 kg of TP is annually transported to Lake Uttran from the Flatenån outlet.

Figure 4.3 below shows that the absolute bulk, about 90%, of the TP load to Lake Flaten origins from urban areas. This is not surprising given the large urban proportion of the total catchment area and the high area specific load from urban land cover classes. Since the runoff coefficients (see section 3.6) of urban land cover classes are high, another conclusion is that most of the TP load on the lake origin from surface runoff, i.e. stormwater, from these areas.

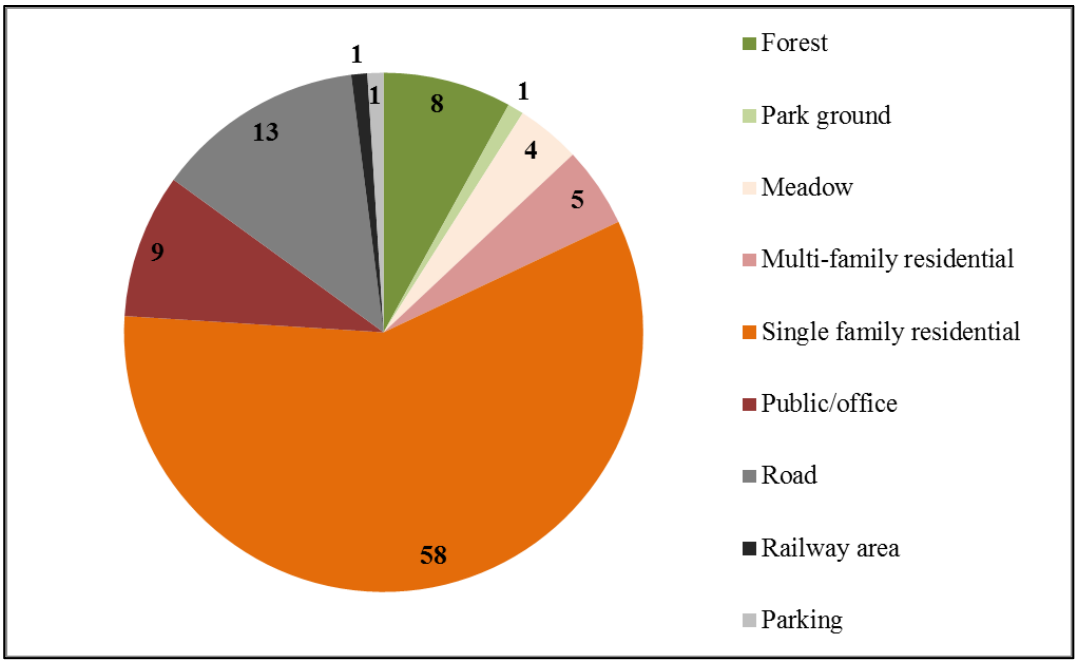


Fig 4.3: Diffuse TP load to Lake Flaten, fraction per land cover class, percent.

4.2.3 Export per subcatchment results

Using the catchment feature (see section 3.2) in zonal statistics and summarising operations, diffuse TP export from Lake Flaten subcatchments (table 4.5) and catchment 1 (see fig 3.1) was estimated with both the raster and vector approach.

Table 4.5: Diffuse TP load per subcatchment within the Flatenån catchment, vector, raster, "urban density" approaches and national 25 m resolution land cover grid from Lantmäteriet.

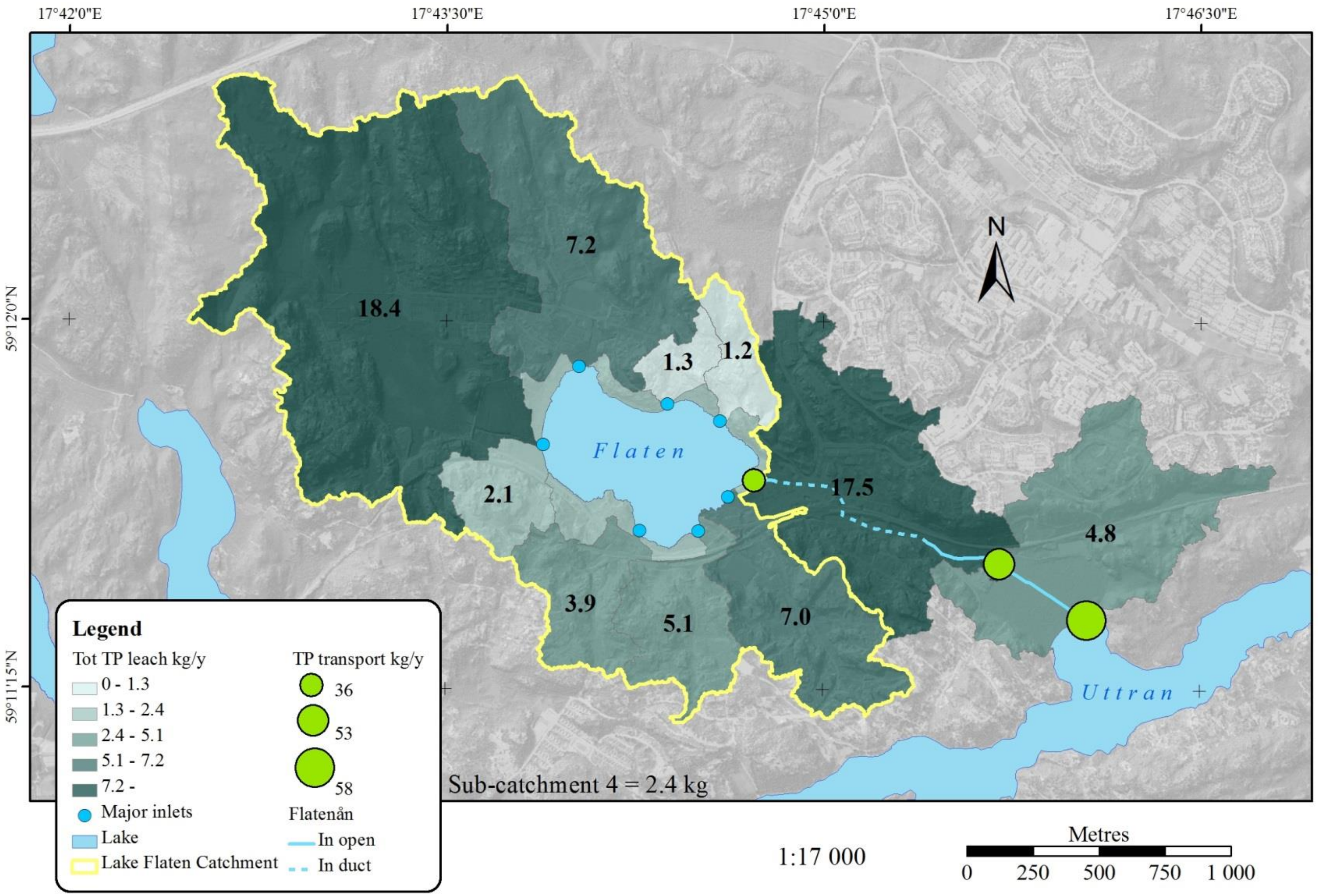
Catchment	Subcatchment	Vector land cover, kg	Raster land cover, kg	Raster Urban density, kg	Land cover grid 25 m kg
1	n/a	4.8	7.5	6.8	5.9
2	n/a	17.5 (measured)	17.5 (measured)	17.5 (measured)	14.5
Lake Flaten (3)	4	2.4	1.9	1.8	2.8
	5	7.0	9.4	9.5	6.0
	6	5.1	5.1	5.2	4.3
	7	3.4	4.0	4.0	3.7
	8	2.1	3.2	3.0	1.5
	9	15.4	15.2	12.8	16.4
	10	7.2	7.7	6.7	6.4
	11	1.3	1.3	1.4	1.2
	12	1.2	1.0	0.9	1.2
Sum Lake Flaten		45.0	48.8	45.3	43.5

The comparison show some overall resemblance between export estimations based on the four different land cover layers. There are however large relative differences considering some subcatchments.

All four identify the subcatchments with the largest TP export and the consecutive order between subcatchments is similar. As previously stated the vector approach was however considered more reliable.

Results confirm that the largest amount of phosphorus enter Lake Flaten via the ditch watering subcatchment number 9 (fig 4.4). This subcatchment is the largest surrounding the lake and contains a large proportion of urban areas as well as several households with private sewage systems. Catchments number 5 and 10 contribute with large relative amounts of TP as well; number 10 due to its size and 5 due to its large amount of relative high density urban areas (fig 4.5). Apart from the Lake Flaten subcatchments mentioned, the area between the Lake Flaten outlet and the sampling point (catchment 2) contribute with large amounts of phosphorus to Lake Uttran due to relatively high urban density (fig 4.4).

The map of area specific export (fig 4.6) confirms that the relative TP export is highest from catchments containing high proportions of urban areas, mainly the south-eastern parts of the research area, while the forested north-west contributes with smaller amounts of TP per area unit.



SWEREF99 - Transverse Mercator

Fig 4.4: Current annual TP export kg per subcatchment within the Flatenån catchment and TP transport in Flatenån

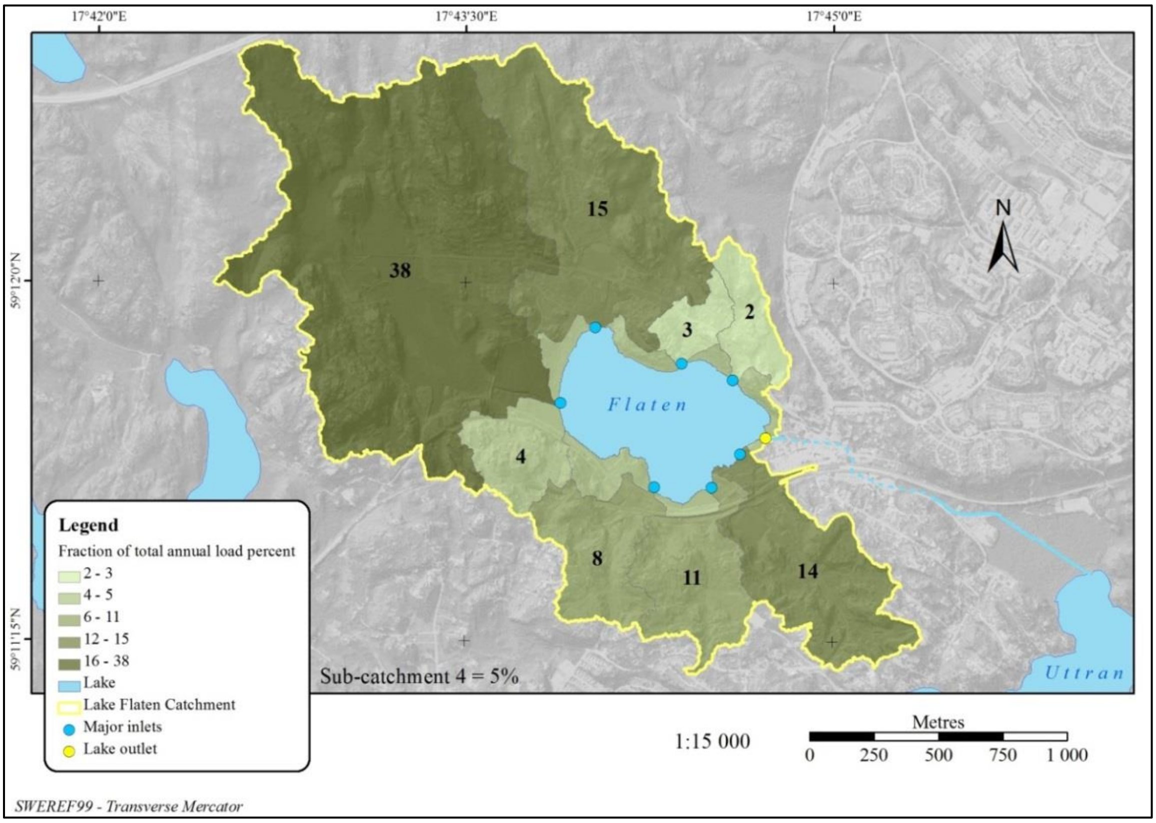


Fig 4.5: Proportion percent of total annual TP load to Lake Flaten per subcatchment.

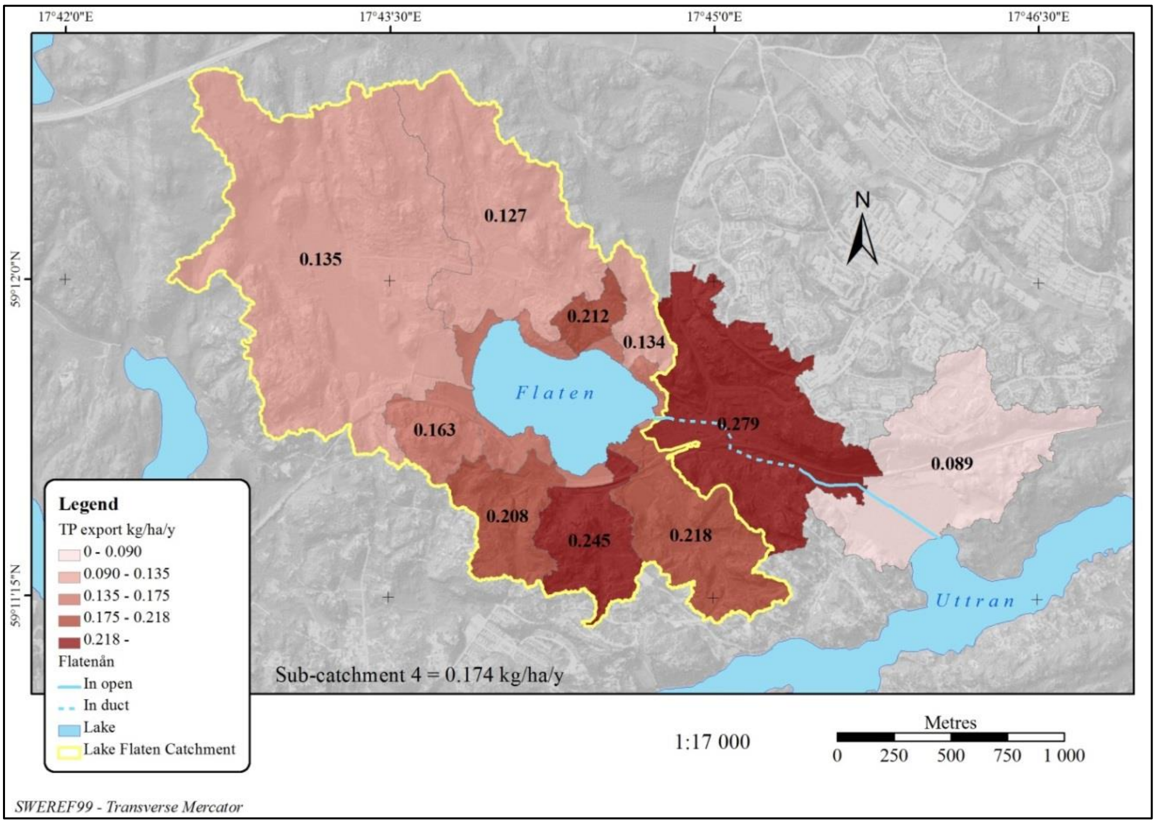


Fig 4.6: Annual TP export (kg/ha/y) per subcatchment within the Flatenån catchment.

4.3 Results modelled scenarios

Scenarios of changed water flow, urban development, removal of private sewages and use of a wetland to the west of the lake were simulated, in order to quantify the change in TP load to the lake and the effects on the water TP content (table 4.6). As with the estimation on current TP load to the lake a ± 15% uncertainty may be expected on the TP load parameter when modelling scenarios as well.

A calculated increase of planned urban development, combined with retention in a developed wetland and removal of private sewages, would lead to a decrease of the annual TP load on Lake Flaten of around 6.5 kg. The effect on water quality would be a decrease to approximately 50 µg/l of TP. Additional measures of TP leach mitigation, e.g. addressing the internal load are necessary (fig 4.7).

The external TP load to Lake Flaten should be brought down with approximately 12 kg from current level to around 35 kg annually, and the internal load from bottom sediments cease, in order to reach an annual average TP level of 25µg/l.

Table 4.6: Annual TP load and water content Lake Flaten, different modelled scenarios.

Subcatchment	**Area ha**	**Current Load**	**1. No anthropogenic impact**	**2. No private sewages**	**3. Wetland retention**	**4. Changed flow**		**5. Urban development**	**6. Combination scenarios 2 & 3**	**7. Combination scenarios 2, 3 & 5**	**8. Combination scenarios 2, 3 & 5, no int load**
						-15%	**+15%**				
Total Annual External TP Load kg		49.8	9.5	46.4	45.0	43.1	56.4	51.8	41.5	43.3	43.3
Annual Average TP Content in Lake Water µg/l (H_OECD)[8]		53.5	7.4	51.7	50.9	57.6	50.3	54.5	49.1	50.0	28.1
Annual Average TP Content in Lake Water µg/l (Ngross)[9]		53.6	7.4	51.8	51.1	57.9	50.3	54.6	49.3	50.3	28.1

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[8] See equation 3.11

[9] See equation 3.9

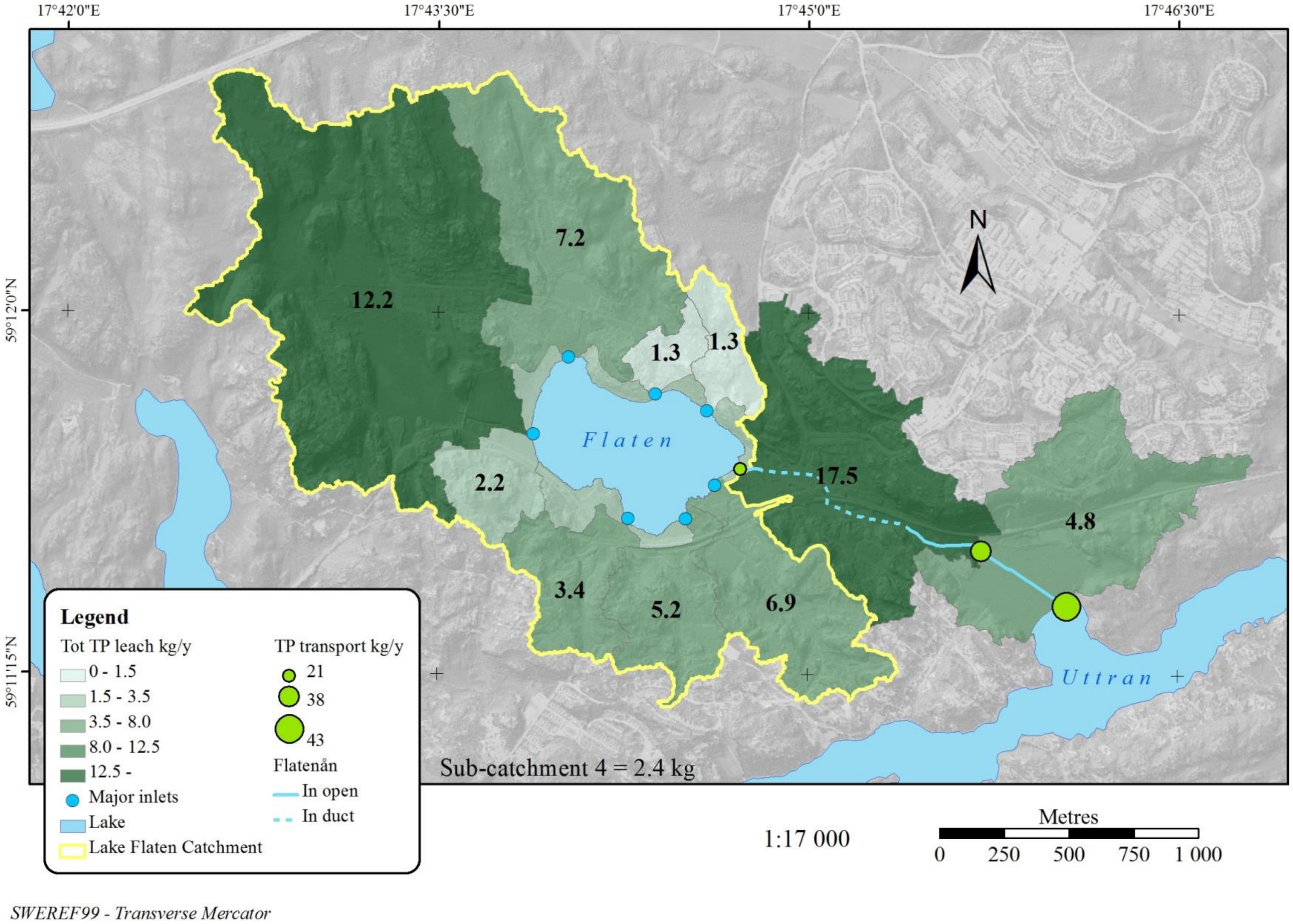

Fig 4.7: TP export per subcatchment and transport within the Flatenån catchment area. Modelled scenarios: Retention in developed wetland, no private sewages, no internal load and 15 ha of new urban development.

5. Discussion

5.1 GIS methodology

The first aim of this study was to try a GIS-based methodology for identifying phosphorus sources and estimating phosphorus transport to Lake Flaten and within the Flatenån catchment based on data collected during 16 years.

5.1.1 Generating catchments and sub-catchments

Two separate Digital Elevation Models (DEMs) were produced. The first was based on contour lines with a one metre vertical resolution provided by the Salem municipality. The landscape around Lake Flaten is broken, yet there were a couple of areas in the resulting DEM that had to be checked directly in the field since the interpolation process produced plateaus, giving uncertainties regarding the flow direction. These plateaus are a result of low vertical resolution and resulting difficulties for the software to determine slope when the distance between adjacent contour lines is too large. The second DEM was produced on a state of the art laser-scanned elevation grid. The two DEMs actually proved to be of comparable quality for the purpose of producing the overall drainage basin demarcation, despite the much higher vertical resolution of the laser-scanned data. There are however differences of significant importance; note e.g. the “bulge” on the contour-line demarcation in the south-western part of the research area (see fig 4.1), that actually contain several households with private sewage systems. Including this area would hence increase the estimated load from point sources.

Given the higher vertical resolution and the fact that it does not have to undergo interpolation processing, the outline derived from the laser-scanned DEM must however be considered more reliable.

A concluding thought is that if cost is an important factor, and digitized contour lines are available, these might be used. However, that will require knowledge on how to interpolate the data for sufficient results, software to do so, and the possibility to examine any uncertainties directly in the field. If the survey area has small relative elevation differences, there could be problems using contour lines as a base; the interpolation process would produce too many plateaus making the DEM less useful for determining flow direction and delineating catchment areas.

5.1.2 Generating land cover classes

Initially it was determined that existing available land cover data (e.g. “the topographical map” and “national 25 m land cover raster”) was too crude in relation to the large mapping scale of the research area, and that it was thus necessary to delineate land cover classes in higher detail. It did however become evident when using retrieved export coefficients on the 25 m raster that the difference in load from using the high detail vector layer was not very large (see table 4.5). The important conclusion must be that it is not necessary to manually edit land cover for this type of estimation; the available national 25m grid is sufficient. There was however large differences within some subcatchments that might be due to that the national grid is not up to date (from the year 2000), and the fact that standard concentration values, runoff coefficients and export coefficients are not adapted to the land cover delineation of this layer. Elaborating regional or national driving variables modified to the 25m national land cover grid would facilitate and speed up the process of assessing nutrient load per land cover class considerably, disregarding the mapping scale.

Disregarding the level of detail, a land cover feature must be constantly updated. This is one of the reasons why map accuracy has to be checked even though the feature is based on high-detail large-scale images; although the details on the ground are easily distinguishable and the level of pre-understanding of the characteristics of the landscape is high, land cover characteristics may change rapidly over time. One disadvantage of manual editing in high detail is that it is demanding and time-consuming. It also requires a high level of consistency regarding for instance class divisions and editing scale, as well as some knowledge about the area studied. Another disadvantage is that vector data is time consuming to update, since delineations have to be redrawn. Updating a raster layer like the national 25m land cover grid through reclassification is much faster and easier.

If time is a crucial factor, a semi-automatic process like the raster methods described above could be used. These approaches do however demand a possibility to delineate a sufficient number of separate land cover classes and reliable estimations of mass transport from the areas upon which the estimations are based. Using a true-colour image, like the one in this study with its limited multispectral range, might work if the intention is to produce just a couple of classes. The results from the two raster approaches based on aerial photographs were surprisingly true to the results derived from the vector land cover layer, and especially the “urban density” method could be used to get a quick overall estimation on the subcatchment proportions of diffuse phosphorus load within a catchment. The method could be used in areas with agricultural fields mixed with forest as well, since the export coefficient for agricultural land cover is also much higher than that of forest.

Just outside the research area of this study there were however agricultural fields that returned spectral signatures very similar to urban areas with the limited range of an aerial photograph, and therefore if included would have made a remote sensing approach more difficult. With more image material and overlays with other spectral bands e.g. false-colour infrared photographs or NIR and IR satellite bands, it would be possible to produce suitable vegetation indices and maps that better separate different types of crops and vegetation.

Finding ways to use automatic or semi-automatic methods to classify land cover when mapping in large scale could produce a usable land cover layer in hours instead of days or even weeks of manual editing.

The delineation of land cover classes is partly a subjective process based on interpretation of images, especially when editing manually. The raster methods are less sensitive in this sense; i.e. carries a small risk of a deliberate or unintentional change of priority during the rendering process that may bias the map, since the image is created in an instant.

5.1.3 Estimating load from point sources

Initially point sources, in this case private sewage systems, were not available as digitized data. Each parcel had to be identified on a cadastre map. With the map and sewage system information, the process of editing was straightforward based on corresponding parcel designations. The purpose of the 2008 Salem Municipality survey on private sewage systems was however mainly to determine whether previously ordered measures on individual facilities had been attended to, not to invent the type of facility. Information on sewage type was missing in most cases and could not be retrieved from the municipality. Since the capability to retain phosphorus fluctuates widely between different types of sewage facilities an average value for all systems had to be used. This reduced the accuracy of the point source leach estimation since the actual load from private sewages may be significantly higher or lower depending on the type of sanitation solution. Moreover the quantity of point sources is based on a survey more than four years old; some of the private sewage systems may have been modernized or connected to the common network since then.

5.2 The state of Lake Flaten

The second aim of this study was to assess the state of Lake Flaten and its contribution of phosphorus to Lake Uttran.

The average productive season water TP content in Lake Flaten was found to be high (60 µg/l). According to the Swedish EPA lakes with a summer TP average of more than 50 µg/l need “powerful measurements” in order to decrease the content to acceptable levels (Naturvårdsverket 2003). To reach the general threshold value of 25µg/l (see section 2.1.3), the average annual TP content in the water of Lake Flaten has to decrease by approximately 30 µg/l.

Since there were only measurements twice a year from Lake Flaten itself, it was important to determine whether there was a correlation between TP content in the lake and Flatenån (the creek), where monthly measurements had been made during a sixteen year long period. Monthly values were needed for calculations on annual mass transport from the lake as well as estimations on the annual average lake water content. With correlation established between TP content in the lake and the creek water, monthly TP values in Lake Flaten could be interpolated. The statistical significance was strong, which is expected since all the water from the lake pass the sampling point in Flatenån.

Occasional extreme TP values are probably caused by the overall shallowness of the lake. Wind-induced stirring of the loose bottom sediment causes phosphorus rich particles to whirl through the water column, so-called resuspension (Søndergaard 2007). If such an event coincides with a sampling occasion, the resulting TP content of that particular sample could be very high. The sample is however not representative when calculating a long term average, since the occasions are short in time and the larger particles to a great extent resist in their bound form and resettle. It was therefore decided to treat the most extreme of these peak values as outliers. Measuring dissolved fractions of phosphorus, e.g. SRP, would probably make it possible to avoid such peaks, but would on the other hand complicate assessments on transport and lake modelling since most straightforward models and estimators are based on TP measurements.

Extreme values in the creek could be due to release of TP deposited in ditches and ducts and released as a pollution pulse during heavy rains. A measurement sampled during such an event would detect high levels of TP. These events are however important when assessing mass transport.

The correlation between Flatenån and Lake Flaten is obvious, but the question is whether this correlation is adequate for drawing conclusions on monthly TP levels in the lake water? According to the linear regression analysis the answer is yes. The problem is the uneven spread in time of the lake samples. Is for instance the correlation between samples in Flatenån and Lake Flaten during February and August valid also for other months? Both these months represent low flow periods (see fig 3.6), so the influence from lake water at the sampling point might be higher than months when a larger proportion of the flow consist of storm water and surface runoff. The area between the lake outlet and the sampling point (catchment 2) mainly contains urban land cover and hard surfaces with a relatively high area specific leach of phosphorus. This might induce increased TP content in the creek water during months with high discharge, in turn biasing and exaggerating corresponding estimations of lake water content. In this sense the correlation might be valid for February and August only, and not the rest of the year.

On the other hand, the hard surfaces and large amount of storm water drains and ducts within catchment 2 mean that precipitation causes short discharge peaks. A survey conducted over a long time period, with many samples, should hence be less affected by these pulses simply because of the larger chance to pick samples during low or normal discharge when lake water influence should be larger. The exception might of course be the more constant high flow during periods of snow melt. In this sense the TP values in Flatenån reflect the values in Lake Flaten, since the chance of picking samples in the creek with high influence from the lake is higher.

The clear summer increase of TP content in Lake Flaten, even though discharge decreases, shows that large parts of the phosphorus load to the lake origins from internal sources.

According to this study Lake Flaten receives 85-90 kg of TP annually, from external and internal sources, of which approximately half is retained in the lake. The phosphorus load to the lake must decrease substantially before the phosphorus pool in the lake sediment starts to decrease.

A survey on sixteen Danish lakes (J. Jensen et al. 2006) indicates that in lakes with large internal load, it may take a long time before lake sediment phosphorus deposits are exhausted after mitigation measures on the external load have been implemented. It may therefore be relevant to attend to the internal load as well, when implementing measures to mitigate the external load. Since many of the houses that surround Lake Flaten might be older than the common sewage system, there is reason to suspect that phosphorus from untreated sewage has been deposited during a long time. The sediment TP pool may for this reason be large.

In order to assess the size of the phosphorus pool in Lake Flaten, a sediment TP sample (Yoldia Oct 2007) was converted from dry weight per kg (g/kg), to content per volume unit (g/l). The sample had a 2.2 g/kg TP content and a dry substance proportion of 4.3%; and hence a high water content of 95.7%, which pointed to a sample density very close to 1kg/l. TP content per square metre in the active upper 10 cm of sediment (Søndergaard et al. 2003) could hence be calculated and converted to content per square metre as (eq 5.1):

$$2.2g/kg * 4.3\% = 0.0946g/l = 94.6g/m^3 * \ 0.1 = 9.5\ g/m^2 \qquad \text{[Eq 5.1]}$$

If the area of bottom sediments is equivalent to of the lake surface the mass of the current TP pool in the Lake Flaten bottom sediments is approximately 3 tons.

5.3 Scenario modelling

The third aim of this study was to perform GIS-based modelling of scenarios and of measures to mitigate the effects of the phosphorus load on Lake Flaten, using a raster based approach. These scenarios include the effects of additional urban development, increased water discharge, measures to remove private sewage systems and the effect of possible altering of the wetland to the west of the lake so that it may retain phosphorus.

The two lake models used show similar results regarding change in water flow to the lake. Using calculation grids to represent increase and decrease as within this study is a basic approach, since it presupposes that the effects of changes in precipitation, evapotranspiration, temperature, growing season etc. are uniform disregarding land cover type. There is reason to assume that all these parameters will influence land cover specific flow in different ways.

The estimated load without private sewages was calculated by using the diffuse load grid. A private sewage raster had instead to be added when the current total TP load to the lake was to be calculated. Using standard point values to represent not only load per source but also retention in ditches and ducts is however a simplified methodology, as it presumes that retention is the same disregarding distance to the particular water body. With additional knowledge on these processes, distance or buffer operations could be used in order to assign the retention parameter to each point.

The possible retention in the wetland is hypothetical since retention capacity varies considerably depending on type of wetland and how it is applied and maintained. If however the retention capacity is known this catchment area approach makes it possible to quantify mitigation easily. Since this wetland might have potential considering nutrient impact mitigation, further investigation is recommended.

5.4 Future Directions and Recommendations

Since especially flow estimations in Flatenån and the assessment of lake water TP content of this study rely on interpolations, additional data would make it possible to further calibrate the results of this study, and perform a more exact assessment on the phosphorus load to the lake and the effects on water quality.

Samples from the major inlets of Lake Flaten may guarantee a much more accurate quantification on the nutrient transport to the lake, but there are some difficulties, as described below. The high detail land cover classification, both grid and vector, and catchment delineations now available, should guarantee area specific assessments if reliable measurements could be retrieved. The three largest Lake Flaten subcatchments, 5, 9 & 10, (see fig 3.1), all have inlets easily accessible and the size of the areas guarantees that as many land cover classes as possible will be represented, in turn assuring adequate standard leach concentration values or export coefficients.

There will also be a smaller risk of no flow at all during droughts, than if collecting samples at the inlets from smaller subcatchments. If more accurate automated flow proportional sampling is used very low flows may still bias the result due to e.g. sedimentation in ducts and ditches. Parts of these sedimented fractions may wash out in storm surges later, but perhaps not during the sampling period. As a consequence even though sampling is made on flow from larger areas using automated flow-weighted methods, it is still important that the sampling period is long, so that sedimented particles may have time to flush out during higher flows and storm surges.

All in all, given the difficulties retrieving reliable TP samples from small streams due to large in-water concentration fluctuations and flow irregularities, flow proportional samples collected over a long time period are recommended for a reliable assessment. If this is not possible due to lack of resources it might be better to model the transport based on existing standard values and case studies, i.e. modelled results may in this case be more reliable than a short term survey based on relatively few samples.

The constant flow of water at the lake outlet should make it possible to get a good estimation on the export from the lake. Since the water body is well mixed all year round (see section 3.4), samples collected here should also reflect the general TP content of the water; i.e. it is not necessary to collect samples in the lake itself. Combined with measurements of corrected stream velocity, mass transport from the lake could then easily be calculated. Several samples each month should be collected in order to rule out e.g. TP peaks caused by wind induction stirring bottom sediment. If concurrent TP samples and flow measurements could be collected at the Flatenån outlet into Lake Uttran as well as from the existing sampling point, reliable estimations could be made with the methodology described in this study given the rather large catchment area and good number of land cover types between Lake Flaten and the Flatenån outlet. Both these sampling points are easily accessible. Having mass transport estimations from two catchments (catchment 1 and 2, see fig 3.1) would also make it possible to better calibrate export coefficients, standard concentration values and runoff coefficients per land cover class.

A renewed survey on point sources within the catchment should be conducted. This survey must include a thorough inventory on the type of sewage facilities. With such an inventory a more precise estimation on TP load from point sources could be made. The inventory could be complemented by further studies on the phosphorus retention in ditches so that the distance from source to recipient could be included in the calculation.

Using the results of this thesis will facilitate the eventual survey that will be performed on the larger Lake Uttran the coming years, in accordance with the EU framework directive. If it will be possible to further calibrate transport and leach figures within the Flatenån catchment, export coefficients might be used for corresponding land cover classes around Lake Uttran. Since both lakes are affected by internal load (Huononen 2011) it will be important to find good estimators on this factor, as it is crucial for assessing the water quality in the lakes.

6. Conclusions

A GIS based methodology for calculating TP load and transport within and from a small catchment area in Salem, Sweden has been elaborated. TP transport within the Flatenån catchment and the impact on the water quality of Lake Flaten has been assessed by first producing sufficient catchment boundaries, land cover data, and a point source layer. Secondly water discharge, in-water concentrations, lake internal load and mass transport based on measurements have been assessed through regression analysis/interpolation and by using static mass balance lake models. Three basic approaches in order to estimate TP load to Lake Flaten on subcatchment level have been used: One based on edited vector polygons, another on a raster rendered from aerial photographs and the third based on an available national land cover grid. The methods produced similar results, but the vector method based on a larger number of land cover classes was considered more reliable, and was used for further estimations and scenario modelling.

From output of mass transport calculations and TP load to the lake, overall external load, retention within Lake Flaten and TP transport from Lake Flaten and to Lake Uttran have been estimated. Furthermore the Lake Flaten subcatchments with the highest load to the lake, both absolute and per area unit, have been identified. Against a Trophic State Index and guidelines from the Swedish EPA, Lake Flaten has been found to be in a eutrophic state with high seasonal and annual TP levels. Due to uncertainties induced by interpolated flow measurements and water content estimations, additional measurements have been recommended to further calibrate the results from this study. The results do also point to a substantial internal load from lake sediments.

Methods for predicting scenarios of changes in TP load to Lake Flaten based on projected urban development, hypothetical retention in a developed wetland, removal of private sewage systems and addressed internal load have been suggested. The overall reduction of TP from these scenarios is not sufficient in order to bring the lake water TP content down to healthy levels in accordance with the Swedish EPA guidelines. Apart from addressing the internal load, further measures to mitigate the external load than those proposed in this study will have to be implemented.

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