Norwegian University of Life Sciences

Preface

I would like to give a special thank to my supervisor Gunnhild Riise and co-supervisor Aleksandra Trnic Romarheim for your guidance, quick feedback and great patience. You have inspired me and been an invaluable support throughout my master thesis. Further I would like to thank my co-supervisors Inggard Blakar, Tore Krogstad, Johannes Deelstra (Bioforsk) and Tom Andersen (UiO) for your help, guidance and constructive comments. Johannes has been a great help guiding me through hydrological issues, while Tom has been invaluable in the MyLake modelling.

Many thanks also go to Johnny Kristiansen for your help with the GPRS logger, even though we did not get the blasted thing into the water. I guess we will work it all out later. Tuomo Saloranta at NIVA also deserves special thanks for your MyLake expertise.

To all my friends and to the good-people inhabiting the smallest study room at IPM ("kottet"), I thank you for your smiles, your laughs, and generally all the small things that makes every day durable. Especially, I thank Marte Gro for your support and company.

And, let us not forget my dear proofreader, Astri, who managed to read through my thesis, even though spring examination period was dangerously close.

And as always I would like to thank my family, my great mum and dad, and a special thanks to my two older brothers who taught me the necessity of speed when I was young and annoying. Last, but not least, I will thank ever-supporting Raptus. This autumn, we will learn the Norwegian moose how to really feel fear.

Abstract

Eutrophication is threatening freshwater and coastal marine ecosystem all over the world. Excessive nutrient supply leads to algal blooms that may develop into a toxic cyanobacteria bloom, and so reduce the utility and aesthetic value of water. Phosphorus is assumed to be the limiting nutrient for algal growth in freshwater systems and thus much restoration has focused on reducing phosphorus supply in the water ecosystems (bodies). Lake Årungen is a shallow lake, situated 33 m above sea level in SE Norway. It has been eutrophic since the 1950s, due to high runoff of nutrients from surrounding agriculture area and sewage systems. In the middle of the 1980s, much of the phosphorus supply to Lake Årungen had been reduced. Since then, despite efforts of restoration, little improvement has been seen. Models could improve our understanding and insight of how Lake Årungen responds to managerial measures, and why the present lake management today has not succeeded in improving the water quality in the lake.

The MyLake is a one-dimensional, process based model code for simulation of daily vertical profiles of lake temperature and phosphorus-phytoplankton dynamics. It is developed to make it well suited for Monte Carlo simulation, which makes the model applicable to comprehensive sensitivity and uncertainty analysis. The forcing data constitutes of meteorological data and inflow properties (e.g. inflow volume and nutrients). Even though the meteorological data is easy accessible at the meteorological station at Ås, the available inflow data to Lake Årungen are scarce.

This thesis aims to assess the data availability in the Årungen catchment with respect to runoff of nutrients and flow of water, and to evaluate the applicability and uncertainty of existing data to run the MyLake model.

With the MyLake model, lake managers may simulate how much nutrient reduction is needed to meet the goals set by decision makers, and also determine how, where and when the phosphorus reduction may have the highest impact on the lake system. This study gives an opinion on how the MyLake model may be adapted to make it well suited as a managerial tool in the restoration of Lake Årungen.

Sammendrag

Eutrofiering truer innsjøer og marine økosystemer over hele verden. Overdrevet tilførsel av næringsstogger fører til algeoppblomstringer, som kan utvikle seg til oppblomstinger av giftige blågrønnalger, og dermed redusere bruken og de estetiske kvalitetene ved vannet. Fosfor er ofte sett å være det begrensende næringsstoffet for algevekst i ferskvannssystemer, og mange innsjørestaurerende tiltak har derfor fokusert på å begrense fosfortilførselen til ferskvann. Årungen er en grunn innsjø, og ligger 33 meter over havet i sørøst Norge. Den har vært eutrof siden 1950-tallet, hovedsakelig på grunn av høy tilførsel av næringsstoffer fra omkringliggende jordbruksområdet og kloakk. Mye av fosfortilførslene ble redusert fram til midten av 1980-tallet, men har siden den gang, på tross av nye restaureringstiltak, vist liten bedring. Modeller kan hjelpe oss i å få økt forståelse og innsikt i hvordan Årungen blir påvirket av restaurerende tiltak, og hvorfor forvaltningen i dag ikke klarer å bedre vannkvaliteten i innsjøen.

MyLake er en endimensjonal, prosessbasert modellkode for å simulere daglige vertikale profiler av innsjøtemperatur og fosfor- planteplankton dynamikken. Den er utviklet til å passe bra for Monte Carlo simuleringen, noe som gjør modellen godt tilpasset krevende sensitivitets- og usikkerhetsanalyser. Innføringsdataene består av meteorologiske data tilførselsdata (for eksempel tilførselsvolum og næringsstoffer). Selv om meteorologiske data er lett tilgjengelig fra den meteorologiske stasjonen på Ås, er tilgjengeligheten av tilførselsdata begrenset.

Målet i denne oppgaven var å evaluere datatilgjengeligheten i Årungens nedbørfelt, med tanke på tilførsler av næringsstoffer og vannføring, og evaluere i hvor stor grad de eksisterende datakildene kan brukes i MyLake modellen.

Med MyLake modellen kan forvaltere av innsjøen simulere hvor mye reduksjon av næringsstoffer som skal til for å møte de mål som er satt av beslutningstakerne, men også bestemme hvordan, hvor og når reduksjonen i fosfor har størst innvirkning på innsjøsystemet. Modellen gjør det også mulig å estimere effekten av klimaforandringer. Dette viser hva som kan gjøres for at MyLake modellen kan bli et godt verktøy i forvaltning og restaurering av Årungen.

Contents

Thesaurus of acronyms

Acronym	Description
Dataset 1	Water balance and nutrient transport in the Lake Årungen catchment area 1977-1979 (Grøterud & Rosland 1981)
Dataset 2	Limnological, local water quality surveillance 1996-2009 (Løvstad 1996-2009)
Dataset 3	Mass balance studies in Lake Årungen (Gunnarsson 2007)
Dataset 4	Data from the Skuterud monitoring area (JOVA program)
DOC	Dissolved organic carbon
DIP	Dissolved inorganic phosphorus
DOP	Dissolved organic phosphorus
FIP	The mass fraction of phosphorus bound to inorganic solids (mg kg^{-1})
F_{MAX}	The saturation level describing the Langmuir isotherm used to model the equilibrium between FIP and DIP
F_{STABLE}	The inactive fraction of phosphorus firmly bound in the particles
JOVA	The Agricultural Environmental Monitoring Programme in Norway.
MyLake	Multi-year simulation model for Lake thermo-and phytoplankton dynamics
NAO	North Atlantic Oscillations
P-AL	Ammonium acetate lactate extractable phosphorus
PIP	Particulate inorganic phosphorus
POP	Particulate organic phosphorus, assumed proportional to chlorophyll
PP	Particulate phosphorus
P_{SAT}	Half saturation level inorganic phosphorus concentration used to model the equilibrium between FIP and DIP
SIP	Suspended inorganic particulate matter
The Water Regulation	The Norwegian framework regulation on water management
Tot-P	Total phosphorus
TRP	Total reactive phosphate
WFD	The Water frame directive; Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy
z_{max}	Maximum lake depth
z_{mean}	Mean lake depth

1 Introduction

Eutrophication is one of the foremost problems threatening freshwater and coastal marine ecosystems (Schindler 2006). Eutrophic lakes are often characterized by having a large external supply of nutrients, leading to a high primary production, and high sedimentation rate of organic particles. High primary production can lead to bad taste/smell of the water, and may develop into toxic algae blooms (Reid et al. 1990). Particularly many lakes near populated areas have undergone eutrophication, and lakes that are natural eutrophic from natures side, are typically highly eutrophic today (Carpenter et al. 1998; Morand & Briand 1996). Even though signs of eutrophication in freshwater lakes have been recognised since the early post-war period, it was not until the 1960s that researchers began to link algal blooms with excessive nutrient supply from the catchment area. Phosphorus, and in some cases nitrogen, was discovered as the limiting factor controlling algal growth (Vollenweider 1968), as was later rather elegant demonstrated in the Experimental Lake Area (ELA), north-western Ontario, in 1968-1973 (Schindler 1974). In the beginning it was believed that eutrophication was an unrecoverable state, but was disproved by Edmondson (1970) who documented that eutrophic Lake Washington recovered rapidly after diverting sewage from the lake. Recent debate have again focused on how universally limiting phosphorus really is for algal growth in freshwater systems. Even so there is substantial evidence of its importance in many lakes.

With implementation of the EU Water Frame Directive (WFD 2000), an increasing awareness of water quality has spread across Europe. The WFD is a legislative act, committing the members of the EU to achieve good qualitative and quantitative status for all water bodies by 2015. Objectives for all water bodies are defined based on ecological status. The five ecological classifications (high, good, moderate, poor and bad) use biological, as well as chemical, physico-chemical and hydromorphological parameters, to estimate the status of the given water body (WFD 2000). Even though Norway is not a part of the EU, the WFD is incorporated in the legislation of the European Economic Area (EEA). The Norwegian framework regulation on water management incorporates to a large extent the WFD into Norwegian law (The Water Regulation 2006). The five ecological classifications of ecological status that is used in the EU, are also applied in Norway (The Water Regulation 2006).

Other physical and chemical factors may have large influence on a lake's trophic state. Temperature and water supply, and thus nutrient supply, particulate transport and water residence time, are among the most important factors affecting water quality in Lake

Årungen. Besides nutrients, phytoplankton growth is to a great deal determined by the CO_2 level, pH, dissolved oxygen, light and temperature, where the two last factors usually are the two most important (Khan & Ansari 2005). Lake temperature is important in determining the ecological and trophic state for several reasons. As well as controlling microbial decomposition rate of organic matter, water temperature also controls the growth rates of phytoplankton, epiphytes and macrophytes (Wade et al. 2002; Whitehead & Hornberger 1984). Temperature is the main factor determining stability of lake stratification. Like most Norwegian lakes (Økland & Økland 2006), Lake Årungen is dimictic, i.e. it has two periods of stratification and two periods of circulation every year. The periods of stratification takes place when temperature-derived density differences prevent the mixing of the epilimnion and the hypolimnion, creating a layer in between that is characterised by rapid drop in temperature. Changes in wind and air temperature regimes can affect the stability of lake stratification. During stagnation episodes, decomposition of organic matter can lead to anaerobic conditions, especially in and just above the sediment, which in turn will affect the redox potential (Christophoridis & Fytianos 2006). If phosphorus is bound to organic aggregates or mineral particles (e.g. iron complexes) in the sediments, it can be released back to the water when iron is reduced to a more mobile state (Sundareshwar & Morris 1999). A situation of positive feedback can therefore occur, as resuspension leads to increased algae growth, which again may increase the probability of reducing conditions in the sediments. Many eutrophic lakes today have problems with internal phosphorus loading from anoxic sediments (Schindler 2006). Residence time can also influence growth rate of algae by affecting the nutrient (and algae) sedimentation rate, where higher residence time has been linked with enhanced potential for toxic algal blooms (Whitehead et al. 2009).

The complexity of nature is unquestionable, and the need for a simplistic way of estimating effects of climate and nutrient supply is obvious. The numerical model MyLake functions as such a solution. Mathematical models have become an important part of applied sciences, and an increasing use can be seen in most scientific fields (Blunden & Indraratna 2000; Chau 2003). Models are invaluable as a tool in management, since this represent a way to test, estimate and evaluate issues, aims and measures without the need of major actions. MyLake (Multi-year Lake simulation model) is a one-dimensional, process based model code (Saloranta & Andersen 2007). The model simulates daily vertical profiles of lake temperature, and thus simulates density stratification and evolution of seasonal lake ice and snow cover, as well as phosphorus-phytoplankton dynamics. The MyLake is developed to make it well suited for Monte Carlo simulation, which makes the model applicable to comprehensive sensitivity and uncertainty analysis (Saloranta & Andersen 2007). MyLake focuses mainly on the most important biological, chemical and physical processes, and is very fast to run. It is a simple and transparent model, but will in contrast to a much simpler Vollenweider type model, give the executer better information of responses to nutrient input in the lake system (Saloranta et al. 2009). Originally developed for the THERMOS-project (Lydersen et al. 2003), the model has later been used in another Norwegian lake system, Lake Vansjø-Storefjorden, with good results (Saloranta 2006; Saloranta & Andersen 2007).

Even though most Norwegian lakes and rivers have good water quality compared to much of Europe's surface water (for status of water bodies in the EU, see http://www.eea.europa.eu/themes/water/mapviewers/water-live-maps/status-of-water-bodies), eutrophication is often a problem in areas with dense population and / or much agriculture (Bechmann et al. 2005a; Ulen et al. 2007). Lake Årungen is a dimictic lake in SE Norway, and has during the past 50 years been highly eutrophic, mainly due to high runoff of nutrients from surrounding agriculture and sewage systems (Borch et al. 2007). The phosphorus supply was especially high from the 1960s to the middle of the 1980s, resulting in high concentrations of phosphorus in the lake. The mean total phosphorus (Tot-P) concentration (May-September values) in the period 1962-1984 was 127-400 µg Tot-P (Skovgaard et al. 2009), which is extremely high for Norwegian conditions. Since the late 1970s, several counter measures have been conducted to improve the ecological state of Lake Årungen. This includes measures such as higher sanitation standards, improved use of fertiliser and reduced tillage in agricultural areas, and reduced use of soap and detergents containing phosphorus, and 1997-2001 four retention ponds were build in the catchment area. During the period 2004-2006 an extensive exploitation of large sized pike (*Esox lucius*) prone to cannibalism was conducted (Sharma & Borgstrøm 2008). After 1985 the concentration has been significant lower, and has rarely been above 55 µg Tot-P (Skovgaard et al. 2009). Even though the original goal was to achieve good ecological status by the year 2015, the water quality of Lake Årungen is still bad according to standards set by the Norwegian Climate and Pollution Agency (Skovgaard et al. 2009). Because of high level of recreation activities, it has at municipality level been agreed that the objective is to get water quality suitable for recreational use, like swimming, in eight out of ten summers (Borch et al. 2007). This corresponds to a Secchi depth of about three meters and a maximum average phosphate concentration of 15 µg Tot-P l^{-1} (Borch et al. 2007). Despite measures to reduce external loading of phosphorus, algae blooms are still a common problem during the summer period (Romarheim & Riise 2009).

Through the recent years of Lake Årungen restoration, it has become clear that more information about the dynamic interactions between climate, catchment area and the lake pool is needed if further restoration shall be successful. Through the MyLake model decision makers can get a better insight of the timing and effects of thermal processes and nutrient supply, which is crucial in determining trophic status and phosphorus-phytoplankton dynamics (Saloranta 2006). The model needs four types of data input; meteorological data, inflow characteristics, lake morphology, and initial lake values. Among these, good time series of inflow characteristics are often the most expensive and time consuming to measure.

Therefore, the aim of this thesis was to (1) assess the data availability in the Årungen catchment with respect to runoff of nutrients and flow of water, and to (2) evaluate the applicability and uncertainty of existing data to run the MyLake model. Among the available sources of data is the Skuterud catchment, a small catchment area within the Lake Årungen catchment area and part of the Agricultural Environmental Monitoring Programme (JOVA) in Norway. A special effort will be made to analyze the applicability of these data. Based on results from the model run, I further aim to (3) make an opinion of what that is required before the MyLake model can be used as a managerial tool in Lake Årungen.

Based on these aims, this thesis will give a detailed description of MyLake model, how it is used, and what that is required to run it. Further, the applicability of different sources available data will be revised, and the uncertainty of every data set will be discussed. With the most extensive and complete time series data, data from the Skuterud monitoring area, an example of how MyLake can be used in Årungen will be shown. This will include how to recalculate raw data to make it suitable to use, as well as discussing the results of the model run and comparing them with actual *in situ* measurements taken in Lake Årungen.

2 Material and methods

2.1 Study area

Lake Årungen (figure 1) is a shallow (A = 1.2 km^2, z_{mean} = 8 m, z_{max} = 13.1 m) eutrophic lake situated 33 m above sea level in SE Norway (59°41′N and 10°45′E). Five streams (table 1)[1] run into the lake from the 51 km^2 drainage area, consisting of cultivated agricultural areas (53%), forested areas (34%), populated areas (10%) and water (3%). An area of 4.3 km^2 drains directly into the lake, or via smaller stream with marginal catchment area. The whole area is situated below marine sea level (33-160 m above sea level) and large parts consist of marine clay deposits. Lake Årungen is a dimictic lake with short water residence time (0.4 yr), and is because of its morphology and catchment area topography very exposed to wind (Hexum 1963). Bølstadbekken is the largest inlet stream to Lake Årungen (50 % of total water inflow), and about 42 % of the annual phosphorus supply to Lake Årungen is transported in this stream (Borch et al. 2007). The stream originates in the small (A = 0.4 km^2, z_{mean} = 2.5 m, z_{max} = 7 m) and highly eutrophic Lake Østensjøvannet in the eastern part of the Lake Årungen catchment area. The outlet river of Lake Årungen, Årungselva, ends up in Bunnenfjorden, the innermost part of the Oslofjord.

The mean annual temperature at the study area is 5.3°C, and varies from -4.8 °C in January to 16.1 °C in July, while the mean annual precipitation is 785 mm, and varies from 35 mm in February to 100 mm in October (Thue-Hansen & Grimenes 2009). These data is based on standard mean values from the period 1961-1990, and is achieved from the meteorological station at Ås (59°66′N and 10°78′E; available at "http://www.umb.no/fagklim/artikkel/meteorologiske-data-for-as").

Figure 1. A map of Lake Årungen and the catchment area. The Skuterud area is highlighted with red. Adapted from Borch et al. (2007).

[1] Brønnnerudbekken is a small stream that runs together with the stream Vollebekken just before Vollebekken reach Lake Årungen, and phosphorus data from Brønnerudbekken and Vollebekken is sampled separately. Because of this, Brønnerudbekken will be concluded with the other Lake Årungen inlet streams in this study.

Table 1. Size (km^2) and contribution of water (%) of the Lake Årungen six main sub-catchment areas, in addition to the residual areas which is drained by no stream. After Gunnarsson (2007).

Stream	Sub-catchment area (km^2)	% of total water inflow
Bølstadbekken	25.2	50
Storgrava	8.3	17
Smebølbekken	7.2	15
Norderåsbekken	2.7	6
Vollebekken	2	4
Brønnerudbekken	0.8	2
Residual areas	4.3	6

The Skuterud area (JOVA program) is situated 91-145 m above sea level SE in the Lake Årungen catchment area (figure 1). For a detailed description of the Skuterud area see Deelstra (2005). JOVA is a national monitoring program, with the objective to document the effects of various agricultural practices on the environment, which again form the basis of some of the measure analysis that is central in the Water Regulation. The 4.5 km^2 large area, consisting of cultivated agricultural areas (60.5%), forested areas (29%), populated areas (8.5%) and marshland (2%), is chosen to represent grain growth in SE Norway. Monitoring at the Skuterud area started in 1993. The stream Skuterudbekken drains the Skuterud area into Lake Østensjøvannet, and a monitoring station is placed in the lower part of Skuterudbekken just above the inlet of Lake Østensjøvannet. A 2300 m^3 retention pond was established upstream of the station in 2000, and in 2002 another water sampler was placed upstream of the retention pond. The sampling system is based on a volume proportional water sampler collecting composite samples.

2.2 The MyLake model

Originally thought of as a model for thermal modelling in lakes, MyLake was first applied in the THERMOS-project (Lydersen et al. 2003). The process based model code simulate daily vertical distribution of lake water temperature, density stratification and evolution of seasonal lake ice and snow cover, which makes it well suited for Norwegian conditions. Later versions also simulate of daily vertical profiles of phosphorus-phytoplankton dynamics (Saloranta & Andersen 2007). In this thesis the MyLake v.1.2 model code version were applied. The seven main variables that are simulated by the model are summarized in table 2. The tracers, one dissolved and one sedimenting, are conservative, and take no part of the reactions, thus they can be used to study transport processes by the MyLake model. The model input forcing data and initial profiles are summarized in table 3. As the table shows, dissolved inorganic phosphorus (DIP) and particulate inorganic phosphorus (PIP) is not among the inflow force data, but are calculated by MyLake. The sum of DIP and PIP is determined by the Tot-P concentration, not including particulate organic phosphorus (POP), which is assumed proportional to chlorophyll, and dissolved organic phosphorus (DOP), which is assumed to be conservative. The concentration of PIP is further determined by the mass fraction of phosphorus bound to inorganic solids (FIP). An equilibrium partitioning between FIP and DOP is assumed, which is modelled using a Langmuir isotherm approach. FIP is modelled based on the saturation level (F_{MAX}) and the half saturation level inorganic phosphorus concentration (P_{SAT}) (describing the Langmuir isotherm), and the inactive fraction of phosphorus firmly bound in the particles (F_{STABLE}). F_{MAX}, P_{SAT}, and F_{STABLE} are values of the model parameters (Saloranta & Andersen 2007).

Table 2. Main model state variables simulated by the MyLake model. Conservative tracers imply no involvement in any reactions, save for sedimentation.

Variable	Comment
Temperature	
Dissolved tracer	Conservative
Suspended inorganic particulate matter	Conservative sediment tracer
Dissolved inorganic phosphorus	Algae available phosphorus
Phosphorus bound to inorganic particles	
Dissolved organic phosphorus	
Chlorophyll	

Table 3. MyLake input forcing data and initial profiles.

	Variable	Unit
Meteorological and inflow data	Global radiation	MJ m^2 day^{-1}
	Cloud cover	(0-1)
	Air temperature at 2 meter height	°C
	Relative humidity at 2 meter height	%
	Air pressure at station level	hPa
	Wind speed at 10 meter height	m s^{-1}
	Precipitation	mm day^{-1}
	Inflow volume	m^3 day^{-1}
	Inflow temperature	°C
	Inflow concentration of passive tracer	-
	Inflow concentration of suspended matter	kg m^3 day^{-1}
	Inflow concentration of total phosphorus	mg m^3 day^{-1}
	Inflow concentration of dissolved organic phosphorus	mg m^3 day^{-1}
	Inflow concentration of chlorophyll *a*	mg m^3 day^{-1}
	Inflow concentration of dissolved organic carbon	mg m^3 day^{-1}
Bathymetry and initial profile	Horizontal areas	m^2
	Initial profile of temperature	°C
	Initial profile of passive tracer	-
	Initial profile of suspended matter	kg m^3
	Initial profile of total phosphorus	mg m^3
	Initial profile of dissolved organic phosphorus	mg m^3
	Initial profile of chlorophyll *a*	mg m^3
	Initial profile of dissolved organic carbon	mg m^3
	Initial profile of sediment store of total phosphorus	mg m^3
	Initial profile of sediment store of chlorophyll *a*	mg m^3
	Initial sediment solids volume fraction of inorganic matter	-
	Initial value of total ice thickness	m
	Initial value of snow thickness	m

The MyLake model code is developed at the Norwegian Institute for Water Research (NIVA) by Andersen and Saloranta (MyLake version 1.0; 2003 unpublished). Unlike many existing one-dimensional lake model codes, the MyLake is well fitted for Monte Carlo simulation (Saloranta & Andersen 2007). Monte Carlo simulations are non-deterministic methods used to solve mathematically problems which are not easily solved by other numerical methods, and relays on repeated sampling of random or pseudo-random numbers. This makes the model suitable to comprehensive sensitivity and uncertainty analysis (Saloranta & Andersen 2007). The MyLake is a simple model, and hence focuses on the most important physical, chemical and biological processes in a robust and balanced way (Saloranta 2006). A schematic illustration of the flow between the main state variables is given in figure 2. The model is script based and coded in MATLAB (www.mathworks.com). As described by Saloranta and Andersen (2007), adopted from Riley and Stefan (1988), the MyLake model code aims to (1) be general enough to be used at multiple sites with minimum need of alterations, (2) be capable of simulating a wide range of treatment options, (3) incorporate the dominant physical, chemical and biological processes, and especially those directly affected by treatment options, (4) reduce weak links in the modelling process by ensuring that the physical, chemical and biological components of the model are being modelled with similar orders of detail, and (5) be economical enough to be used as a management tool. The MyLake model has already been applied both in several Norwegian (Lydersen et al. 2003; Pedersen 2007; Saloranta 2006) and Finish lakes (Kankaala et al. 2006; Saloranta et al. 2009). For further description and set up of the MyLake model, see Saloranta and Andersen (2004).

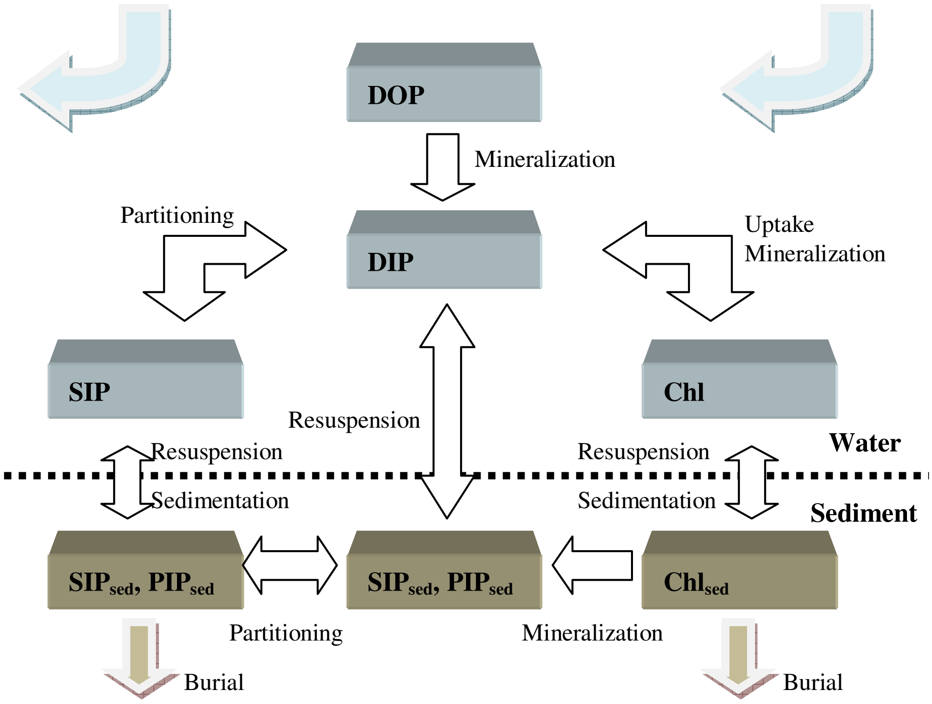


Figure 2. Illustration of the flow and transport processes between the different phosphorus fractions simulated in the MyLake model code; SIP (Suspended inorganic particulate matter), DOP (dissolved organic phosphorus), DIP (dissolved inorganic phosphorus), PIP (particulate inorganic phosphorus) and Chl (chlorophyll). After Saloranta and Andersen (2007).

2.3 MyLake data input and data availability

The model input can be roughly divided into meteorological data, inflow characteristics, lake morphology, and initial lake values. All meteorological data, except cloud cover was obtained from the meteorological station at Ås (no cloud cover data exist after 1987). For calculation of cloud cover, see Reed (1977). Meteorological data has been continuously sampled at Ås from 1859. This thesis used meteorological data for the period 1996-2009 (Thue-Hansen & Grimenes 1996-2003; Thue-Hansen & Grimenes 2004-2010). The source and availability of the inflow data is summarized here, and further discussed in chapter 4. Where no water flow data is available, total inflow concentrations to Lake Årungen are estimated based on the measured nutrient contribution of the Lake Årungen inlet streams (table 4). Lake morphology and initial lake values of the model application are described in section 2.5.

2.3.1 Water balance and nutrient transport in the Lake Årungen catchment area 1977-1979

Original Norwegian title: 'Vannbalanse og stofftransport i Årungens nedbørfelt, 1977-79' (Grøterud & Rosland 1981). This is a thorough report, with usually weekly resolution (1-5 per month) of concentrations of total phosphorus (Tot-P) and suspended matter data from 1977-1979. In this report, the sub-catchment area that drains to Brønnerudbekken is included in the inlet stream Vollebekken, but adds a new sub-catchment area, connected to the very small inlet stream Syverudbekken. This sub-catchment area is incorporated in the residual area in this thesis. The report contains Tot-P data from 1976, and no water flow data is reported from this year. Flow of water data is available in the form of a flow curve, and must be digitalized before use. Several graph digitizing softwares can easily be purchased through the internet. However, the data in this report is sometimes scattered, and within shorter time spans, only sporadic data exist for some of the Lake Årungen inlet streams. This report will from now on be referred to as dataset 1 (table 5).

2.3.2 Limnological, local water quality surveillance 1996-2009

Original Norwegian title: 'Limnologisk, lokal vannkvalitetsovervåkning 1996-2009' (Løvstad 1996-2009). The municipality of Ås has since 1995 monitored total phosphorus and total reactive phosphorus (TRP) data in the Lake Årungen inlet streams. The data exists on an approximately monthly basis from Mars-November. No suspended matter or flow of water data exists. This report will from now on be referred to as dataset 2 (table 5).

2.3.3 Mass balance studies in Lake Årungen

Original Norwegian title: 'Massebalanse studier i innsjøen Årungen' (Gunnarsson 2007). This is a master thesis, and suspended matter and tot-P data exist from approximately every second day in the period 30th March to 6th May, 2006, and ever 1-4 hour in the short period from 26th to 27th October 2006. The thesis uses flow of water based on dataset 4. This thesis will from now on be referred to as dataset 3 (table 5).

2.3.4 Data from the Skuterud area (JOVA program)

Monitoring at the Skuterud area started in June 1993, when a monitoring-station was built at the outlet of the Skuterudbekken into the Lake Østensjøvannet. The station registers flow of water every 30 minute. Through composite volume proportional water sampling every fourteen days an average concentration is obtained for Tot P and phosphate (Deelstra et al. 1998; Deelstra & Øygarden 1998). This dataset represent the most extensive available data, but since the Skuterud area is only a small part of the total Lake Årungen catchment area (9 %), it must be calibrated before use. The equations for the calculations are given in section 2.4. At the Skuterud monitoring station also water temperature is measured. This dataset will from now on be referred to as dataset 4 (table 5).

Table 4. Contribution (%) of the Lake Årungen inlet streams in terms of supply of Tot-P, phosphate and suspended matter (Gunnarsson 2007).

Stream	Tot-P	Suspended matter
Bølstadbekken	42	42
Smebølbekken	20	27
Storgrava	17	12
Norderåsbekken	10	11
Vollebekken	4	1
Brønnerudbekken	1	1
Residual areas	6	6

Table 5. Available sources of inflow data, time series of data, and quick name of the source of interest.

Source	**Year**	**Quick name**
Grøterud and Rosland (1981)	1976-1979	Dataset 1
Løvstad (1996-2009)	1996-2009 (March-November)	Dataset 2
Gunnarsson (2007)	2006 (ultimo March-primo Mai)	Dataset 3
The Skuterud monitoring area (JOVA program)	1993-2009	Dataset 4

2.4 Calculations to make dataset 4 suitable for MyLake modelling

All calculations are originally done at the sub-catchment area, where the sub-catchment areas are later summed up to estimate the total Lake Årungen catchment area.

2.4.1 Calculating nutrient inflow to Lake Årungen based on dataset 4

Proportional factors are the nutrient ratio between each of the Lake Årungen inlet streams and the reference stream Skuterudbekken, and is based on a calibration period between 30th March to 6th May 2006 (Gunnarsson 2007). The proportional factors are summarized in table 6, and uncertainties regarding these factors are discussed in chapter 3. Equation 2.1 shows how to calculate nutrient transport into a Lake Årungen inlet stream based on dataset 4

$$T_j = Q_{j,period} \cdot C_{i,period} \cdot N_{i,j} \qquad (2.1)$$

where T_j is transport of nutrients in stream j, $Q_{j,period}$ is the sum flow of water within a period, $C_{i,period}$ is measured concentrations of nutrients within the same period at the Skuterud area, and $N_{i,j}$ is proportional factors for nutrient i in stream j. Water flow data from the Skuterud area can be used to calculate $Q_{j,period}$. This is further explained in section 2.4.2.

Table 6. Proportional factors ($N_{i,j}$) for estimating nutrient transport in Lake Årungen inlet streams, based on values from dataset 4 (Gunnarsson 2007).

Stream	Tot-P	Suspended matter
Norderåsbekken	1.8	1.8
Bølstadbekken	0.9	0.8
Storgrava	1	0.7
Smebølbekken	1.3	1.7
Vollebekken	1.6	0.6
Brønnerudbekken	0.6	0.6
Residual area	1	1

2.4.2 Hydrology of inlet streams

This section gives a summary of all the equations that were used for estimating flow of water into Lake Årungen. The sub-catchment area of all Lake Årungen inlet streams, except Bølstadbekken, is small with very low water storage capacity. Flow of water can easily be calculated with a very simple equation (eq. 2.2), which assumes that flow of water increases linearly with catchment size in proportion to flow of water and size of the Skuterud catchment area.

$$Q_X = A_X \cdot \frac{q_{Sku}}{A_{Sku}} \qquad (2.2)$$

where Q_X is flow of water in the stream that drains catchment area X [m^3 day^{-1}], and A_X is the surface area in X [m^2], q_{Sku} is the flow of water in Skuterudbekken [m^3 day^{-1}] (the stream that drains the Skuterud area), and A_{Sku} is the surface area of Skuterud [m^2]. This equation does not take into account the differences in land use. Uncertainties regarding this equation will be discussed further in chapter 4.

The inlet stream Bølstadbekken is in addition fed by a large area related to Lake Østensjøvannet. A lake, even a small one like Lake Østensjøvannet, will alter the flow properties of Bølstadbekken. There are mainly two reasons why this is true; (1) all precipitation that hit the lake surface will immediately be added to the lake volume, and (2) the evaporation from the lake surface is as near as unconstrained by water availability. In addition, the runoff from Lake Østensjøvannet will to a large degree be decided by the morphology of the outlet. Because of this, the calculation of Bølstadbekken is more complicated than of the other Lake Årungen inlet streams. Equations 2.4-2.15 show the calculations needed to estimate flow of water for Bølstadbekken, and is based on the simple water balance equation (eq. 2.3) by Ræstad and Otnes (1978), which states that the runoff from catchment area *a* (Q_a) is decided by

$$Q_a = P_a - E_a - dS_a \qquad (2.3)$$

where P_a and E_a are precipitation and evaporation in the catchment area, and dS_a is alterations in water storage of lakes within the area. This equation can be adapted for calculating lake runoff (from Lake Østensjøvannet) instead of discharge from a catchment area. First, the total flow of water into Lake Østensjøvannet Q_{in} [m^3 day^{-1}] is calculated based on measurements from the Skuterud area (eq. 2.4)

$$Q_{in} = A_{\O st} \cdot \frac{q_{Sku}}{A_{Sku}} \qquad (2.4)$$

where $A_{Øst}$ is the surface area of the Lake Østensjøvannet catchment area [m^2]. Second, the water level of Lake Østensjøvannet has to be estimated. Equation 2.3 implies that changes in lake discharge are determined by alterations in lake water level, and today's water level is determined by yesterday's water level, adjusted for today's changes in water level. Equation 2.5 is equation 2.3 modified to calculate water level h [m] in day t (Gunnarsson 2007).

$$h_t = h_{t-1} + \frac{Q_{in\,t} - Q_{out\,t}}{A_L} + P_t - E_t \qquad (2.5)$$

where h_{t-1} is yesterdays water level [m], $Q_{in\,t}$ and $Q_{out\,t}$ [m^3 day^{-1}] is flow of water into and out of Lake Østensjøvannet, A_L is lake surface area, P_t and E_t is precipitation and evaporation at the lake surface [m day^{-1}]. Equation 2.5 is a simple estimation of reality, and assumes that the change in lake area due to increasing water level is neglectable. However, no outflow data exist before day 1 (t=0), and the water level has to be calculated based on the day 1 outflow volume, which for simplicity is set equal to the inflow volume (Q_{in}=Q_{ut} at t=1). Later Q_{ut} will be calculated by equation 2.14. Water level at day 1 (h_1) was then calculated by equation 2.6 (eq. 2.14 adjusted with h as the explanatory factor)

$$h_1 = \sqrt[3/2]{\frac{Q_{out1}}{\frac{2}{3}\mu \cdot b \cdot \sqrt{2g}}} \qquad (2.6)$$

where μ is the outlet coefficient (set to 0.4), b is outlet breadth (2.5 m) and g is the gravitational constant (9.81 m s^{-2} [$7.32 \cdot 10^{10}$ m day^{-2}]). The outlet of Østensjøvannet is a square canal, and the outlet coefficient is set low due to vegetation (Gunnarsson 2007).

Evaporation from the surface of Lake Østensjøvannet is calculated by equation 2.7, from the early work of Howard Penman (Penman 1948; Penman 1956).

$$E = \frac{R_n}{\lambda} \cdot \frac{\Delta}{\Delta + \gamma} + \frac{\gamma \cdot E_{ap}}{\Delta + \gamma} \cdot \frac{1}{1000} \qquad (2.7)$$

where Δ is the slope of the saturation vapour pressure curve [mbar $°C^{-1}$], R_n is net radiation at the surface [MJ m^{-2} day^{-1}], λ is latent heat of vaporization [MJ kg^{-1}], γ is psychrometric coefficient (0.66 mbar $°C^{-1}$ at T = 20 °C and p = 1000 mbar), and E_{ap} is a aerodynamic part [mm day^{-1}]. R_n is measured at the meteorological station at Ås. The saturation vapour pressure curve (Δ) is the relationship between temperature T [°C] and saturation vapour pressure e_s [mbar], and can be found by equation 2.8 (Arnell 2002)

$$\Delta = \frac{4098 \cdot e_s}{(237.3 + T)^2} \qquad (2.8)$$

, where e_s is calculated by equation 2.9

$$e_s = 6.11 \exp \frac{17.3 \cdot T}{(237.3 + T)} \qquad (2.9)$$

The latent heat of vaporization (λ) is found by equation 2.10 (Arnell 2002)

$$\lambda = 2.501 - 0.0002361 \cdot T \qquad (2.10)$$

which means that it takes about 2.5 million joules to evaporate a kilogram (≈0,001m^3) water at all lake temperatures so far measured in Lake Årungen. Evaporation can only take place if the air above the water surface is not saturated by water. For any given amount of energy added to the water surface, the potential evaporation will be proportional to the vapour deficit, which is the difference between e_s and the actual vapour pressure e (Arnell 2002). Because total still air will reach the saturation point fast, evaporation is also highly dependable on air movement. The greater the wind speed (u), the higher is the evaporation rate. But evaporation also depends on surface properties, like roughness and water availability. Therefore, the aerodynamic part (E_{ap}) of the Penman equation (eq. 2.7) can be written as a function of u (eq. 2.11)

$$E_{ap} = f(u)(e_s - e) \qquad (2.11)$$

where e is calculated by equation 2.12, and $f(u)$ by equation 2.13

$$e = \exp\left(20.386 - \frac{5132}{T + 273.15}\right) \qquad (2.12)$$

$$f(u) = \alpha_1 (1 + \alpha_2 u) \qquad (2.13)$$

where α_1 is 0.26 and α_2 is 0.14 for a open water source (Penman 1956). This is of course a roughly estimation, since evaporation of a open water source is also likely to affected by surface temperature, lake area and winter conditions (Ræstad & Otnes 1978).

Flow of water of the Lake Østensjøvannet outlet stream is calculated with equation 2.13, the Kindsvater-Carter rectangular weir equation for rectangular weir (ISO 2008)

$$Q_{out} = \frac{2}{3} \mu \cdot b \cdot h^{3/2} \cdot \sqrt{2g} \qquad (2.14)$$

The total flow of water in Bølstadbekken ($Q_{Bøl}$) can then be calculated (eq. 2.15) by adding the estimated outlet flow of Lake Østensjøvannet (eq. 2.14) with the water that drains directly in to Bølstadbekken from the area downstream of Lake Østensjøvannet (eq. 2.2 adjusted)

$$Q_{Bøl} = Q_{out} + A_{Bøl} \cdot \frac{q_{Sku}}{A_{Sku}} \qquad (2.15)$$

where $A_{Bøl}$ is the area of sub-catchment Bølstadbekken downstream of Lake Østensjøvannet.

2.5 Running the MyLake model application

Based on water flow and nutrient runoff data from dataset 4 and Meteorological data from Ås, a run of the MyLake model from 1st April 1994 to 30th April 2009 was carried out. The model start date (1st April) were set as explained by Saloranta and Andersen (2007). Even though dataset 4 runoff data exist from as far back as summer 1993, the start of modelling was set to 1994 due to missing meteorological data in 1993. Bathymetric curve was retrieved from Hexum (1963), and is schematized in figure 3.

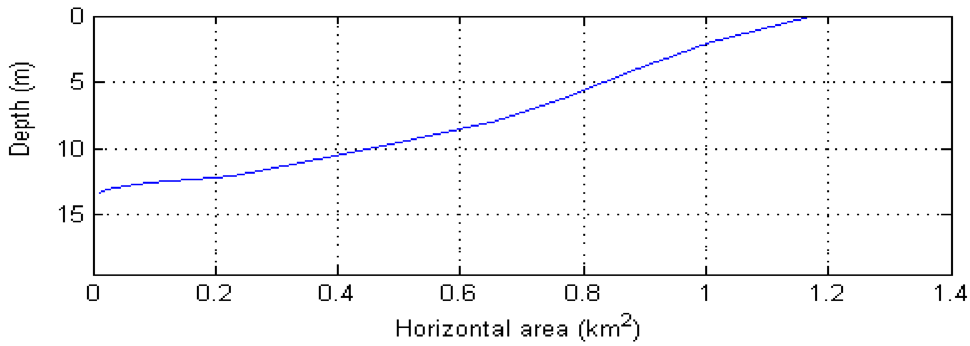


Figure 3. Bathymetric curve of Lake Årungen. From Hexum (1963).

Forcing data of suspended matter and Tot-P was calculated based on dataset 4 as described in section 2.4. No forcing data of chlorophyll was available, and the inflow concentration was assumed to be negligibly small (0.1 mg m^{-3}). This, however, is probably incorrect in summer, when algae might be transported with the inlet stream Bølstadbekken from Lake Østensjøvannet. Inflow of DOP and dissolved organic carbon (DOC) were assumed to be 7 mg m^{-3} and 3 g m^{-3} respectively, as no concentrations of these variables were accessible. Stream inflow temperatures were assumed to be similar to the temperature measured in Skuterudbekken. Homogenous initial profiles of temperature (4 °C), dissolved tracer (0), suspended matter (4 mg m^{-3}), Tot-P (21 mg m^{-3}), DOP (7 mg m^{-3}), chlorophyll (7 mg m^{-3}) and DOC (3 g m^{-3}) were defined for model start date. Results from a sediment survey from the eutrophic Lake Vansjø-Storefjorden (situated 30 km south of Lake Årungen) were used to set values for sediment-related initial values (Saloranta & Andersen 2007). Initial ice and snow cover were set to zero. All model parameters were based on the Lake Vansjø-Storefjorden application by Saloranta and Andersen (2007).

All zero concentrations were deleted, and linearly interpolated concentrations between the two closest known values were inserted instead. The resolution of the MyLake model is preset to 24 hours and the vertical resolution were set to 0.25 meters. For examples of excel input forcing file, initial profiles and parameter file, see appendix 1.

The results from the MyLake run were compared to observed nutrient and suspended matter concentrations and temperature (sampled 04.07.2006-22.04.2009) and ice (Aleksandra Trnic Romarheim, unpubl. data). There are, however, only two observations of ice thickness in the period of the original model run. To get a better basis for comparison, three ice thickness observations were included in a separate model run that was carried out from 1st April 1994 to 30th April 2010. Since only meteorological data were available at the time of modelling, inflow data from the period 01st May 2008 to 30th April 2009 were copied and inserted as values from 1st May 2009 to 30th April 2010.

3 Background

3.1 Phosphorus runoff from agricultural soil and climatic impact

Even though only 3% of Norway's total land area is under agriculture, runoff from these areas has been shown to be a major phosphorus contributor to inland and coastal waters (Ulen et al. 2007). P-AL (ammonium acetate lactate extractable phosphorus) in agricultural soil steadily increased during the twentieth century as a result of surplus application of phosphorus (Ulen et al. 2007). Both soluble and algae available phosphorus (which also includes some of the phosphorus bound to particles) have a positive correlation with P-AL in the soil (Øgaard 1995). A study by Øgaard (1995) showed that P-AL explained 83% of the variation in TRP, which again is highly correlated with algae available phosphorus (Krogstad & Løvstad 1991). P-AL in Norwegian agricultural areas corresponds now to the second highest class used to categorize soil phosphorus status (Ulen et al. 2007). A P-AL value (mg pr 100g soil) of 5-7 is usually thought of as sufficient to achieve optimal yield from cereal and grass production, and at a value of 14, no fertilizing at all is recommended (Krogstad et al. 2008). P-AL classification and advise for fertilizing is summarized in table 7.The mean P-AL value in the Lake Årungen catchment area (1988-2003) is 13.9, while the largest value was found in sub-catchment area Storgrava with an incredible P-AL value of 170 (Borch et al. 2007).

Table 7. Classification and percent (%) correction of the phosphorus norm fertilization based on P-AL in the soil. Class A-D specify classes of P-AL value in soil (mg pr 100g soil); A = low, B = medium/optimal, C1 = moderate high, C2 = high, D = very high. From Krogstad et al. (2008).

Class	P-Value	% correction (Y) of phosphorus need
A	1-5	Y = -25(P-AL) + 125
B	5-7	Y = 0
C1	7-10	Y = -14.28(P-AL) + 100
C2	10-14	Y = -14.28(P-AL) + 100
D	>14	Y = -100

Lundekvam (2007) showed that most of the surface runoff in SE Norway occur during late autumn, winter and early spring due to soil saturation by water. Haraldsen et al. (1995) found a significant correlation between runoff, and concentration levels of phosphorus and suspended matter in winter and spring in SE Norway. Snow melt periods were also responsible for high erosion in April. The study also showed that autumn nutrient losses were strongly correlated with heavy precipitation events and the rate of tilled area. Erosion risk is greatest in periods of no snow cover (Lundekvam 2007). If the top soil layer is thawed while the underlying soil is still frozen, water is prevented from penetrating deeper into the soil, and might accumulate in the top layer and cause great mass movement (McRoberts & Morgenstern 1974). If the circumstances are correct, this might sometimes develop into major landslides (McRoberts & Morgenstern 1974). In winter, the number of freeze-thaw cycles is strongly correlated with phosphorus loss from plant tissue, and lead to elevated concentrations of dissolved phosphorus in runoff (Bechmann et al. 2005b). Even though Bechmann et al. (2005b) did not register any change in phosphorus loss with increasing freeze-thaw cycles in soils mixed with manures, several studies have documented increased phosphorus runoff from both mineral and organic soil that experience freeze-thaw episodes (Henry 2007).

Soil erosion can be a great problem in agricultural areas, and especially on artificially levelled soils (Lundekvam 2007). Before the late 70s, when erosion problems were not being takes seriously, old glacial ravines and other landscape obstacles in SE Norway were commonly levelled to make the area suitable for heavy machinery. Levelling can completely destroy soil structure, reduce the permeability and increase erodibility (Lundekvam 2007; Ulen et al. 2007). Another effect of the levelling was that the slopes became longer. In episodes of precipitation, water is gathered in concavities and can form rills or gullies (Lundekvam 2007).

Different transport mechanisms will occur depending of the form of phosphorus, particulate or dissolved. Particulate phosphorus (PP) is adsorbed to minerals, and detached from the soil by either direct erosion or by preferential flow to the subsurface drainage system. This is especially a problem on structured soils, which form a large proportion of agricultural soils in South Eastern Norway. Dissolved phosphorus is easily washed out of the soil, either by direct loss from soil or fertilizer and plant residues, or it can penetrate the whole soil or wash through macro pores together with particulate matter, and be lost through drainage system. According to Ulen et al. (2007), subsurface drainage in Norway can contribute 12–60%, and surface erosion 40–88%, of the Tot-P transport from agricultural land.

In Norway, farmers are encouraged to diminish nutrient and soil loss from farmed land by carrying out mitigation measures, and they get subsidies for reduced tillage (Ulen et al. 2007). Agricultural practices with the highest risk of erosion are grain crops with autumn ploughing and spring harrow (Lundekvam 2002). Lundekvam (2007) showed that no tillage in autumn could reduce soil loss up to 90% compared to standard autumn ploughing. Meadow and other permanent pastures/vegetation cover are among the low risk practices (Lundekvam 2002).

The main part of the nutrients is transported in periods of high flow of water, and concentrations usually increase when flow of water increase (Grøterud & Rosland 1981; Gunnarsson 2007). In the Lake Årungen catchment area, 2-4 months are typical responsible for 70-80 % of the total annual discharge(Grøterud & Rosland 1981). Due to the low water storage capacity of the Lake Årungen catchment area, floods are both frequent and short spanned, and large differences between low and high flow of water is common (Grøterud & Rosland 1981). The nutrient concentration can change rapidly during events of precipitation, and Gunnarsson (2007) showed that Tot-P concentrations and flow of water in Lake Årungen inlet streams can vary as much as ten-fold within hours. The concentrations are typical higher the first hours after heavy precipitation, which is probably a first flush effect (Gunnarsson 2007).

3.2 Effects of climate change on lake management

Although it is not certain to what degree, many scientists agree that anthropogenic climate change is now occurring. Climate change affects flow velocity, hydraulic characteristics, water levels, inundation patterns and residence time of rivers and lakes (Brown et al. 2007), and European lakes have the last decades undergone changes in eutrophication, which have been linked to climatic changes (Straile et al. 2003). Most climate change responses in freshwater systems are likely to be due to changes in precipitation patterns and air temperature (Whitehead et al. 2009). Air and river temperature are in close equilibrium, thus temperature driven changes in fresh water systems are not unexpectedly the most immediate reaction in a state of climate shift (Hassan et al. 1998). Air temperature influences lake through convective heat exchange, evaporative heat exchange, and the atmospheric emission of long-wave radiation (Straile et al. 2003).

Weather conditions in Europe are partly controlled by the North Atlantic Oscillations (NAO), and winter conditions are especially strongly affected, and thus likely to control ice conditions and spring plankton phenology (Blenckner et al. 2007). Several studies in European lakes have shown a strong correlation between lake temperatures and the NAO (George et al. 2000; Straile & Adrian 2000). A positive winter NAO index (December-March average differences in standardized sea level pressure between the Azores and Island) are characterised by high pressure differences related to high winter temperatures in western and northern Europe, while a negative index is characterized by lower than average winter temperatures. As the name indicates, the NAO oscillates between positive and negative phases and is typically related to five-ten year cycles. The last decades, researchers studying the NAO have observed, beyond natural variability, a trend toward more positive phases (Hurrell 1995), and increasing atmospheric gases, mainly anthropogenic CO_2, have been seen to be responsible for some of these changes (IPCC 2007).

The climate scenarios presented here are developed by RegClim, a coordinated research program supported by The Norwegian Meteorological Institute, The Institute for Marine Research, Department of Geosciences (University of Oslo), Geophysical Institute (University of Bergen), Nansen Environmental and Remote Sensing Centre and The Norwegian Institute for Air Research. Projected future climate scenarios by RegClim are available at http://regclim.met.no/. According to these scenarios, mean precipitation in eastern Norway the next 50 years is likely to increase, except for spring precipitation which is likely to decrease slightly. Meanwhile, mean air temperature is also likely to increase 0.2-0.5 °C per decade. The changes will be most obvious in winter and less in spring and summer. Higher winter and spring temperatures means that the ice cover enhancing stratification will melt sooner, and the growth season is likely to begin earlier. Increased temperature in combination with high nutrient runoff may also lead to increased lake primary production and prolonged growing season. Increased summer temperatures can increase the stability of the summer stratification and deepen the thermocline (Hassan et al. 1998), which combined with increased algae production and decay of organic matter may enhance oxygen depletion in bottom lake areas. Phosphorus resuspension will probably be more significant in periods of high temperatures then colder years, and external loading more important in wet years then dry years. Wind speed in eastern parts of Norway is also likely to increase slightly during the next 50 year, and thus could again reduce lake stability. In what way this may have an impact on the density gradients due to increased temperatures is hard to say, but the effect will be greatest for wind exposed lakes, such as Lake Årungen.

An increase of precipitation in periods vulnerable of erosion, and warmer temperature regimes that lead to changes in agricultural practices can both increase the risk of erosion and loss of phosphorus, which in turn have cascading effect on lake ecosystem and management (Jeppesen et al. 2009; Olesen et al. 2004). High runoff events during snow melting or warm weather episodes during winter will increase runoff of both nutrients and suspended matter. The soil will be more frequently exposed to repeated freezing and thawing, which again will increase phosphorus loss from the soil (Ulen et al. 2007). High erosion and particulate transport will affect lake Secchi depth, and maximum depth photosynthetic compensation.

Because of the low storage capacity, the flow intensity of the Lake Årungen catchment area will probably be more frequent, and the floods will be larger. Higher flow of water combined with increased risk of erosion lead to increased concentrations of phosphorus and suspended matter in to Lake Årungen, and sediments may be highly enriched with phosphorus bound to particulate matter. This will again lead to higher primary production, the probability of anoxic sediment and phosphorus resuspension will increase. The increasing importance of external nutrient loading combined with lake responses to climate change (Whitehead et al. 2009), can make it difficult for some water systems to meet the water quality standards set by the WFD (Wilby et al. 2006), and Lake Årungen might be such a case.

4 Results and discussion

Short-spanned differences in weather can be very important determining density stratification dependent differences in a lake, and hence the basis for algal growth. Nutrient input, however, does not affect lake dynamics in the same rapid way. Lakes are slow moving systems which take longer time to respond to changes in inlet nutrient flux than faster moving systems, e.g. rivers. One can say that lakes have longer memory for nutrients than for weather. Thus, meteorological data is needed at a very high resolution, preferably daily, while high resolution of nutrient concentration might be less important, depending on water residence time, as long as the supply over a given period is reasonably correct. The availability of data with respect to runoff of nutrients and flow of water in the Lake Årungen catchment area are scarce. A special effort was put on determining the applicability and uncertainty of dataset 4, since this represent the longest high resolution time series. Dataset 2 underestimates transport of tot-P and is unsuitable as MyLake data input, while the time series of dataset 3 it to short. Dataset 1 and 4 are probably the best suitable time series for MyLake modelling within their own sample period. Even though the proportional factors for calculating Lake Årungen inlet stream concentrations based on dataset 4 (see section 2.4) probably need further calibration, there seem to be several reasons why both the annual flow of water and nutrient supply may be acceptable. The MyLake Årungen application based on dataset 4 described in this chapter shows that the model to a large degree can be suitable in the management of Årungen, but that sensitivity analysis and calibration is needed before it is applicable.

4.1 Estimating uncertainty of available data

In Dataset 1 (Grøterud & Rosland 1981) the resolution of phosphorus data is approximately weekly. The water flow curve displayed in this report can be digitalized with a graph digitizing software, but it is uncertain how accurate this projection will be. This is the earliest data available of Lake Årungen inflow data, and thus no comparison can be made with other datasets. The Tot-P and suspended matter concentrations can be slightly underestimated, as weekly resolution is unlikely to capture the variance given by the rapid flow episodes. Transport of suspended matter and particulate phosphorus is much higher in episodes with high flow of water, while low flow of water typically has a lower portion of particulate transport. However, the data still gives an approximation of the seasonal nutrient transport, at least for periods were data are not too scattered.

Dataset 2 (Gunnarsson 2007) have a high resolution (2-3 days) from 30th March to 6th May 2006, a period where water flow represent more than the volume of Lake Årungen, and extremely high resolution in 26-27th October 2006 (every 1-4 hour). The flow of water data in this study is based on dataset 4, and although this is the case, there are good reasons to believe that the calculated Tot-P and suspended matter transport in this thesis is a good estimation of reality, as discussed later. Despite the high, this period is unfortunately too short to be of any good use when modelling long spanned lake variations, as we usually do with the MyLake model. On the other hand, this report has given us a great insight in how we may calculate nutrient and suspended matter transport into Lake Årungen based on dataset 4 (see section 2.4.1 and 4.2.2).

Dataset 3 (Løvstad 1996-2009) are on a monthly basis (March-November values). For some years only every second month are sampled. It is the municipality of Ås who is responsible for sampling of data. Dataset 2 and 3 have only one mutual sampling date, but the Tot-P concentrations in both dataset are similar. A comparison of annual data from dataset 2 and dataset 4 (calculated to estimate Lake Årungen inlet stream phosphorus concentration) were made. The calculations based on the dataset 4 are not a perfect representation of reality, but the summed annual transport of Tot-P is probably well estimated, as discussed later. The average annual concentrations of Tot-P in dataset 2 and 4 are very different (figure 4). The figure is based on samples from March to November values from the period 1995-2001. Data from sampling as late as 2009 exists, but the data was not available for this thesis. Values from 1995-1996 in dataset 2 are based on very few samples, and should be interpreted with care. The trend is the same, with highest concentrations in 1998-2000, and lowest in 1995-1997. The Tot-P concentrations in dataset 2 are, however, probably highly underestimated, and the differences reflect an underestimation of PP in the monthly water samples. The data from dataset 2 is sampled at low and medium flow of water (Løvstad 1996-2009), which is probably the reason for underestimating of PP. PP is more prone to changes in flow of water, since high flow of water more easily break aggregates from the ground. The Tot-P concentrations from dataset 2 are not good enough to use as inflow data in this thesis.

Figure 5 shows the comparison of Tot-P and suspended matter concentrations between the Mass balance (broken line) study and concentrations calculated based on dataset 4 (solid line) from 30th March to 06th May. The correlation is very good for the last two thirds of the dataset 3 period, which is expected, as the Tot-P concentrations in dataset 4 is calculated with the proportional factors that is based on the correlation between dataset 3 and 4. The correlation the between the two dataset is not good in the first week of the period. The correlation between estimated suspended matter concentrations based on dataset 4 (solid line) and samples from dataset 3 is, as with Tot-P, also very good for the last two thirds of the period, but not good in the first week. This is a period in the start of a flood episode, when the flow of water is still low (figure 6). The largest peak of both the Tot-P and suspended matter concentrations in dataset 3 is sampled at rising flood, but before the major flow with 10^6 m^3 day^{-1}, and total transport estimated by dataset 3 and 4 is therefore similar. It is difficult to say what the reasons for the differences in concentration are. The Tot-P concentration can, as mention in chapter 3, vary with a factor of ten within hours, and it is possible that some of the samples from dataset 3 unfortunately were sampled in a peak. Dataset 4 is based on a volume proportional water samples, and are less prone to such errors. On the other hand, this may also represent differences in phosphorus run off between the Skuterud area and the whole Lake Årungen catchment area. Nevertheless, the concentrations are similar for most of the period, and most important, they are similar in the days with the highest flow of water.

The MyLake model needs inflow properties of Tot-P and suspended matter to estimate the phosphorus-phytoplankton dynamics in Lake Årungen. Because of the reasons mentioned above, we can state that data from dataset 1 probably are good enough to use in the MyLake modelling. Dataset 3 is also probably of a good quality, but the sampling period is unfortunately very short. Dataset 2 probably highly underestimates particulate phosphorus, and cannot be used in the model as it is. On the other hand, as figure 3 indicate, the correlation between the data from dataset 2 and 4 is fairly linear (x plotted against y), and an calibration factor for estimating annual Tot-P concentrations based on dataset 2 can be found. Concentrations based on dataset 4 are probably the best solution for the MyLake modelling from summer 1993 to present (except for the short period that is covered by dataset 3), since it represent a very long time series with high resolution, and the calculated concentrations based on this data corresponds to a great degree with measured samples. There are however several uncertainties regarding dataset 4, as are discussed in section 4.2.

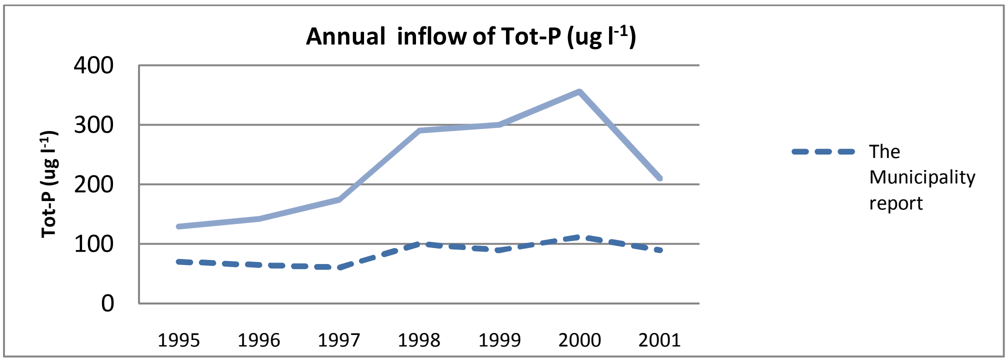
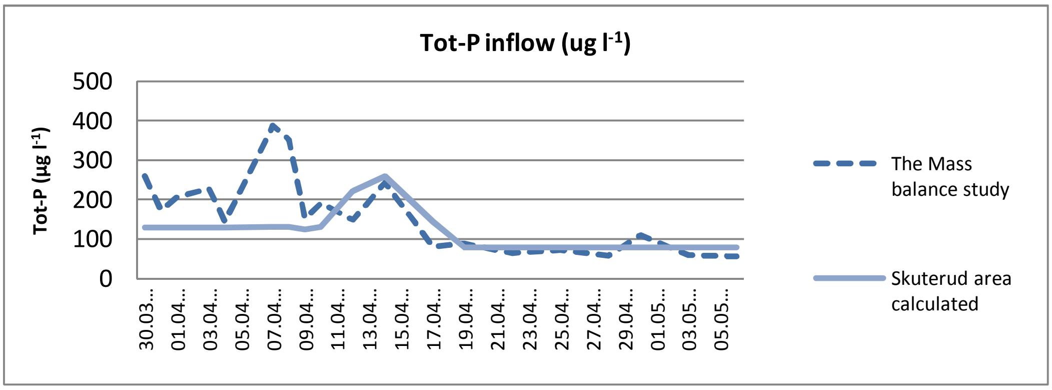


Figure 4. Annual Lake Årungen inflow concentrations of Tot-P (µg l^{-1}) from 1995 to 2001. The solid line indicates the *in situ* samples of dataset 2 (Løvstad 1996-2009), while the solid line is values from dataset 4, calculated based on given proportional factors (see section 2.4). The values are based on samples from March to November.

A



B

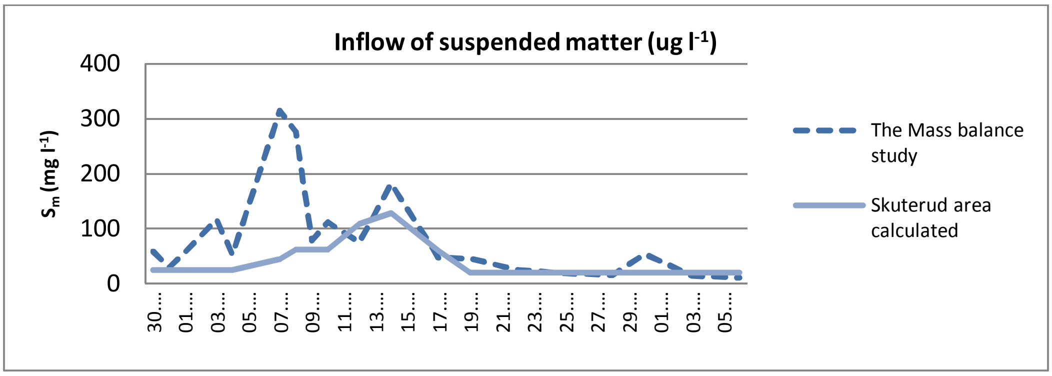


Figure 5. Lake Årungen inflow concentrations of (A) Tot-P (µg l^{-1}) and (B) suspended matter (mg l^{-1}) into Lake Årungen from 30th March to 06th May. The solid line indicates the *in situ* samples of dataset 3 (Gunnarsson 2007), while the solid line is values from dataset 4, calculated based on given proportional factors (see section 2.4). Flow of water data are based on dataset 4.

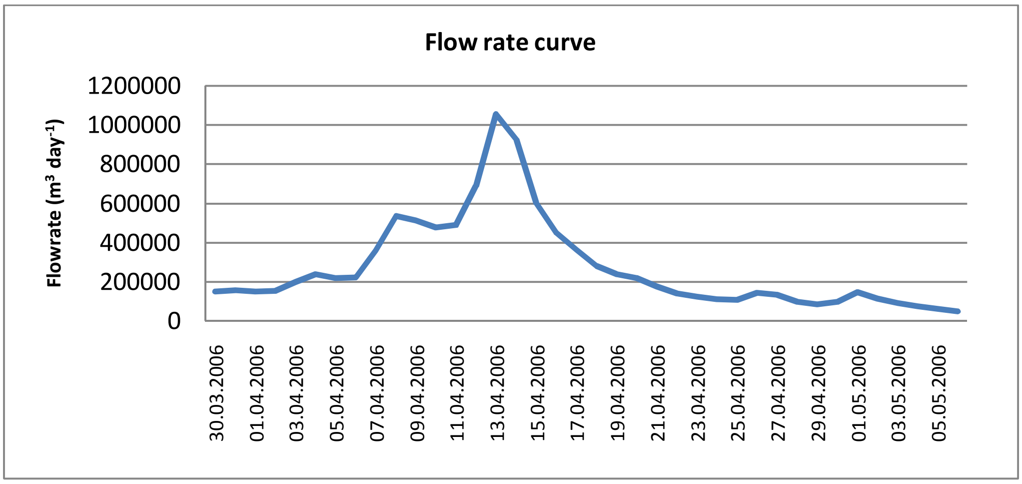


Figure 6. Flow of water into Lake Årungen from 30th March to 06th May, based on dataset 4.

4.2 Uncertainty regarding dataset 4

Uncertainties regarding the use of dataset 4 to estimate inflow properties to Lake Årungen (see section 2.4), is divided into hydrological properties (water flow), and uncertainties regarding the proportional factors used to estimate Tot-P and suspended matter concentrations in the Lake Årungen inlet streams.

4.2.1 Uncertainty regarding the hydrological properties

There are several reasons why it can be presume that dataset 4 is for the most part suitable for estimating flow of water into Lake Årungen. First, both distances and differences in elevation within the Lake Årungen catchment area are small, so we can assume that spatial differences in climate and precipitation are neglectable. Secondly, and probably more important in this case, is evapotranspiration (ET) and infiltration rate of water into the soil. It is now well documented that vegetation and land use significantly alters ET (Zhang et al. 2001) and the infiltration rate of water into the soil (Fetter 2001). ET is the sum of evaporation and plant transpiration from the earth's surface to the atmosphere. Based on calculations from this study, approximately 39 % of the annual precipitation the last 13 years has been lost due to ET. ET tends to be high in vegetated areas, and deep rooted plants have higher ET than plants with shallower root system. Thus, forested areas usually have especially high ET, and conifer forests tend to have higher rates of ET than deciduous forests (Zhang et al. 2001). Likewise, rate of infiltration varies with land use, and is often very low in populated areas. Soil texture and composition (roads and constructions in urban areas) are the main factors controlling infiltration rate. Both the Skuterud area and the Lake Årungen catchment area are composited of a mixture of marine beach deposits and ocean- and fjord deposits (see http://www.ngu.no/kart/arealis/ for map of quaternary deposit). Figure 7 show that the differences in land use between the Skuterud area and the Lake Årungen catchment area are small (Gunnarsson 2007). The largest differences in land use is in the agricultural areas (Skuterud = 60.5%, Årungen = 53%). Smaller are the differences in forested areas (Skuterud = 29%, Årungen = 34%), populated areas (Skuterud = 8.5%, Årungen = 10%), and water and marshlands (Skuterud = 2%, Årungen = 3%). Even though the land use in each sub-catchment area are different, the sum of differences between the whole Lake Årungen catchment area and Skuterud are small, and ET and water infiltration rate in the Lake Årungen catchment area and the Skuterud area might be similar.

Since sub-catchment area Bølstadbekken is assumed to have larger water storage capacity then the other sub-catchment areas (because of Lake Østensjøvannet), it is expected that the Lake Årungen inlet stream Bølstadbekken have a longer response time (time lag) to changes in precipitation and water flow properties. However, no differences could be found between the timing of estimated and measured water level when using the calculations described in section 2.4 (Gunnarsson 2007).

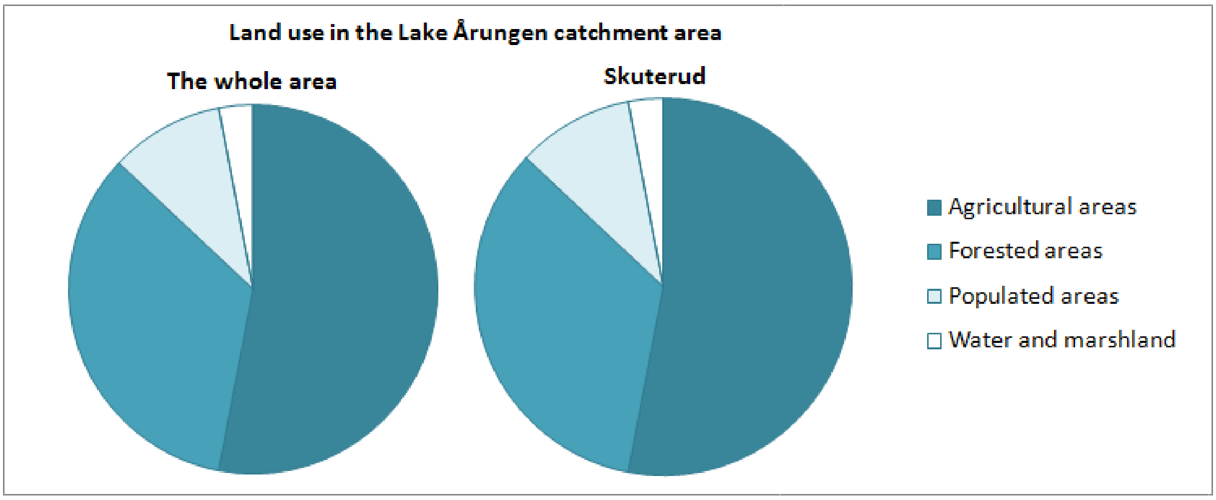


Figure 7. Relative land use in the whole Lake Årungen catchment area compared to the Skuterud area. From Gunnarsson (2007).

4.2.2 Uncertainty regarding Tot-P and suspended matter transport

The factor used to estimate phosphorus concentrations in the Lake Årungen inlet streams, is based on 19 samples in every Lake Årungen inlet streams (table 1) in the period 30.03.06-06.05.06 (Gunnarsson 2007). There are several reasons why the use of these proportional factors can be uncertain.

The proportional factors are based on samples from a high flow period during spring flood, and there are reasons to believe that the correlation between samples at the Skuterud area and the rest of the Lake Årungen catchment area are not proportional rest of year. Even though the Lake Årungen catchment area much higher P-AL values then the Skuterud area, this is not expected to ye have affect the proportional factors to any large degree, since changes in soil P-AL are slow, approximately 0.58 unit per year if no fertilizer are added (Krogstad et al. 2008).This may, however, have an effect in a longer time perspective. A reason why the proportional factors may not be constant is mainly because of expected variations in sewage leakage, soil erosion classes and agricultural practice.

The degree of sewage leakage differs greatly within the Lake Årungen catchment area. The most heavily affected Lake Årungen inlet stream is probably Vollebekken, which drain the area where The Norwegian University of Life Sciences is situated (Borch et al. 2007). However, as long as no major improvement of the sanitary conditions are made, the portion of the proportional factors that can be explained by differences in sewage leakage, are expected to remain unchanged.

Erosion class 3 represent soil that have high risk of erosion, and the Lake Årungen catchment area have a higher part of class 3 soil then that of Skuterud area (figure 8). However, runoff from the residual areas does not affect the nutrient concentration of the Lake Årungen inlet streams, and if the class 3 soils from these areas are subtracted, the differences between the Lake Årungen catchment area and the Skuterud area decrease. Erodibility affects the probability of nutrient runoff from agricultural areas. More important though, are probably agricultural practices.

As Lundekvam (2007) showed, agricultural practice are very important determining nutrient loss, and might overshadow some of the differences in erodibility. Even though farmers are encouraged by the Agricultural Authorities to minimize phosphorus runoff by applying reduced tillage in autumn, they decide, to a large degree, what agricultural practices should take place on their own land. These differences are not always distributed equally throughout the lake catchment area. There are, however, reasons to believe that some annual changes in agricultural practice are the same for the Lake Årungen catchment area and the

Skuterud area. Some changes are likely to occur as a response to annual variations in climate, e.g. timing of autumn flood. If conditions for a certain agricultural practice are especially good, it is highly likely that it is equally good for the whole Lake Årungen catchment area, and that differences in practice is evenly distributed.

The uncertainties regarding Tot-P and suspended matter transport are probably larger than those of the hydrological properties. However, exactly how much the calculated Tot-P and suspended matter vary from *in situ* observations in the Lake Årungen inlet streams is unknown. The proportional factors should be compared and correlated with values from other years, sampled at different times of the year, but no such data of high resolution exists. However, there are reasons to believe that the method is better if the alternative is few random samples (Gunnarsson 2007). The applicability of a dataset based on concentrations from the Skuterud area are summarized and discussed in section 4.3.

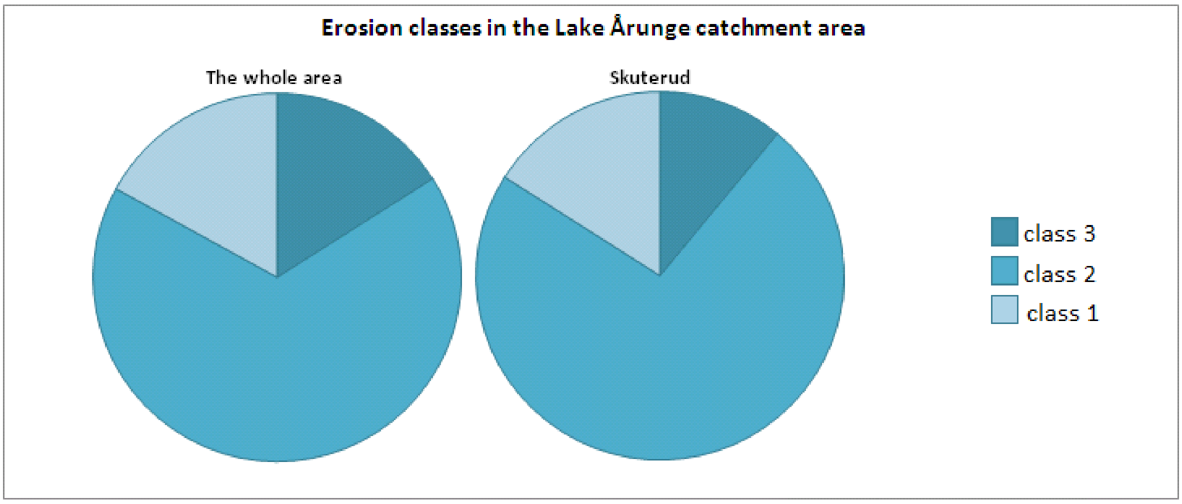


Figure 8. Relative erosion in the whole Lake Årungen catchment area compared to the Skuterud area. Class 1-3 specify the different erosion classes; 1 = small risk of erosion (annual soil loss <50 kg daa^{-1}), 2 = medium risk of erosion (annual soil loss 50-200 kg daa^{-1}), 3 = high risk of erosion (annual soil loss 200-800 kg daa^{-1}). From Gunnarsson (2007), based on erosion risk maps from The Norwegian Forest and Landscape Institute.

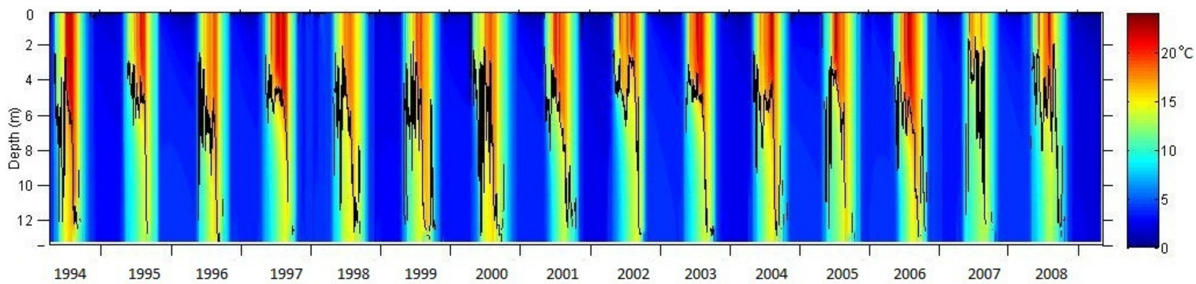
4.3 MyLake Årungen application

The MyLake Årungen application was based on dataset 4 and run from 1st January 1994 to 30th April 2009. A special focus was put on the period from 1st January 2006 to 30th April 2009, since this is a period with high resolution of observed values. All parameters used in this model run is based on the Vansjø-Storefjorden application by Saloranta and Andersen (2007).

4.3.1 Water temperature

As figure 9A show, there are large variations in summer lake stability in Lake Årungen. The deep blue colours represent the cold winter temperatures, with small temperature variations in the water column, while the warmer yellow and red colours indicate the summer temperatures. A special feature of Lake Årungen is the deep thermocline (black line) compared to lake depth. The upper half is often circulated, and for some summers, almost no stable stratification exists. Figure 9B show the temperature profiles from 1st January 1994 to 30th April 2009. The lake was particular stably stratified in 2006, but still in this year, thermocline depth varied much throughout the algal growth season. Thermocline depth mostly varied between 3-8 m in this period.

A



B

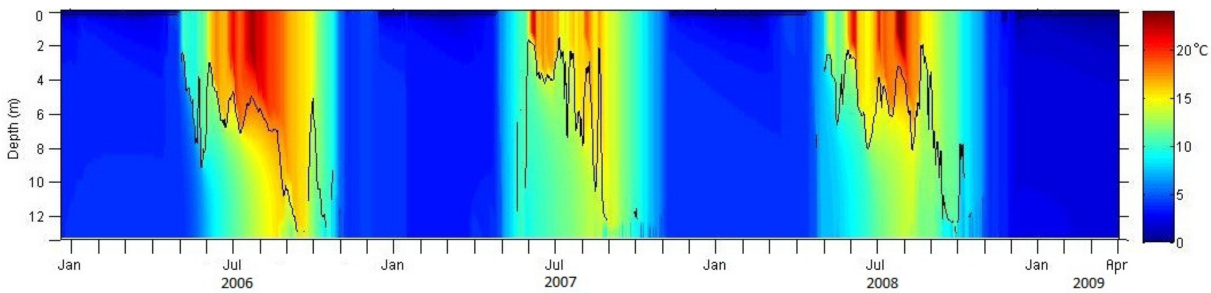


Figure 9. Modelled temperature profiles from (A) 1st April 1994 to 30th April 2009 and (B) 1st January 2006 to 30th April 2009 in Lake Årungen. Black lines denote the depth of the thermocline.

There is very good correlation between simulated and observed surface temperatures (figure 10), but the correlation often gets weaker with depth, especially in summer (figure 11). Very often thermocline depth is simulated at a higher depth than observed, and lake bottom temperatures are colder than simulated. Saloranta (2006) showed that the two parameters that had largest influence on thermocline depth in Lake Vansjø-Storefjorden, were the wind sheltering parameter (C-shelter) and the light attenuation coefficient (swa_b1). Lake Vansjø-Storefjorden is a big and complex lake system, with several large bays and islands. Lake Årungen is, because of its lake morphology and situation in the landscape, very exposed to wind (Hexum 1963). The lake is approximately 3 km long and only around 0.5 km wide, and with no islands, fetch is probably large compared to other lakes with similar area. Even though no sensitivity analysis was run in this study, there are several reasons to believe that the wind sheltering parameter is very different from that of Lake Vansjø-Storefjorden. Before any further assumptions can be made, the model need to be calibrated based on observations from Lake Årungen.

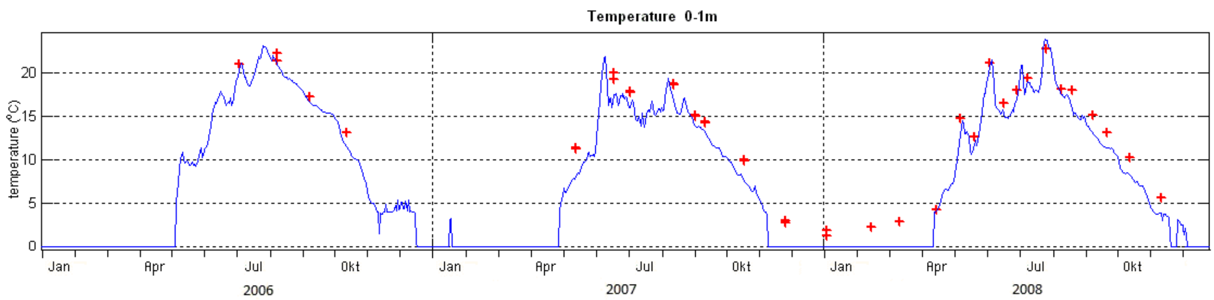


Figure 10. Simulated (solid lines) and observed (+) surface (0-1 m) temperatures in Lake Årungen from 1st January 2006 to 31st December 2008.

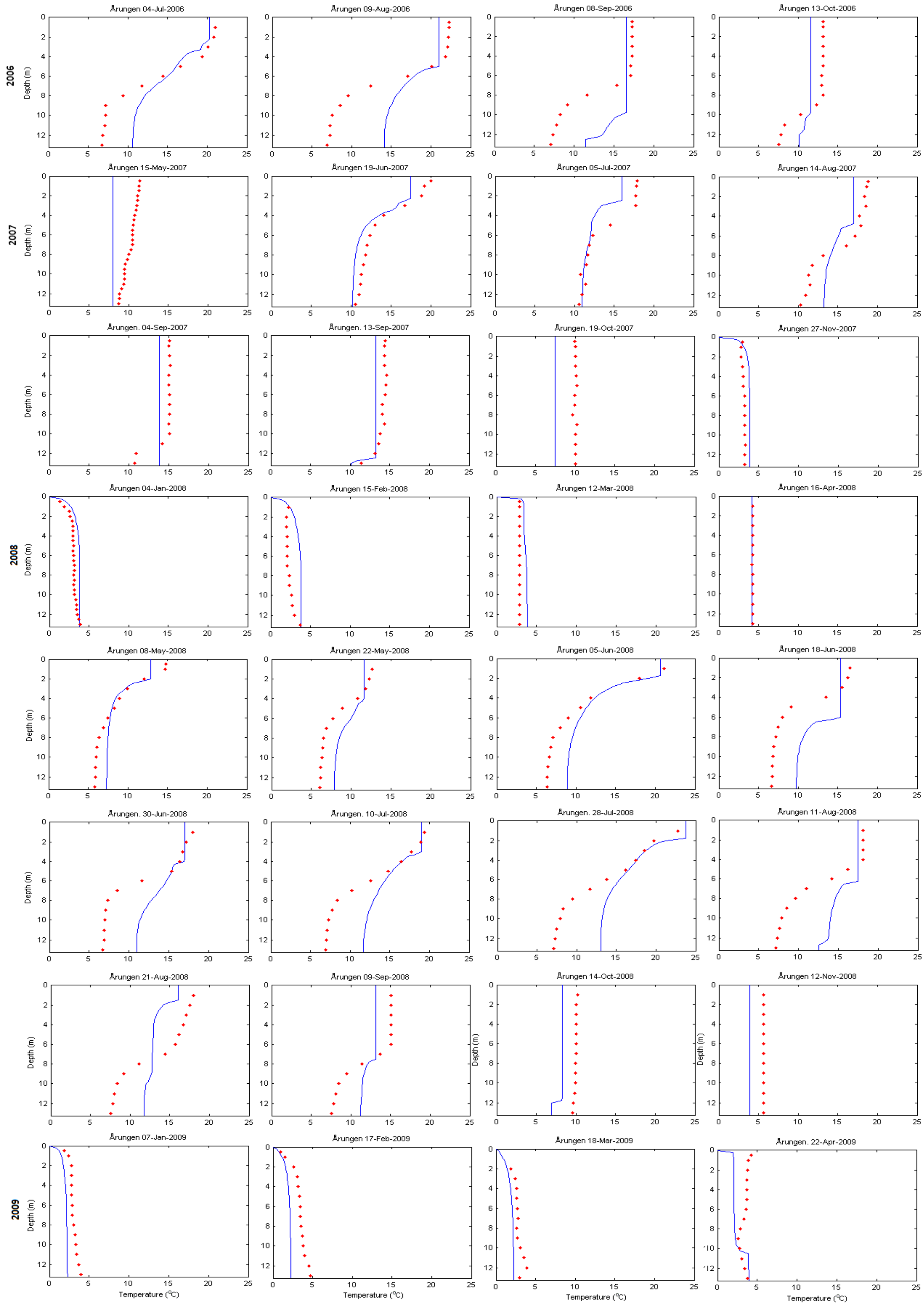


Figure 11. Simulated (solid lines) and observed (dots) temperature profiles in Lake Årungen from 4[th] July 2006 to 22[nd] April 2009.

4.3.2 Ice thickness and snow cover

The MyLake model show large annual variations in ice and snow cover for Lake Årungen, from highly variable ice conditions in winter 1997/1998 with maximum thickness of 27 cm and no permanent snow cover, to the winter of 2008/2009 with almost half a meter thick ice and 15 cm snow cover (figure 12A).

Except for some differences with the latest ice thickness observations of March 2010, the correlation between simulated and observed ice thickness is very good (figure 12B). No observations of snow cover are registered, but there are reasons to believe that MyLake modelling of both ice thickness and snow cover are reliable.

A

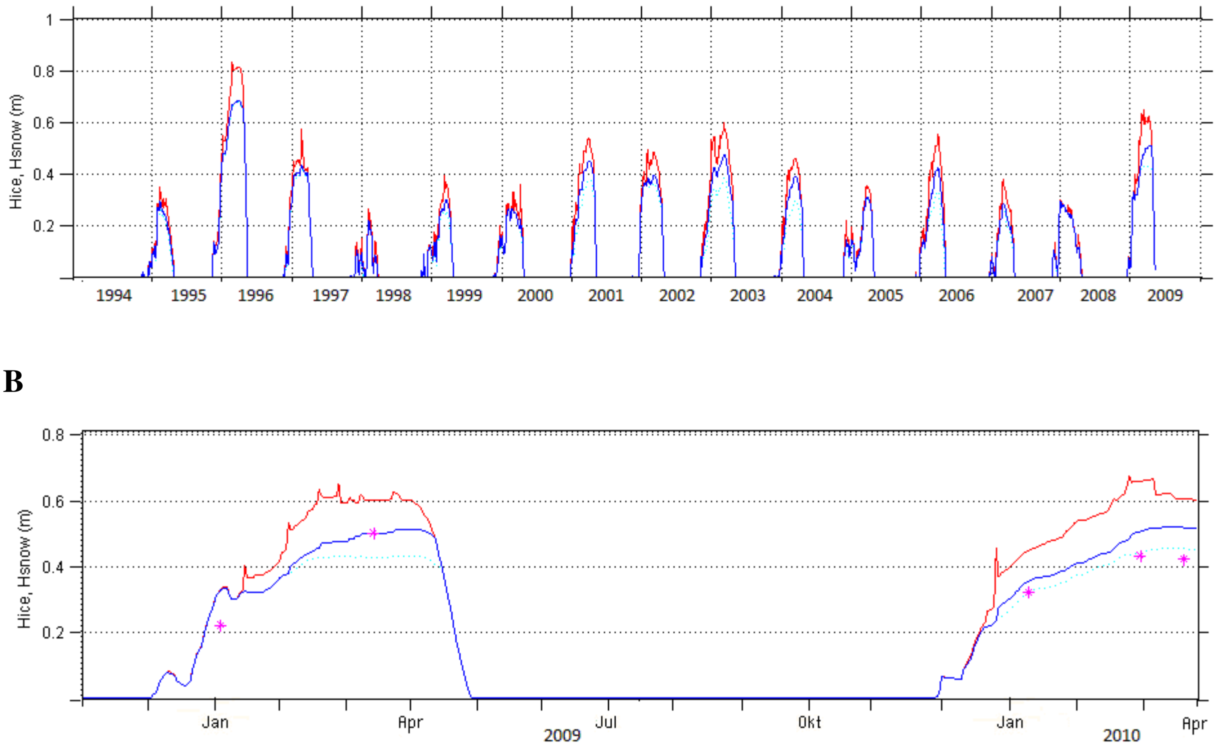


Figure 12. Modelled thickness of ice (solid lines) and snow cover (lines drawn on top of ice thickness) in Lake Årungen from (A) 1st April 1994 to 30th April 2009 and (B) 1st November 2008 to 31th March 2010. Asterisks (*) in 11B indicate observations of ice thickness (two asterisks in 2009 and three in 2010).

4.3.3 Suspended matter and phosphorus

As with temperature, there are large annual variations of phosphorus concentrations in the surface layer. Figure 13 show phosphorus (Chlorophyll, DIP, PIP and DOP) concentrations in the surface layer (0-4m) of Lake Årungen from 1994-2009. The figure is cumulative, which means that the very top line display the tot-P concentration, divided again into the contribution of the phosphorus fractions. The connection between the various simulated phosphorus fractions were reproduced in section 2.2. The concentrations of chlorophyll (algae) are directly related to the concentration of algae available. The highest phosphorus concentrations are found during winter, after nutrients from the catchment area have been spilled into the lake by the autumn flood, and water with high phosphorus concentrations from deep areas are mixed with rest of the lake. The phosphorus concentration will, however, dramatically decrease after the start of algal growth season, and the lowest concentrations of phosphorus is seen right after a peak in algal growth. Figure 14 show profiles of dissolved phosphorus (A), chlorophyll (B), PIP (C) and suspended matter (D) throughout the study period. While lake concentrations of dissolved phosphorus and chlorophyll concentrations show negative related variations during the algal growing season, concentrations of PIP and suspended matter are more sporadic, and typically connected with spring and autumn floods, and measures against erosion in the catchment area.

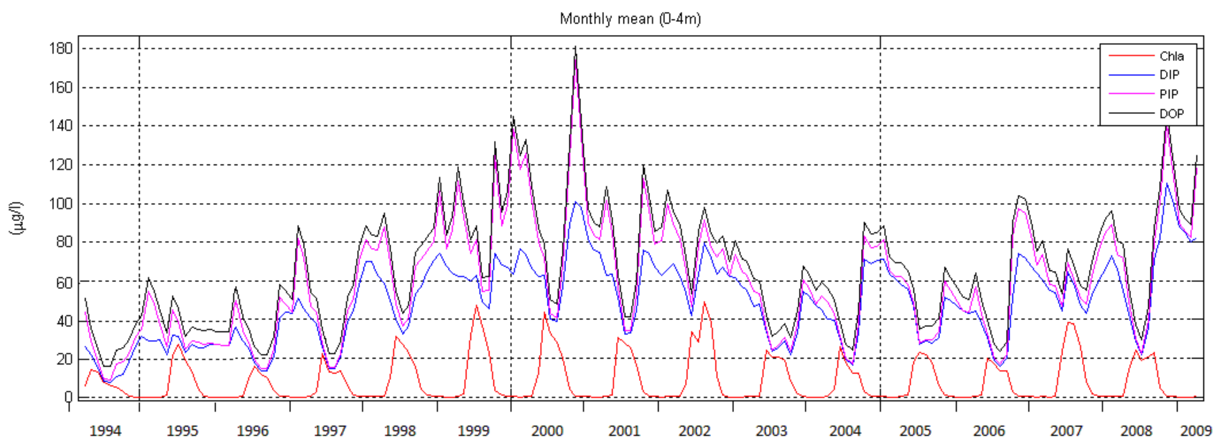


Figure 13. Modelled cumulative concentrations ($\mu g\ l^{-1}$) of the phosphorus fractions. From the bottom; chlorophyll (Chla), dissolved inorganic phosphorus (DIP), particulate inorganic phosphorus (PIP) and dissolved organic phosphorus (DOP) in Lake Årungen from 1st April 1994 to 30th April 2009.

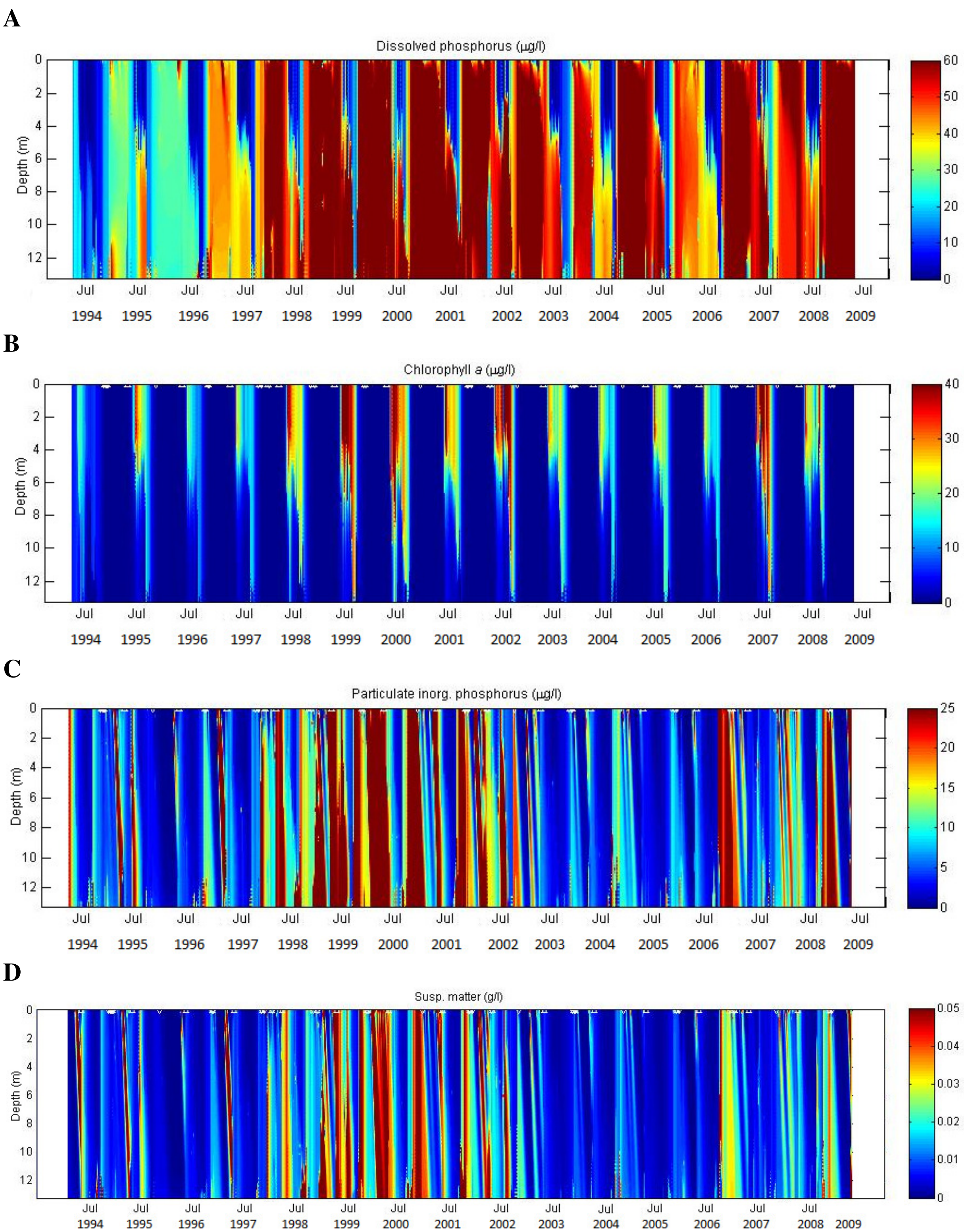
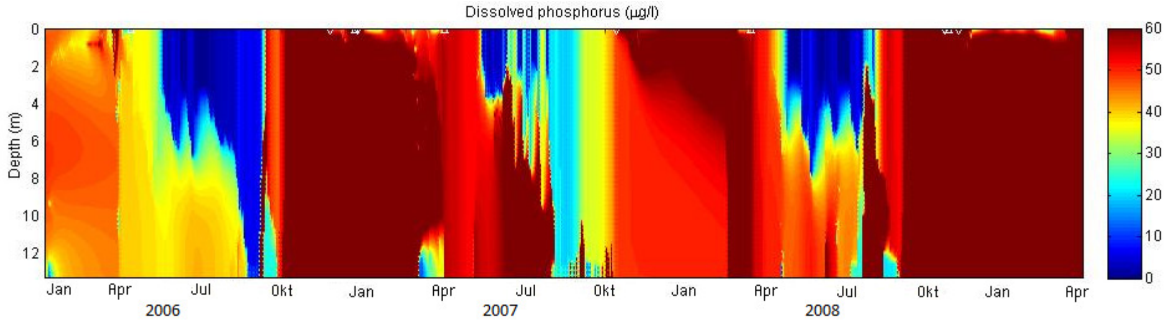


Figure 14. Modelled profiles of (A) dissolved phosphorus (µg l^{-1}), (B) chlorophyll (µg l^{-1}), (C) particulate inorganic phosphorus (µg l^{-1}) and (D) suspended matter (g l^{-1}) in Lake Årungen from 1st April 1994 to 30th April 2009.

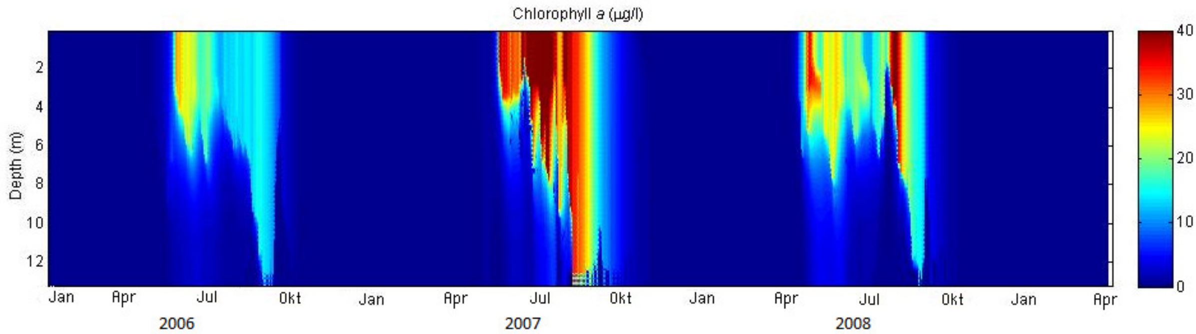
Figure 15 shows simulated profiles of dissolved phosphorus (A), chlorophyll (B), PIP (C) and suspended matter (D) in Lake Årungen from 1st January 2006 to 30th April 2009. The correlation between simulated and observed surface layer (0-4m) concentrations varies for the different phosphorus fractions. Simulated Tot-P concentrations are similar to the modelled (figure 16A). The most obvious exceptions are the last three observations in 2008 and the very last in 2009 (April), which are much lower than the simulated, and one observation the 16th April 2008, which is much higher than the simulated one. The correlation between simulated and observed DIP (figure 16B) is not as good as for Tot-P. As with Tot-P, the simulated 2006 concentrations are more similar to the observed than later values. Simulated concentrations from November 2008 to April 2009 are the least similar compared with the observations. Simulated concentrations of suspended matters (figure 16C) are also similar to the observed values, with especially six exceptions. The differences are especially large the 13th October 2006 and 22nd April 2009, while the differences 4th January, 16th April, 17th September and 14th October are smaller. Overall, the simulated concentrations for both Tot-P, DIP and suspended matter tend to be higher than the observed concentrations.

As mentioned earlier, the proportional factors used to calculate nutrient runoff from the Lake Årungen catchment area should be calibrated. The lack of correlation between modelled and observed concentrations might be because no such calibration has been made. Another obvious reason is that since the MyLake model failed to accurately simulate the density stratification dependent properties of Lake Årungen, which might have a cascading affect on the simulated nutrient concentration. However, as with temperature, the parameters used to simulate phosphorus-phytoplankton dynamics in Årungen were also calibrated for Lake Vansjø-Storefjorden, and further calibration is needed before further assumption can be made. This only emphasizes the need for sensitivity analysis and calibration of the MyLake model parameters pursuant to Lake Årungen.

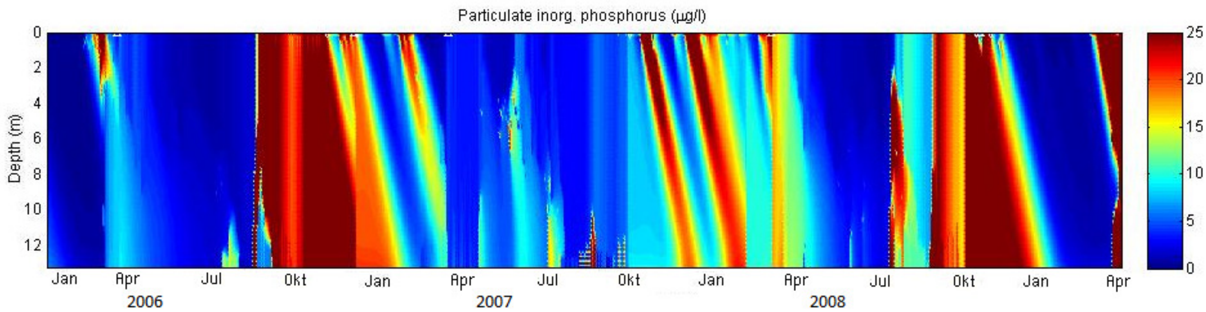
A



B



C



D

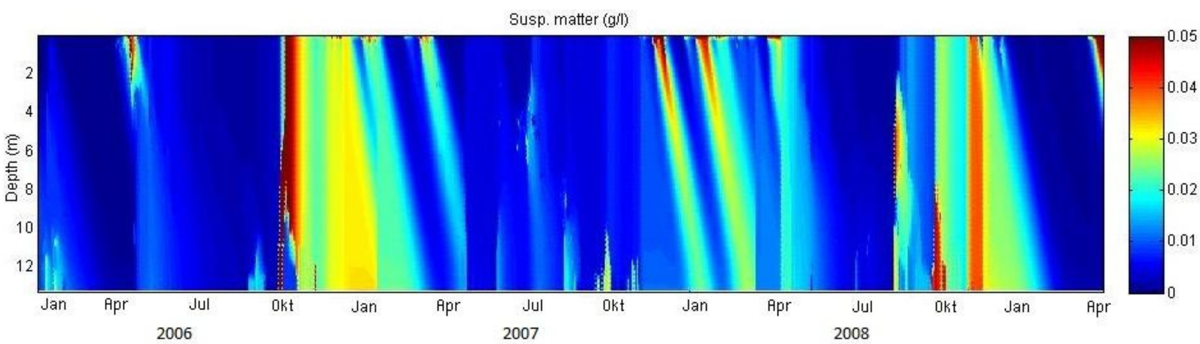


Figure 15. Modelled profiles of (A) dissolved phosphorus (μg l^{-1}), (B) chlorophyll (μg l^{-1}), (C) particulate inorganic phosphorus (μg l^{-1}) and (D) suspended matter (g l^{-1}) in Lake Årungen from 1st January 2006 to 30th April 2009.

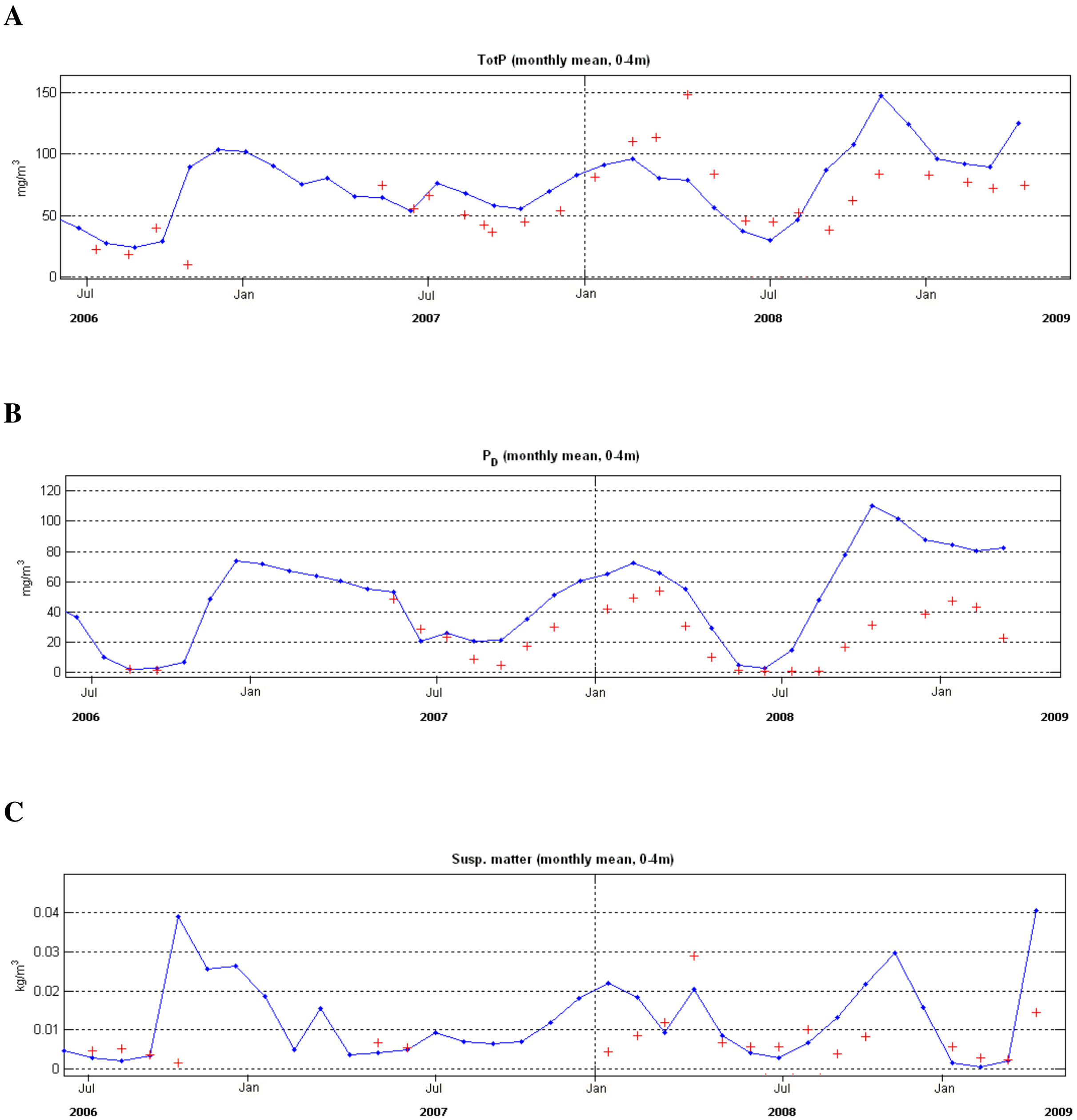


Figure 16. Simulated (solid lines) and observed (+) surface layer (0-4 m) monthly mean concentrations of (A) total phosphorus (mg m^{-3}), (B) dissolved inorganic phosphorus (mg m^{-3}) and (C) suspended matter (kg m^{-3}) in Lake Årungen from 1st June 2006 to 30th April 2009.

4.4 MyLake as a tool for present and future Lake Årungen management

As the results from this MyLake evaluation has shown, some simulated values are different from the observed. Before MyLake can be used as a managerial tool, certain steps have to be evaluated. These steps are further discussed in Saloranta (2006) and Saloranta and Andersen (2007):

- Step 1 – Sensitivity analysis. To run a satisfactory sensitivity analysis hundreds and thousands of model runs are needed, where the model has access to and the alternative to change parameters and variables at each model run. Because the MyLake model is developed to run Monte Carlo simulations, the model is well suited for this kind of analysis. The goal is to analyse the models sensitivity to changes in the parameter values, e.g. by an Extended Fourier Amplitude Sensitivity Test (Extended FAST) global sensitivity method. This method traces and calculates the contribution from different parameters to the total variance of the model output.
- Step 2 – Calibration. The next thing is to calibrate parameters found in the sensitivity analysis to observed values, e.g. monthly mean values. The goal is to minimize the sum of squares between simulated and observed values. The calibration will change the values of the parameter file.
- Step 3 – Evaluation. After calibration, the model needs an evaluation period, where simulated and observed values are compared. For obvious reasons, this period cannot be within the same as the calibration period. If the result of the evaluation period is unsatisfactory, further parameter calibration may be carried out. If the result is satisfactory, the model is now ready to be applied in the lake management.
- Step 4 – Uncertainty analysis. To assess the effect of different phosphorus reduction scenarios, uncertainty analysis will have to be run. This is important, as it will give the decision makers the probability and range of model output. As with sensitivity analysis, uncertainty analysis needs hundreds and thousands of model runs.

Regardless if future climate change is “natural” or anthropogenic, climate models are among the strongest tools in assessing future impacts on water quality. Even though nutrient runoff is expected to increase due to climate change (Bouraoui et al. 2002), the impact on eutrophication is difficult to assess as lake trophic level is a result of the interactions between nutrient availability, light conditions, temperature, residence time and flow conditions (Jeppesen et al. 2005). The MyLake model makes it possible to simulate the effect of future climate forecasts, as well as estimate how much nutrient reduction is needed to meet managerial goals under the new climate regimes. Saloranta et al. (2009) simulated the thermodynamic impact of projected future climate on one shallow and one deep lake in Finland using the MyLake model. The results showed among others that the largest temperature changes probably will occur in April-May, affecting lake ice cover and spring plankton phenology.

Models can provide much information and understanding of what can happen in an ecological system, but not necessarily what it will do (Saloranta & Andersen 2007). Applying a model in lake management without taking regard of model uncertainties can lead to misleading results and wrong decisions. However, with caution, the MyLake model may be well suited as a managerial tool in Lake Årungen restoration.

5 Conclusion

Even though mathematical numerical models have become very important in lake management, many model codes are too advanced and expensive, and may limit the applicability for lake managers. Although MyLake is a relatively simple model, it describes to a large extent various lake processes affected by weather and catchment area in a clear and satisfactory manner (Saloranta & Andersen 2007). Unlike many much simpler models (like the Vollenweider type model), MyLake can increase our understanding of not only how a potential phosphorus reduction may have an impact on the lake system, but also when, where and under what climate conditions (Saloranta et al. 2009).

Dataset 1 (Grøterud & Rosland 1981) is the only available data of Lake Årungen inflow properties from the late 1970s. However, there are reasons to believe that these data for the most part represent the annual nutrient run off and flow of water in a satisfactory way. Inflow properties based on dataset 4 (JOVA program) are probably the best available time series after 1993, although newly measurements for further calibration should be carried out. However, there are several reasons to believe that dataset 4 gives a better estimation of nutrient transport and water flow, than transport surveys based on few random samples. The model might, when combined with dataset 4 and the meteorological station at Ås, prove to be a very useful tool in the management and evaluation of Lake Årungen.

6 References

Arnell, N. (2002). *Hydrology and global environmental change*. Harlow: Prentice Hall. 346 pp.

Bechmann, M. E., Berge, D., Eggestad, H. O. & Vandsemb, S. M. (2005a). Phosphorus transfer from agricultural areas and its impact on the eutrophication of lakes - two long-term integrated studies from Norway. *Journal of Hydrology*, 304 (1-4): 238-250.

Bechmann, M. E., Kleinman, P. J. A., Sharpley, A. N. & Saporito, L. S. (2005b). Freeze-thaw effects on phosphorus loss in runoff froin manured and catch-cropped soils. *Journal of Environmental Quality*, 34 (6): 2301-2309.

Blenckner, T., Adrian, R., Livingstone, D. M., Jennings, E., Weyhenmeyer, G. A., George, D. G., Jankowski, T., Jarvinen, M., Aonghusa, C. N., Noges, T., et al. (2007). Large-scale climatic signatures in lakes across Europe: a meta-analysis. *Global Change Biology*, 13 (7): 1314-1326.

Blunden, B. G. & Indraratna, B. (2000). Evaluation of surface and groundwater management strategies for drained sulfidic soil using numerical simulation models. *Australian Journal of Soil Research*, 38 (3): 569-590.

Borch, H., Yri, A., Løvstad, Ø. & Turtumøygard, S. (2007). Tiltaksplan for Årungen. *Bioforsk Rapport*, 2 (52).

Bouraoui, F., Galbiati, L. & Bidoglio, G. (2002). Climate change impacts on nutrient loads in the Yorkshire Ouse catchment (UK). *Hydrology and Earth System Sciences*, 6 (2): 197-209.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N. & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 8 (3): 559-568.

Chau, K. W. (2003). Manipulation of numerical coastal flow and water quality models. *Environmental Modelling & Software*, 18 (2): 99-108.

Christophoridis, C. & Fytianos, K. (2006). Conditions affecting the release of phosphorus from surface lake sediments. *Journal of Environmental Quality*, 35 (4): 1181-1192.

Deelstra, J., Vagstad, N. & Øygarden, L. (1998). *Sampling technique and strategy. In: Øygarden L. & Botterweg P. (eds.), Measuring runoff and nutrient loss from agricultural land in Nordic countries.* TemaNord, Nordic Council of Ministers. Copenhagen, Denmark. 27-35 pp.

Deelstra, J. & Øygarden, L. (1998). *Measurement of runoff. In: Øygarden L. & Botterweg P. (eds.), Measuring runoff and nutrient loss from agricultural land in Nordic countries.* TemaNord, Nordic Council of Ministers. Copenhagen, Denmark. 13-26 pp.

Deelstra, J. (2005). *A general description of the Skuterud catchment*. Jordforsk report no. 61/05. Ås, Norway: Bioforsk. 46 pp.

Edmondson, W. T. (1970). Phosphorus, nitrogen, and algae in Lake Washington after diversion of sewage. *Science*, 169 (3946): 690-691.

Fetter, C. W. (2001). *Applied hydrogeology*. Upper Saddle River, N.J.: Prentice-Hall. XVII, 598 s. pp.

George, D. G., Talling, J. F. & Rigg, E. (2000). Factors influencing the temporal coherence of five lakes in the English Lake District. *Freshwater Biology*, 43 (3): 449-461.

Grøterud, O. & Rosland, F. (1981). *Vannbalanse og stofftransport i Årungens nedbørfelt 1977-79*. Ås-NLH. 54, [39] bl. pp.

Gunnarsson, J. O. (2007). *Massebalanse studier i innsjøen Årungen. MSc Thesis*. Ås: University of Life Sciences. 146 s. pp.

Haraldsen, T. K., Oygarden, L., Rognerud, B. & Aastveit, A. H. (1995). Correlations between concentrations of plant nutrients in runoff from small catchments in Norway. *Nordic Hydrology*, 26 (2): 91-110.

Hassan, H., Aramaki, T., Hanaki, K., Matsuo, T. & Wilby, R. (1998). Lake stratification and temperature profiles simulated using downscaled GCM output. *Water Science and Technology*, 38 (11): 217-226.

Henry, H. A. L. (2007). Soil freeze-thaw cycle experiments: Trends, methodological weaknesses and suggested improvements. *Soil Biology and Biochemistry*, 39 (5): 977-986.

Hexum, E. (1963). *En limnologisk undersøkelse av Årungen i Ås kommune. MSc Thesis*. Oslo: E. Hexum. 88 s. pp.

Hurrell, J. W. (1995). Decadal trends in the North-Atlantic Oscilliations - Regional temperatures and precipitation. *Science*, 269 (5224): 676-679.

IPCC. (2007). *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC Fourth Assessment Report: Climate Change 2007 (AR4). IPCC, Geneva, Switzerland. 77 pp.

ISO. (2008). *Hydrometry - Open channel flow measurement using thin-plate weirs*. ISO 1438 (E).

Jeppesen, E., Sondergaard, M., Jensen, J. P., Havens, K. E., Anneville, O., Carvalho, L., Coveney, M. F., Deneke, R., Dokulil, M. T., Foy, B., et al. (2005). Lake responses to reduced nutrient loading - An analysis of contemporary long-term data from 35 case studies. *Freshwater Biology*, 50 (10): 1747-1771.

Jeppesen, E., Kronvang, B., Meerhoff, M., Sondergaard, M., Hansen, K. M., Andersen, H. E., Lauridsen, T. L., Liboriussen, L., Beklioglu, M., Ozen, A., et al. (2009). Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. *Journal of Environmental Quality*, 38 (5): 1930-1941.

Kankaala, P., Huotari, J., Peltomaa, E., Saloranta, T. & Ojala, A. (2006). Methanotrophic activity in relation to methane efflux and total heterotrophic bacterial production in a stratified, humic, boreal lake. *Limnology and Oceanography*, 51 (2): 1195-1204.

Khan, F. A. & Ansari, A. A. (2005). Eutrophication: An ecological vision. *Botanical Review*, 71 (4): 449-482.

Krogstad, T. & Løvstad, Ø. (1991). Available soil phosphorus for planktonic blue-green algae in eutrophic lake water samples. *Arch. Hydrobiol*, 122: 117-128.

Krogstad, T., Øgaard, A. F. & Kristoffersen, A. Ø. (2008). New P recommendations for grass and cereals in Norwegian agriculture. *NJF Report*, 4 (4): 42-46.

Lundekvam, H. E. (2002). *ERONOR/USLENO Empirical erosion models for Norwegian conditions*. Rep 6/2002 Agricultural University of Norway. 40 pp.

Lundekvam, H. E. (2007). Plot studies and modelling of hydrology and erosion in southeast Norway. *Catena*, 71 (2): 200-209.

Lydersen, E., Aanes, K. J., Andersen, S., Andersen, T., Brettum, P., Bækken, T., Lien, L., Lindstrøm, E. A., Løvik, J. E., Mjelde, M., et al. (2003). *THERMOS-prosjektet: Fagrapport 1998–2002*. NIVA report 4720-2003, Norwegian Institute for Water Research, Oslo, Norway, 119 pp.

Løvstad, Ø. (1996-2009). *Limnologisk, lokal vannkvalitetsovervåkning*. [S.l.] Limno-consult: Ås kommune. 14 pp.

McRoberts, E. C. & Morgenstern, N. R. (1974). The Stability of Thawing Slopes. *Canadian Geotechnical Journal*, 11: 447–469.

Morand, P. & Briand, X. (1996). Excessive growth of macroalgae: A symptom of environmental disturbance. *Botanica Marina*, 39 (6): 491-516.

Olesen, J. E., Rubaek, G. H., Heidmann, T., Hansen, S. & Borgensen, C. D. (2004). Effect of climate change on greenhouse gas emissions from arable crop rotations. *Nutrient Cycling in Agroecosystems*, 70 (2): 147-160.

Pedersen, T. (2007). *Klaretjern: limnologisk undersøkelse og termikkmodellering. MSc Thesis*. Oslo: T. Pedersen. vi, 67 s. pp.

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 193 (1032): 120-145.

Penman, H. L. (1956). Estimating evaporation. *Trans. American Geophysical Union*, 37 (1).

Reed, R. K. (1977). Estimating insolation over ocean. *Journal of Physical Oceanography*, 7 (3): 482-485.

Reid, P. C., Lancelot, C., Gieskes, W. W. C., Hagmeier, E. & Weichart, G. (1990). Phytoplankton of the North-Sea and its dynamics - A review. *Netherlands Journal of Sea Research*, 26 (2-4): 295-331.

Riley, M. J. & Stefan, H. G. (1988). MINLAKE - A dynamic lake water-quality simulation-model. *Ecological Modelling*, 43 (3-4): 155-182.

Romarheim, A. T. & Riise, G. (2009). Development of cyanobacteria in Årungen. *Vann*, 4: 384-393.

Ræstad, E. & Otnes, J. (1978). *Hydrologi i praksis*. Oslo: Ingeniørforlaget. 314 s. pp.

Saloranta, T. M. & Andersen, T. (2004). *MyLake (v.1.1):Technical model documentation and user's guide.* NIVA report 4838, Norwegian Institute for Water Research, Oslo, Norway, 44 pp.

Saloranta, T. M. (2006). Highlighting the model code selection and application process in policy-relevant water quality modelling. *Ecological Modelling*, 194 (1-3): 316-327.

Saloranta, T. M. & Andersen, T. (2007). MyLake - A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecological Modelling*, 207 (1): 45-60.

Saloranta, T. M., Forsius, M., Jarvinen, M. & Arvola, L. (2009). Impacts of projected climate change on the thermodynamics of a shallow and a deep lake in Finland: model simulations and Bayesian uncertainty analysis. *Hydrology Research*, 40 (2-3): 234-248.

Schindler, D. W. (1974). Eutrophication and recovery in experimental lakes - Implications for lake management. *Science*, 184 (4139): 897-899.

Schindler, D. W. (2006). Recent advances in the understanding and management of eutrophication. *Limnology and Oceanography*, 51 (1): 356-363.

Sharma, C. M. & Borgstrøm, R. (2008). Increased population density of pike *Esox lucius* - A result of selective harvest of large individuals. *Ecology of Freshwater Fish*, 17 (4): 590-596.

Skovgaard, H., Løvstad, Ø. & Åstebøl, S. (2009). *Erfaringer med innsjørestaurering og perspektiver for Årungen og Østensjøvann*. Pura rapport, Oslo, Norway, 14 pp.

Straile, D. & Adrian, R. (2000). The North Atlantic Oscillation and plankton dynamics in two European lakes - two variations on a general theme. *Global Change Biology*, 6 (6): 663-670.

Straile, D., Johnk, K. & Rossknecht, H. (2003). Complex effects of winter warming on the physicochemical characteristics of a deep lake. *Limnology and Oceanography*, 48 (4): 1432-1438.

Sundareshwar, P. V. & Morris, J. T. (1999). Phosphorus sorption characteristics of intertidal marsh sediments along an estuarine salinity gradient. *Limnology and Oceanography*, 44 (7): 1693-1701.

The Water Regulation. (2006). *The Norwegian framework regulation on water management. Downloaded 13th April 2010, from Lovdata http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20061215-1446.html*.

Thue-Hansen, V. & Grimenes, A. A. (1996-2003). *Meteorologiske data for Ås 1996-2003.* Agricultural University of Norway.

Thue-Hansen, V. & Grimenes, A. A. (2004-2010). *Meteorologiske data for Ås 2004-2010.* Norwegian University of Life Sciences.

Thue-Hansen, V. & Grimenes, A. A. (2009). *Meteorologiske data for Ås 2009*. Norwegian University of Life Sciences.

Ulen, B., Bechmann, M., Folster, J., Jarvie, H. P. & Tunney, H. (2007). Agriculture as a phosphorus source for eutrophication in the north-west European countries, Norway, Sweden, United Kingdom and Ireland: a review. *Soil Use and Management*, 23: 5-15.

Vollenweider, R. A. (1968). *Water management research. Scientific fundamentals of theeutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication: technical report*. Paris. 1 b. (mult. pag.) pp.

Wade, A. J., Whitehead, P. G., Hornberger, G., Jarvie, H. P. & Flynn, N. (2002). On modelling the impacts of phosphorus stripping at sewage works on in-stream phosphorus and macrophyte/epiphyte dynamics: a case study for the River Kennet. *Science of the Total Environment*, 282: 395-415.

WFD. (2000). *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Downloaded 9th May 2010, from Lovdata* http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32000L0060:EN:NOT.

Whitehead, P. G. & Hornberger, G. M. (1984). Modeling algal behaviour in the river Thames. *Water Research*, 18 (8): 945-953.

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M. & Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological sciences journal*, 54 (1): 101-123.

Wilby, R. L., Orr, H. G., Hedger, M., Forrow, D. & Blackmore, M. (2006). Risks posed by climate change to the delivery of Water Framework Directive objectives in the UK. *Environment International*, 32 (8): 1043-1055.

Zhang, L., Dawes, W. R. & Walker, G. R. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, 37 (3): 701-708.

Øgaard, A. F. (1995). Effect of phosphorus fertilisation and content of plant-available phosphorus (P-AL) on algea-avaiable phosphorus in soils. *Acta Agriculturae Scandinavica, Section B - Soil and Plant Science*, 45: 242-250.

Økland, J. & Økland, K. A. (2006). *Vann og vassdrag 3 - Kjemi, fysikk og miljø*. Stabekk: Vett & viten. 206 pp.

Appendices

Appendix 1. MyLake model input files. The files are written in Excel.

	A	B	C	D	E
1	-999	MyLake model parameters for Lake Årungen			
2	**Parameter**	**Value**	**Min**	**Max**	**Unit**
3	dz	1	0,5	2	m
4	Kz_ak	0,0162	NaN	NaN	(-)
5	Kz_ak_ice	0,000898	NaN	NaN	(-)
6	Kz_N0	7,00E-05	NaN	NaN	s-2
7	C_shelter	7,32E-01	NaN	NaN	(-)
8	latitude	59,42	NaN	NaN	dec.deg
9	longitude	10,83	NaN	NaN	dec.deg
10	alb_melt_ice	0,3	NaN	NaN	(-)
11	alb_melt_sno	0,77	NaN	NaN	(-)
12	PAR_sat	3,00E-05	1,00E-05	1,00E-04	mol m-2 s-1
13	f_par	0,45	NaN	NaN	(-)
14	beta_chl	0,015	0,005	0,045	m2 mg-1
15	lambda_I	5	NaN	NaN	m-1
16	lambda_s	15	NaN	NaN	m-1
17	sed_sld	0,36	NaN	NaN	(m3/m3)
18	I_scV	2,15	NaN	NaN	(-)
19	I_scT	0	NaN	NaN	deg C
20	I_scC	1	NaN	NaN	(-)
21	I_scS	0,466	0,2	0,6	(-)
22	I_scTP	0,466	0,3	0,7	(-)
23	I_scDOP	1	NaN	NaN	(-)
24	I_scChl	1	NaN	NaN	(-)
25	I_scDOC	1	NaN	NaN	(-)
26	swa_b0	2,5	NaN	NaN	m-1
27	swa_b1	1,05	0,8	1,3	m-1
28	S_res_epi	3,63E-07	7,30E-08	1,82E-06	m d-1 (dry mass)
29	S_res_hypo	3,63E-08	NaN	NaN	m d-1 (dry mass)
30	H_sed	0,03	NaN	NaN	m
31	Psat_Lang	2500	NaN	NaN	mg m-3
32	Fmax_Lang	8000	5000	10000	mg kg-1
33	Uz_Sz	0,25	0,1	0,5	m d-1
34	Uz_Chl	0,2	0,1	0,4	m d-1
35	Y_cp	1	NaN	NaN	(-)
36	m_twty	0,2	0,1	0,3	d-1
37	g_twty	1,5	1	1,5	d-1
38	k_sed_twty	2,00E-04	NaN	NaN	d-1
39	k_dop_twty	0	NaN	NaN	d-1
40	P_half	0,2	0,2	2	mg m-3

Lake / Ark2 / Ark3

Figure A1. Example of MyLake model parameter file. For full description of the parameter list, readers are referred to Saloranta and Andersen (2004).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	-999	MyLake model input for Lake Årungen												
2	Z (m)	Az (m2)	Tz (deg C)	Cz	Sz (kg/m3)	TPz (mg/m3)	DOPz (mg/m	Chlaz (mg/m	DOCz (mg/m	TPz_sed (mg	Chlaz_sed (n	Fvol_IM (m3/	Hice (m)	Hsnow (m)
3	0	1180000	4	0	0,004	21	7	7	3000	756732	196747	0,92	0	0
4	0,5	1137500	4	0	0,004	21	7	7	3000	756732	196747	0,92		
5	1	1095000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
6	1,5	1052500	4	0	0,004	21	7	7	3000	756732	196747	0,92		
7	2	1010000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
8	2,5	980000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
9	3	950000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
10	3,5	920000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
11	4	890000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
12	4,5	862500	4	0	0,004	21	7	7	3000	756732	196747	0,92		
13	5	835000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
14	5,5	807500	4	0	0,004	21	7	7	3000	756732	196747	0,92		
15	6	780000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
16	6,5	747500	4	0	0,004	21	7	7	3000	756732	196747	0,92		
17	7	715000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
18	7,5	682500	4	0	0,004	21	7	7	3000	756732	196747	0,92		
19	8	650000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
20	8,5	600000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
21	9	550000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
22	9,5	500000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
23	10	450000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
24	10,5	395000	4	0	0,004	21	7	7	3000	756732	196747	0,92		
25	11	340000	4	0	0,004	21	7	7	3000	756732	196747	0,92		

Lake / Ark2 / Ark3

Figure A2. Example of MyLake model morphometry and initial profile file. From left; Layer (depth), Horizontal areas, Initial profile of temperature, Initial profile of passive tracer, Initial profile of suspended matter, Initial profile of total phosphorus, Initial profile of dissolved organic phosphorus, Initial profile of chlorophyll *a*, Initial profile of dissolved organic carbon, Initial profile of sediment store of total phosphorus, Initial profile of sediment store of chlorophyll *a*, Initial sediment solids volume fraction of inorganic matter, Initial value of total ice thickness, and Initial value of snow thickness. For variable unit, see table 3.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	-999	Innførsel Årungen, Harald Askilsrud master - 2010																
2	Year	Month	Day	Global_rad	Cloud_cov	Air_temp	Relat_hum	Air_press	Wind_speed	Precipitation	Inflow	Inflow_T	Inflow_C	Inflow_S	Inflow_TP	Inflow_DOP	Inflow_Chla	Inflow_DOC
3	1996	1	1	0,41	0,78	-6,8	92,3	1010,0	0,7	0,3	484	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
4	1996	1	2	0,61	0,67	-11,8	85,4	1012,4	1,2	0,1	380	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
5	1996	1	3	0,79	0,57	-14,3	85,4	1015,3	0,8	0,1	344	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
6	1996	1	4	0,97	0,49	-14,1	85,3	1013,0	0,7	0,1	312	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
7	1996	1	5	0,63	0,68	-11,1	87,8	1009,6	0,9	0,0	278	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
8	1996	1	6	0,28	0,87	-10,2	87,7	1010,6	1,6	9,0	654	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
9	1996	1	7	0,19	0,92	-1,5	92,6	999,5	2,3	0,0	551	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
10	1996	1	8	0,50	0,77	0,0	96,2	1002,6	1,3	4,5	696	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
11	1996	1	9	0,33	0,86	0,5	96,6	1003,7	2,0	3,0	740	0,0	0,5	0,0243	136,8	7,0	0,1	3000,00
12	1996	1	10	0,28	0,88	1,3	96,8	1004,0	2,0	4,9	1018	0,6	0,5	0,0243	136,8	7,0	0,1	3000,00
13	1996	1	11	0,24	0,90	1,2	96,0	1000,9	2,4	1,6	3859	1,0	0,5	0,0041	23,2	7,0	0,1	3000,00
14	1996	1	12	0,24	0,91	1,0	95,2	1000,6	2,3	0,0	5341	1,1	0,5	0,0066	28,0	7,0	0,1	3000,00
15	1996	1	13	0,26	0,90	0,9	96,0	1004,2	1,7	10,5	5377	1,0	0,5	0,0092	32,8	7,0	0,1	3000,00
16	1996	1	14	0,35	0,87	1,0	96,3	1015,7	1,4	0,0	22358	1,0	0,5	0,0117	37,6	7,0	0,1	3000,00
17	1996	1	15	0,62	0,76	1,0	97,0	1020,5	1,4	0,7	20569	1,0	0,5	0,0143	42,4	7,0	0,1	3000,00
18	1996	1	16	0,63	0,77	-0,7	96,0	1016,8	2,7	0,1	15803	0,4	0,5	0,0168	47,2	7,0	0,1	3000,00
19	1996	1	17	0,61	0,78	-2,3	96,6	1018,4	1,4	0,0	8448	0,0	0,5	0,0194	52,0	7,0	0,1	3000,00
20	1996	1	18	0,48	0,84	-2,6	90,7	1018,2	1,5	0,2	5889	0,0	0,5	0,0219	56,9	7,0	0,1	3000,00
21	1996	1	19	0,61	0,80	-2,0	89,0	1019,8	1,7	0,0	4444	0,0	0,5	0,0245	61,7	7,0	0,1	3000,00
22	1996	1	20	1,36	0,53	-1,9	80,9	1025,0	2,3	0,0	3661	0,0	0,5	0,0270	66,5	7,0	0,1	3000,00
23	1996	1	21	2,68	0,09	-7,4	83,9	1027,0	1,5	0,0	3157	0,0	0,5	0,0296	71,3	7,0	0,1	3000,00
24	1996	1	22	0,84	0,74	-5,4	85,1	1027,0	2,2	0,1	2502	0,0	0,5	0,0321	76,1	7,0	0,1	3000,00
25	1996	1	23	0,78	0,77	-6,5	84,1	1025,4	2,5	0,4	2259	0,0	0,5	0,0347	80,9	7,0	0,1	3000,00

timeseries / Ark2 / Ark3

Figure A3. Example of MyLake model forcing data file. From left; Year, Month, Day, Global radiation, Cloud cover, Air temperature at 2 meter height, Relative humidity at 2 meter, Air pressure at station level height, Wind speed at 10 meter height, Precipitation, Inflow volume, Inflow temperature, Inflow concentration of passive tracer, Inflow concentration of suspended matter, Inflow concentration of total phosphorus, Inflow concentration of dissolved organic phosphorus, Inflow concentration of chlorophyll *a*, and Inflow concentration of dissolved organic carbon. For variable unit, see table 3.