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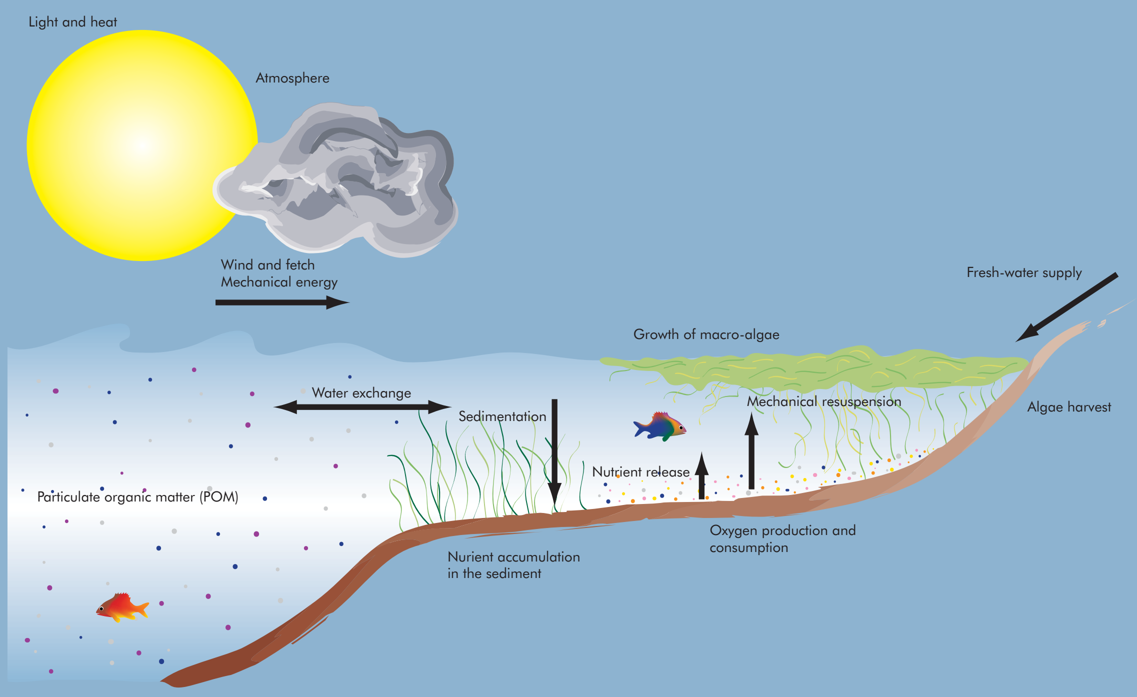
# *Modelling filamentous algae mats in shallow bays*



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# Förord

Denna rapport, *”Modelling filamentous algae mats in shallow bays”*, har tagits fram inom projektet EU Life algae och ingår i projektets rapportserie, se omslagets bakre insida.

Rapporterna i serien redovisar arbete och resultat från delprojekt, seminarier och konferenser. Materialet har legat till grund för slutrapporteringen till EU Life, *”Final Report 2001*”, och en populärvetenskaplig sammanfattande broschyr på svenska och engelska; *”Alger i överflöd skördas för livet”* - *”Algae in excess* - *harvesting for Life”*. Författarna svarar för rapporternas innehåll och Projekt Management Unit för slutredigeringen. Rapporterna kan läsas på eller laddas ner från projektets webbplats;

www.o.lst.se/projekt/eulife-algae

Projektets grundläggande idé och mål är att återskapa en långsiktigt hållbar miljö i de grunda havsvikar som sedan flera år tillbaka under somrarna täcks av algmattor till nackdel för såväl fisk och andra organismer i områdena som friluftsliv och turism. Projektet har utvecklat och testat algskörd som en metod att restaurera dessa viktiga rekryterings- och uppväxtområden för fisk och ryggradslösa djur.

Kunskapen om vilka faktorer som styr uppkomsten av mattor av fintrådiga alger är trots god uppfattning om problemets utbredning bristfällig. Denna rapport *”Modelling filamentous algae mats in shallow bays”* har sammanställt befintlig kunskap om hur olika faktorer styr tillväxten hos algerna och bidrar på ett utomordentligt sätt till att öka kunskapen om hur dessa komplexa ekosystem fungerar. Modellen kan också utgöra ett verktyg att användas för riktade åtgärder i lokala avrinningsområden samt att bedöma effekter av algskörd.

Projekt Management Unit

| | | |
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| Harald Sterner | Anna Jöborn | Mattias Sköld |
| Projektdirektör | Projektledare | Projektledare |

# Contents

# 1. Preface

During the last decades it has been observed in the county of Bohuslän that areas covered by mats of filamentous algae have increased in many shallow bays (water depths less than a few metres). To take measures preventing the development of such algae mats one needs to know under which conditions the mats may develop. The intention of the present project was to find out these conditions using available information and to develop a model predicting the possible development of mats of algae in shallow bays. This empirical model might serve to support decisions on removal of algae and regulations of land-based discharges. Using the model it should be possible to find means to reduce and maybe even prevent the development of algae mats in a specific bay, e.g. by reducing local nutrient supplies and/or increasing the water exchange. The developed model was also intended to be used to determine the effects upon sediment quality of removal of algae.

The scientific work needed to reach the objective of the project is partitioned into four work packages (Wp):

**Wp1: Project management**

Proposed start: September 1998

Estimated duration: Summer 2000

**Wp2**: **Gathering of data, literature review and formulation of the working hypothesis.**

Proposed start: September 1998

Estimated duration: November 1998

**Wp3**: **Analysis and construction of an algaecoverage model for shallow bays.**

Proposed start: November 1998

Estimated duration: May 1999

**Wp4**: **Construction and test of the expert system PC-model**

Proposed start: November 1998

Estimated duration: November 1999

# 2. Summary

A model has been assambled that is capable of predicting the occurrence of filamentous algae in shallow bays of the Swedish west coast. It seems that the model produces results which are quite similar to the observations obtained from specific bays on the coast. The model results of nutrient concentrations in the water and sediments of the modelled bays are in accordance with reported observations. Nutrient fluxes from modelled bay sediments to the water column fall within the ranges of sediment to water nutrient fluxes reported in the literature. The biomass of algae and the timing of algae growth in spring and summer obtained in the modelled bays are in accordance with observations from bays on the Swedish west coast. A mechanism simulating natural mechanical harvest of algae in the model reproduces fairly well the degree of algae cover in bays depending on the degree of exposure.

The most important result from the present modelling effort is that the model may explain the general occurrence of filamentous algae mats in shallow bays on the Swedish west coast. According to the model such mats are mainly caused by the accumulation in the bay sediments of organic matter containing nutrients, derived from the sedimentation of particulate organic matter produced in the surface layers of the coastal waters outside the bays. Remineralization of organic matter and the subsequent release of nutrients may then cause the enhanced nutrient concentrations in the bays which are the main driving force of the extensive growths of filamentous algae. The state of filamentous algae cover in a specific bay may then of course further depend on the time of year, the topographic dimensions of the bay, the water exchange, the degree of exposure to winds and waves, the specific supplies of nutrients from land and from the adjacent water body and possibly from other factors as well.

The model may be used as a tool to increase our understanding about processes in shallow bays. The model may also be used as a tool to evaluate the response in a specific bay to varying actions against the growth of macroalgae. Most of the input data to the model are relatively easy to obtain from existing data bases and from sea charts. Possibly one has to do a brief visit to a specific bay in order to obtain information about the average depth of the bay if this can't be estimated from a sea chart. The most difficult part is to find continuos information about the state of the adjacent water body outside the bay and the freshwater supply to the bay. However, these tasks may probably be overcome in the future by models describing both the freshwater supply and the state of the adjacent water body.

One may use the results from the present investigation and from the present model to design future measuring campaigns in shallow bays and to guide further literature research for the continuing development and validation of the model. The major model elements and processes of the bay are presented in Figure 2.1 below.

During the course of the project it was found that several "new" processes had to be formulated and implemented into the model in order to describe the characteristics of a specific bay. These formulations are believed to be good enough for the purpose of the present model. However, a thorough investigation of all the processes was not possible within the present project. The aim here has been to formulate general but simple descriptions of the processes which can be further tested and tuned if found necessary. The preliminary research within the project also has pointed out the lack of understanding about some processes. These may need to become further investigated and implemented in the model in the future.

The "new" process formulations produced within the present project are found in the following sections:

5.3.1 The supply of organic matter with imported particulate organic matter

5.1.2 The wind-driven water exchange

5.3.2 The benthic model

5.4.2 The growth rate of filamentous algae

5.4.4 The natural and man made harvest of filamentous algae

The following processes need to be further investigated and if necessary implemented in the model.

- The effect of swell in bays close to the coast.
- The possible export of drifting mats of algae from the bay to adjacent waters especially at occasions when the wind is directed out of the bay.
- The benthic microalgae.
- The observed massive spring bloom of brown microalgae in the bays of the Tjärnö archipelago.

The model formulations of the mortality, remineralization and sedimentation rates of filamentous algae are perhaps too simple and should therefore also be further studied in the future. The simple description of energy flux from

wind waves to the mechanical resuspension of nutrients and harvest of algae in the bay probably needs to be further improved. The general absence of algae in winters also needs to be further investigated. To make enhanced tests and tuning of the model parameters it is important to further investigate the water exchange, sediment-water nutrient fluxes, oxygen and nutrient concentrations, and the mechanical energy flux from wind waves to the bay.


# Sammanfattning

En modell som kan förutsäga förekomsten av fintrådiga alger i grunda vikar på svenska västkusten har tagits fram. Det verkar som om modellen producerar resultat som liknar de observationer man har från specifika vikar längs kusten. Modellresultaten för näringskoncentrationer i vattnet och i sedimenten från de modellerade vikarna överensstämmer med rapporterade observationer. Näringsflöden från modellvikarnas sediment till vattenkolumnen ligger inom gränserna för näringsflöden från sediment till vattenkolumnen som finns rapporterade i litteraturen. Algbiomassa och tidpunkt för algtillväxt under vår och sommar i de modellerade vikarna överensstämmer med observationer från vikar på svenska västkusten. En mekanism som simulerar naturlig mekanisk skörd av alger i modellen reproducerar tämligen bra algtäckningsgraden beroende på vikarnas exponeringsgrad.

Det mest betydelsefulla resultatet från modelleringsprojektet är att modellen verkar kunna förklara den generella förekomsten av fintrådiga algmattor i grunda vikar på svenska västkusten. Enligt modellen uppkommer algmattorna huvudsakligen på grund av ackumulation i vikarnas sediment av bunden näring i organiskt material, vilket tillförs sedimentet genom sedimentation av partikulärt organiskt material producerat i ytlagren av kustvattnet utanför vikarna. Remineralisering av organiskt material med efterföljande frigörelse av näringsämnen kan sedan förorsaka förhöjda koncentrationer av näringsämnen i vikarna, vilket är den huvudsakliga drivkraften för en omfattande tillväxt av fintrådiga alger. Tillståndet med täckning av fintrådiga alger i en specifik vik kan naturligtvis även bero på årstid, vikens topografiska dimensioner, vattenutbyte, exponeringsgrad för vind och vågor, specifika tillskott av näring från land och från angränsande vattenområden, och eventuellt även på andra faktorer.

Modellen kan användas som ett verktyg för att öka vår förståelse om processer i grunda havsvikar. Modellen kan också användas som ett verktyg för att uppskatta reaktionen i en specifik vik för olika åtgärder mot tillväxt av makroalger. Det mesta av indata till modellen är relativt enkelt att få tag i från befintliga databaser och från sjökort. Möjligtvis måste man göra ett kort besök till en specifik vik för att erhålla information om medeldjupet för viken om detta inte kan uppskattas från sjökort. Det svåraste är att få tag på kontinuerlig information om tillståndet i det angränsade vattenområdet utanför viken och om färskvattentillförseln till viken. Arbetet med att samla in dessa uppgifter kan dock sannolikt övervinnas i framtiden med hjälp av modeller som beskriver både färskvattentillförseln och tillståndet i det angränsade vattnet. Man kan använda resultaten från undersökningen och modellen till att ta fram framtida åtgärdsprogram i grunda vikar och vägleda mer litterär forskning för fortsatt utveckling och validering av modellen. Modellens huvudsakliga beståndsdelar och processerna i viken presenteras i Figur 2.1 nedan.

Under projekts gång framgick det att flera ”nya” processer måste formuleras och implementeras i modellen för att kunna beskriva karakteristiken hos en specifik vik. Dessa formuleringar anses vara tillräckligt bra för att uppfylla syftet med den nuvarande modellen. Det var emellertid inte möjligt att genomföra en grundlig undersökning av alla processer inom detta projekt. Syftet här har varit att formulera generella men enkla beskrivningar av processerna, som kan bli ytterligare testade och anpassade om det behövs. Förstudier inom projektet har också pekat på saknaden av förståelse om några processer. Dessa kan eventuellt behöva undersökas ytterligare och implementeras i modellen i framtiden.

De ”nya” processformuleringar som tagits fram inom projektet finns i följande avsnitt:

5.3.1 The supply of organic matter with imported particulate organic matter

5.1.2 The wind-driven water exchange

5.3.2 The benthic model

5.4.2 The growth rate of filamentous algae

5.4.4 The natural and man made harvest of filamentous algae

Följande processer behöver undersökas ytterligare och eventuellt implementeras i modellen.

- Effekten av svall i vikar nära kusten
- Den möjliga exporten av drivande algmattor från viken till angränsande vatten, speciellt vid de tillfällen då vinden är riktad ut från viken.
- De bentiska mikroalgerna
- De observerade massiva algblomningarna av bruna mikroalger i Tjärnö arkipelagens vikar

Modellens formuleringar av mortalitets-, remineraliserings- och sedimentationshastigheter av fintrådiga alger är kanske för enkel och borde därför också bli ytterligare studerade i framtiden. Den enkla beskrivningen av energiflödet från vindvågor till mekanisk resuspension av näring och till skörd av alger i viken, behöver troligtvis förbättras. Den generella frånvaron av alger på vintern behöver också studeras mer. För att göra utökade tester och finjusteringar av modellens parametrar, är det viktigt att göra fortsatta undersökningar av vattenutbyte, sediment-vatten näringsflöden, syre- och näringskoncentrationer, och av det mekaniska energiflödet från vindvågor till viken.

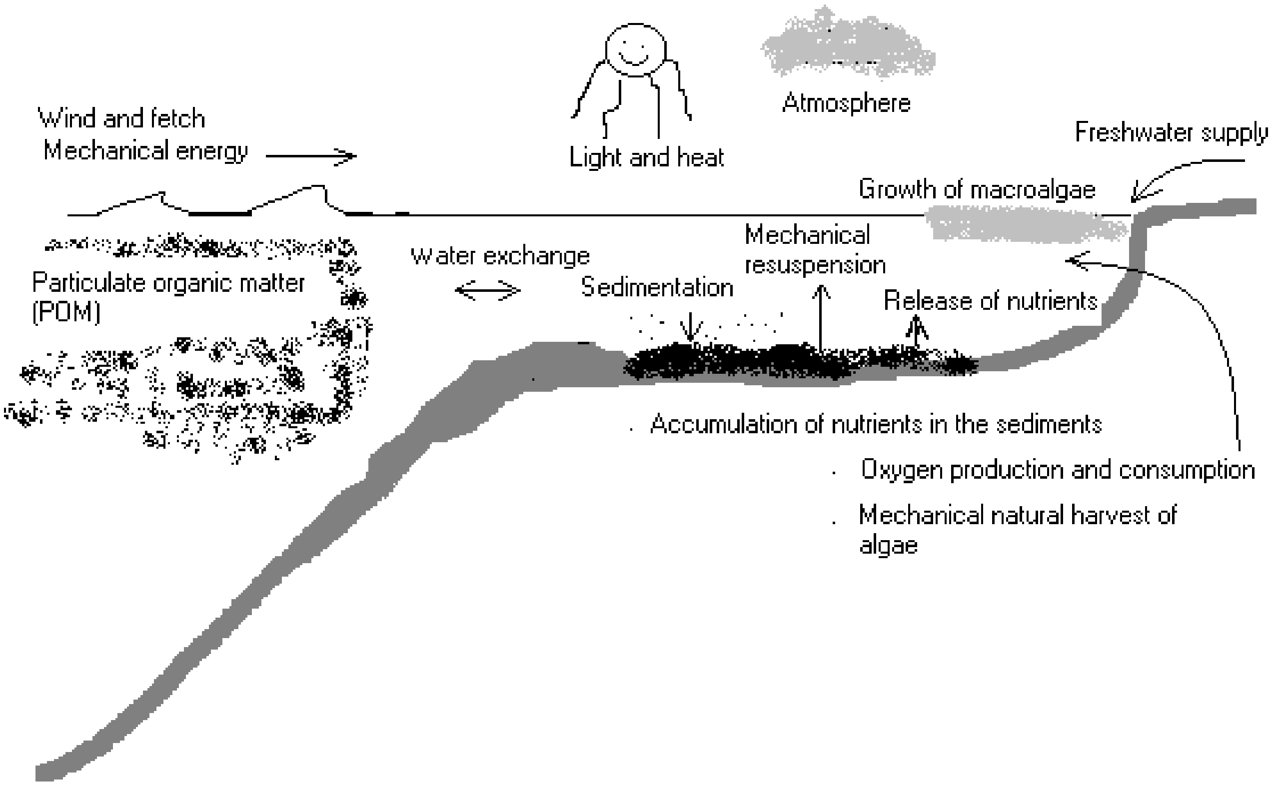


**Figure 2.1**. *Major model elements and processes of the modeled shallow bay.*

# 3. The shallow bay

The intention of the present project is to develop and put together a numerical model and a PC program capable of predicting the development of filamentous algae mats in shallow bays, in particular bays located on the Swedish west coast. This is a great task to do within the limited funding of the present project. Hence, in order to achieve fast results the background research of the model has been limited mainly to investigations of available literature and data sets. The aim of the preliminary studies of this project is to find out the most important characteristics of a shallow bay and of the growth of different kinds of algae in the bays, and finally to put together a model including these main characteristics. Öberg (1999) recently presented a master thesis at Göteborg University including a model describing the growth and decay of filamentous algae in an idealized shallow bay on the Swedish west coast. In the thesis he presents a vast list of literature describing much of the growth dynamics of algae. Some of his results are incorporated in the present model. We therefore refer to Öberg's thesis for further background descriptions and a brief literature review of the growth dynamics of macroalgae. However, relative to the model presented by Öberg, the present model includes more general and complete descriptions of the environmental conditions that constitute the characteristics of a specific bay. We further refer to Pihl et al. (1999) and references therein for a summary and discussion of the distribution of mats of filamentous algae in shallow bays on the Swedish west coast. Valiela et al. (1997) also present a vast list of literature and discussions regarding macroalgal blooms in shallow estuaries.

The aim of this chapter is to describe the characteristics that have to be included to a model of a shallow bay in order to achieve results that can be compared with observations from real bays. The preliminary background studies and investigations performed within the project before the final formulation of the shallow bay model are presented in the appendix. The text of these studies is written in Swedish and the brief summaries of the studies should be regarded as notes to memorize results by and mainly for Kari Eilola.

## 3.1 Marine plants of a shallow bay

The marine plants of a shallow bay have been divided into classes of more or less desired species depending on their characteristics. The seagrass beds and the coarse long-lived types of algae are desired species because of their functioning as nurseries for young fish. The short-lived fast growing types of algae, e.g. filamentous algae, are undesired as they rapidly may obtain huge biomasses and cover entire bays with bad smelling decaying matter causing oxygen depletion killing the benthic fauna in the bays. There are of course several factors not discussed in the present report that might have influence on which plants may dominate at a specific growth place. The present study is however mainly focused on the importance of the nutrient concentrations in the water since these seem to have the major control on the growth rate of the algae. The light conditions are usually sufficient for the growth of algae around the year in the shallow bays on the Swedish west coast (Öberg, 1999).

The great difference between the seagrass and the benthic living algae is their abilityto utilize the nutrients in the sediments through their roots. Thus, the seagrass may obtain a positive net growth independent of the nutrient concentrations in the water. The seagrass is however usually found at depths below about 1m depth on the Swedish west coast. The upper limit to which the seagrass beds extends is quite visible from air and has been used at interpretations of aerial photographs to define the extension of shallow bays (Pihl and Svensson, personal comm.). The reason why the seagrass beds are limited to depths below 1m depth is at present largely unknown for the authors. This issue is not further investigated here since the present model is aimed to describe bays shallower than 1m depth. Further discussions of the issue may be found in Valiela (1997).

A more important question to answer is why microalgae do not out-compete the macroalgae in the shallow bays. We know that the microalgae has a ten-fold greater maximum uptake rate of nutrients and that they may obtain a positive net growth at ten times lower concentrations of nutrients in the water than the macroalgae (Hein et al., 1995). Thus, if microalgae could obtain their full growth potential in the shallow bays, the nutrient concentrations would become much too low for an efficient growth of the macroalgae. The limitation of the net growth of the pelagic community of phytoplankton in shallow bays may be caused by the short residence times of water in shallow bays as suggested by Valiela et al. (1997). Here we suggest that the main limiting factor of phytoplankton growth in shallow bays is the combined effect of the vertical sinking velocity of phytoplankton and the limited depth of the shallow bay. For the computations we used a formula from Stigebrandt and Djurfeldt (1996) describing the net growth of a pelagic phytoplankton community with an average plankton sinking velocity of 1m per day.

The results show that a positive net growth of the phytoplankton community may only occur at depths exceeding about 1.5m. This is quite well in accordance with the upper limit of the seagrass beds discussed above. Hence, these results support what we already know, a dominance of phytoplankton and corresponding low nutrient concentrations during the summer in the deeper waters outside shallow bays.

A question remains to be answered regarding the quantitative importance of the benthic living microalgae. We know from results by Sundbäck et al. (1996) that microbial mats of diatoms may develop on soft bottoms and that they may grow beneath the mats of filamentous algae in the shallow bays. We also know that the diatoms to some extent may regulate the benthic fluxes of nutrients and oxygen. During the investigation of the development of pelagic and benthic nutrient concentrations within the present project we also found that the bays of the inner Tjärnö archipelago became fully covered by some kind of aggregated forms of brown microalgae in early spring. Two weeks later the brown algae had disappeared and the bays were covered with the filamentous green algae. We can not explain the observations, but we suggest that the brown microalgae might have been a kind of diatom growing in early spring while there still were large amounts of silicate left in the water. However, the functioning and importance of the brown microalgae and the benthic diatoms have to be further investigated before they may become a part of the present shallow bay model.

The succession of the algae community from the desired domination of long-lived coarser algae to the fast growing filamentous algae may be explained in terms of their differences in nutrient uptake rates. Magnusson (1997) have presented figures showing that the ephemeral algae have rapidly increasing uptake rates of nitrogen with increasing concentrations of nitrogen in the water. The long-lived algae types on the other hand seem to have low and constant uptake rates compared with the ephemeral algae. From these results we may expect that the growth of ephemeral algae may out-compete the long-lived algae and become the dominating species in shallow bays with increased levels of nutrient concentrations. This conclusion is also in accordance with the study of size-dependent uptake kinetics among algae made by Hein et al. (1995). They also suggest that low nitrogen availability may provide room for larger algae to become dominante despite inherently slower growth rates and possible nitrogen limitation because their loss rates are slower. Since the main interest of the present modelling is bays having an extensive growth of ephemeral algae we do not have to further investigate the competitive behavior between these types of algae within the present project. The task is therefore instead focussed on the question: what determines the nutrient concentrations of a specific shallow bay?

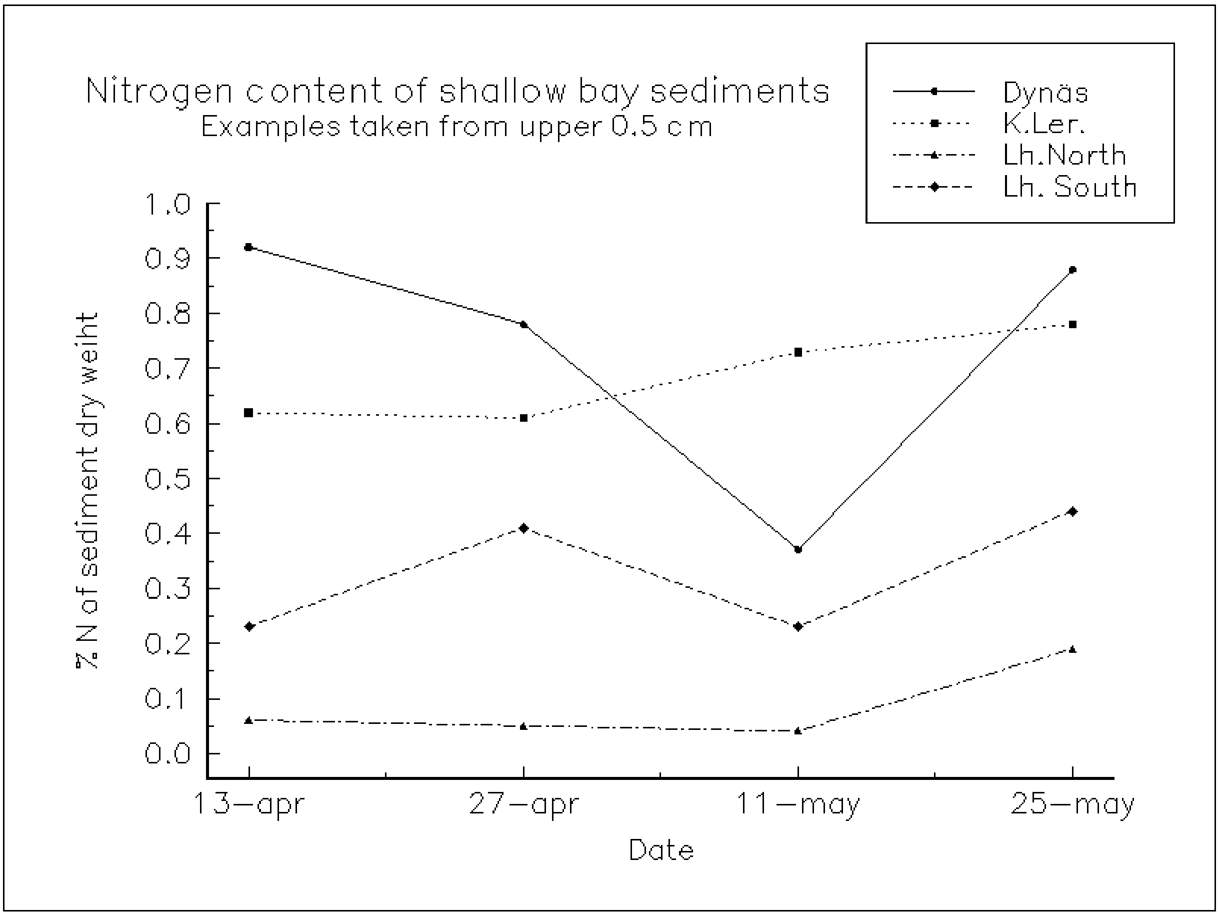


**Figure 3.1**. *The nitrogen content in the top 0.5 cm of soft bottom sediments. Data were collected in spring 1999 from four bays in the Tjärnö archipelago. Dynäs and K.Ler. are sheltered shallow bays in the inner archipelago. Lh. South is an example from a sheltered, and Lh. North from a less sheltered bay in the outer archipelago.*

## 3.2 Nutrients in a shallow bay

We know from investigations of the distribution of green algal mats (Pihl et al., 1999) that there is no correlation between the local supply of nutrients from point sources or rivers and the degree of algae cover in the bays on the Swedish west coast. Ephemeral algae are found also in bays having no supply at all of land derived nutrients. Intensive studies of the distribution and growth dynamics of ephemeral macroalgae in shallow bays on the Swedish west coast in the period 1992 to 1994 (Pihl et al., 1996) showed that rapid increase in algae biomass generally occurred from mid-May to end of June. An investigation of the coastal surface-water nutrient concentrations show that inorganic phosphorus is completely exhausted by the spring bloom of phytoplankton at this time of year. From these results we therefore conclude that the nutrients used for the extensive growth of the algae in shallow bays are generally neither directly supplied from the inorganic nutrients in the coastal waters outside the bays nor from the land runoff. The only remaining possible major source of inorganic nutrients is nutrient fluxes from the sediments of the shallow bays. The fluxes of nutrients from the sediments to the water of a bay should be proportional to the sediment-water area of the bay. From this we may conclude that the water exchange of the bay should be an important regulating mechanism of the nutrient concentrations in the bay. Hence, since the nutrient concentrations are thought to be the main driving function for the growth rate of ephemeral algae, the present task can be constricted mainly to an investigation of the water exchange of a bay and the exchange of nutrients with sediments of the bays.

The field investigation made in the present project of the spring-time development of nutrient concentrations in four shallow bays shows that there may be great differences between the waters of the inner archipelago and the coastal waters. Thus, to obtain realistic results from a model of a shallow bay contained between the islands of the archipelago one has to obtain information about the waters residing just outside the bay. This would require a separate model for the inner archipelago or a complete set of measurements from outside the bay. This task is however out of the scope of the present project.

## 3.3 Sediments of a shallow bay

Investigations of sediment data from soft bottom shallow bays on the Swedish west coast (Pihl et al., 1999) show that locations with (without) algae mats have average nitrogen concentrations of about 0.1-0.2% (<0.05%) in the upper 2 cm of the sediment. The results indicate that the sedimentation of nutrients assimilated into organic matter may be an important factor which needs to be understood.

Preliminary investigations of the nutrients bound in the particulate organic matter found in the coastal waters in spring and summer showed a great potential to be the source of nutrients to the sediments of the shallow bays (Appendix 8.2). Using the rough estimate that the average sinking velocity of particulate pelagic organic matter is 1m per day showed that the sedimentation of particulate organic matter imported from the coast may supply most of the nutrients needed for the observed growth of algae in the bay of Trälebergskile on the Swedish west coast. In the computations we used monthly measurements of particulate organic carbon outside the bay and assumed a particulate nutrient composition according to the molecular stoichiometric value given by Redfield et al. (1963) (C:N:P= 106:16:1). The field investigation within the present project (Appendix 8.1) of the spring-time development of nitrogen in the top 0.5 cm of sediments in four shallow bays show average concentrations as high as 0.9% in the bays of the innermost archipelago. The aim of the investigation was to see whether the accumulation of particulate matter from the spring bloom might become visible at the surface of the sediments. Unfortunately, because of ice cover in the inner parts of the archipelago, the data collection had to begin after the spring bloom had started in the coastal waters outside the Tjärnö archipelago. So we do not know how much the initial data already had been influenced by the deposition of particulate organic matter from the plankton bloom. The data anyway indicates that there is an increase of nitrogen concentrations (~0.1%-0.2% of sediment dry weight) in the sediments during the period and therefore an accumulation of nitrogen in three of the bays. The Dynäs Bay, however, with the highest initial concentrations first shows a decrease of the nitrogen content until the beginning of May and thereafter a rapid increase to the initial conditions again. Five samples were collected at each sampling occasion from each bay and the mean values of the data were computed. These values are presented in Figure 3.1 above.

Nutrients from the previous years and the present spring may thus accumulate in the bay sediments and become released back to the water column as the benthic remineralization rates of nutrients increases with increasing water temperatures in the summer. The possibility to accumulate nutrients in the sediments as well as mechanisms causing the observed differences between the more or less exposed bays have to be incorporated into the present model to obtain the right nutrient potential for algae growth.

## 3.4 Wind waves in a shallow bay

The effect of winds and waves on the natural harvest of algae mats was observed e.g. in 1994 in Trälebergskile when the biomass disappeared after a few days with strong winds in late June (Pihl et al., 1996). A preliminary investigation was made in Appendix 8.3 to roughly find out whether it is the stress directly from the winds on the algae mats, or the stress from the wind induced waves that mainly causes the observed harvest. Using the drag coefficients of wind above grass and water below ice as rough estimates of the respective drag coefficients of algal mats, one may find that the subsurface stress from water is equivalent to the wind stress at a water velocity of 3.6% of the wind velocity. It is then easy to show that long waves or swell, having an amplitude of about 10cm at a half meters depth, may cause a stress on the algae mats equal to that of a $15ms^{-1}$ gale wind. These estimations show that the exposure of the bays for winds and corresponding fetch lengths for wind waves have to become important for the regulation of algae coverage in a certain bay. The effect of waves on the erosion of sediments and the resuspension of nutrients and particulate organic matter to the water from the sediments of a bay may also be used in the model to explain the observed differences of nutrient concentrations in sediments between the more or less exposed bays mentioned above. The exposure to swell from the adjacent coastal waters may of course also have the same regulating effect as the locally generated wind waves. However, the swell effect is not accounted for in the present model.

In order to investigate the relationship between the exposure to wind waves and the degree of algae cover in a shallow bay we developed a model to estimate the wave climate of a given bay. The energy flux of a wave having the height of a significant wave for a given wind speed and fetch length at the entrance of a specific bay was computed for fetch limited shallow water wind waves. This flux was used in the model as a rough representative for the total energy flux from an integrated wave energy spectra. The length of the

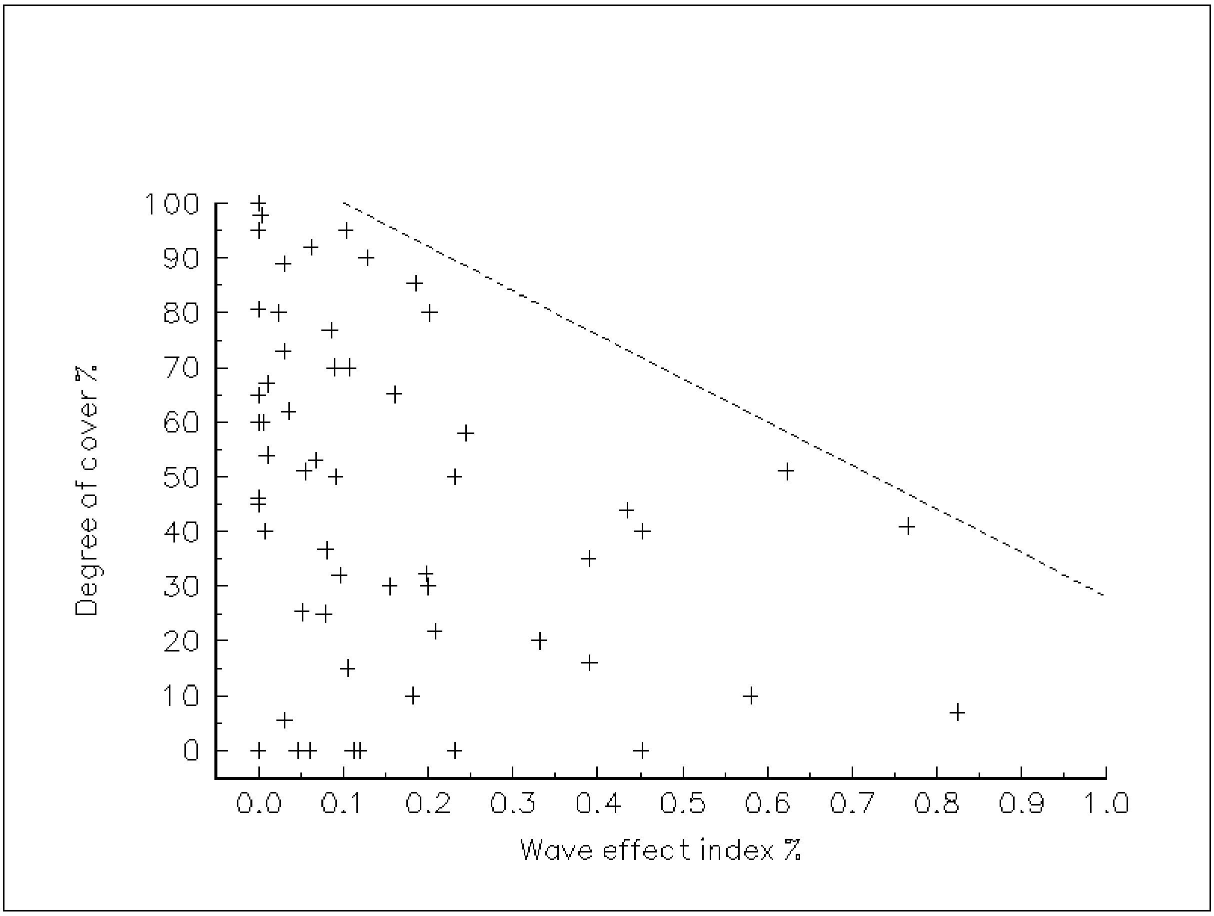


**Figure 3.2.** O*bservations from the period 1994-1996 (plus) showing the degree of algae cover as function of an exposure index in a random collection of shallow bays on the Swedish west coast. The dashed line is arbitrarily used as an indication of an upper limit of algae cover.*

bay periphery relative to the width of the entrance was used to describe the energy flux density in the bay and the possibility of breaking waves and shoaling effects of the waves were also accounted for in the computations. The energy flux was scaled relative to the maximum wave energy flux obtained by waves at the breaking point. A probability distribution of winds in the area was used to estimate the probability for different energy flux densities in the bay. Finally the average relative energy flux density of the bay was used as a measure of the wave climate in the bay. This measure is here called the wind wave effect index or exposure index. The index was computed for a large number of randomly chosen bays on the Swedish west coast and compared with observations of the degree of algae cover (Figure 3.2).

The results show that there is an obvious relationship between the maximum cover of algae and the degree of exposure to wind waves of a given bay. There are of course large variations in the degree of algae cover within the data set which are due to varying dates of sampling time and other environmental factors not accounted for in the exposure index. Thus, the results emphasize that the effect of the energy flux from wind waves has to be implemented to limit the maximum degree of algae cover in the modelled shallow bays.

## 3.5 Growth of algae in a shallow bay

Growth dynamics of filamentous algae are described in a vast amount of literature, therefore the present discussion is used to emphasize the most critical points regarding the modelling of algae growth in shallow bays on the Swedish west coast. The aim of the present model is mainly to describe the seasonal behavior of algae growth and the accumulated amounts of biomass in the bays. Hence, the dynamics of an internal pool of nutrients in the algae used e.g. in the model by Öberg (1999) are excluded from the present model. The growth of algae on the Swedish west coast is usually limited by the nutrients available in the water. The growth rate of algae in the present model is therefore assumed to be limited by the uptake rate of nutrients from the water according to Michaelis-Menten like kinetics. The descriptions of the light limitation, the mortality and the decay of the filamentous algae were taken from the thesis by

Öberg (1999). A still unresolved task is to explain the general absence of filamentous algae in the winters when there is enough light and nutrients in the water. We know from measurements by Owens and Stewart (1982) that the uptake rate of nutrients by algae is largest in spring and that the uptake rate rapidly decreases in late summer and autumn. We do however not yet have any satisfactory explanation for this observation. It is anyway important to describe the observed change in the uptake rates of the algae in the model in order to obtain the slower growth in autumn and the absence of algae in winter. We also know from investigations of shallow bay sediments that there is a huge potential for renewed growth of filamentous algae in spring from spores passing the winter in the sediments (Schories, 1995). The investigation within the present project of the spring-time development of filamentous algae in four shallow bays showed that the growth and decay of filamentous algae is quite rapid in spring. The innermost bays became covered with large amounts of green algae within a fortnight, and a fortnight later the algae had almost disappeared from the bay. Hence, the germination of the spores and the growth of juvenile sprouts in spring has to be incorporated to the model to simulate the growth potential of algae in spring.

# 4. Model description

In accordance with the requirements described above the model must be able to resolve the pelagic concentration changes of, nutrients, oxygen, salinity, temperature and biomass of algae in the bay. The model also has to include a simple description of some benthic state variables in order to give some information about the sediment status of the bay.

The model is based on a mass balance budget for each of the state variables incorporated into the model. The water of the bay is assumed to be well mixed. The transfer of mass between elements of the model are controlled by processes. Descriptions of these are mainly found in the literature. These descriptions are kept as simple as possible to make the model able to run for long time periods. During the analysis of gathered data, however, it was found that some process descriptions could not be found in the literature, at least not within the time limit of the project. In these cases simple process descriptions have been formulated within the project. The processes which may need further research are mentioned in the summary of this report.

The mass change (DM) of a pelagic state variable (M) in the shallow bay during a given time step Dt is in the model described by

$$DM = DM_{PHYS} + DM_{BIO} + DM_{ATM} + DM_{BENT} \qquad (4.1)$$

where the index PHYS, BIO, ATM and BENT denotes the mass exchange caused by water exchange with adjacent coastal waters and freshwater supply, biological processes, atmospheric exchange, and the benthic exchange, respectively. The atmospheric exchange of nutrients and salt, as well as the benthic exchange of heat and salt are not accounted for in the present model.

The PHYS part consists of

$$DM_{PHYS} = DM_{IN} + DM_{QF} - DM_{OUT} - DM_{HARV} \qquad (4.2)$$

where the index IN and OUT denotes the mass changes caused by in and out flows of the bay and QF the mass changes caused by the freshwater supply to the bay. The exchange of filamentous algae caused by the water exchange are neglected in the model. The effect of physical harvesting of filamentous algae is denoted by the index HARV

$$DM_{HARV} = DM_{HARV}^{NAT} + DM_{HARV}^{MAN} \qquad (4.3)$$

where the index NAT denotes natural harvesting of algae by wind or waves, and MAN the harvesting caused by manmade machines. Natural harvesting caused by e.g. grazing birds are neglected in the model.

The BIO part consists of

$$DM_{BIO} = DM_{PROD} - DM_{CONS} \qquad (4.4)$$

where the index PROD and CONS denotes mass changes caused by biological production and biological consumption, respectively. The biological exchange of heat and salt are neglected in the model.

The concentration ($C_M$) of the state variable M is obtained using the actual volume (V) of the bay

$$C = \frac{M}{V} \qquad (4.5)$$

The volume change of the bay during the time step Dt is in the model obtained from

$$DV_{PHYS} = DV_{IN} + DV_{QF} - DV_{OUT} \qquad (4.6)$$

The mass change of a benthic state variable (BM) in the shallow bay during a given time step Dt is in the model described by

$$DBM = DBM_{LAB} + DBM_{REF} \quad (4.7)$$

where the index LAB and REF denotes the mass change of the labile and refractory fraction, respectively, of the organic matter in the sediment. The benthic exchange $DM_{BENT}$ occurring in Equation (4.1) is then in the model described by Equation (4.8)

$$DM_{BENT} = -DM_{SED} - DM_{SINK} + \gamma \cdot DBM \quad (4.8)$$

where $DM_{SED}$ is the net sedimentation of organic matter, $DM_{SINK}$ is the possible permanent sink of nutrients and $\gamma$ denotes a transformation factor between the organic matter in sediments and the remineralized nutrients or consumed oxygen. More detailed discussions of the model elements described in the equations above are found in the following sections.

# 5. Process modelling

The model descriptions of the water exchange of a shallow bay ($DV_{IN}$, $DV_{OUT}$), and the exchange of heat and oxygen with the atmosphere ($DM_{ATM}$) will be described in the present section. The mass changes in the bay due to the water exchange are in the model computed using the concentrations of the bay for the out flowing water, and the surface concentrations of the adjacent water body for the in flowing water, respectively.

## 5.1 Water and heat exchange of a shallow bay

The modelling of water exchange between a shallow bay and an adjacent deeper water-body is here divided into four different processes. Wind-, sea level- and density driven water exchange as well as the water exchange caused by large scale currents outside of the bay entrance are first discussed. To describe the difference in temperatures of the shallow bay relative to the deeper coastal waters we also compute the heat fluxes through the sea surface in the bay. The water exchange model is finally run for the year 1992, forced by observations of actual atmospheric and hydrographic data from the Swedish west coast.

The long term annual variation of the coastal sea surface salinity and temperature of the Bohus coast are also presented as a background data set to be compared with the modelled time period.

### 5.1.1 Sea level model

First we implement in the model the barotropic water exchange caused by varying sea levels outside the bay and by the freshwater supply to the bay. Since sea level variations usually are relatively slow and the freshwater supply relatively small, one may approximately assume that the sea level inside the small bay equals the sea level off the coast. However, in the model we also implement a choking model to introduce the possibility to account for flow resistance from topographic and frictional drag in the entrance area (Stigebrandt, 1989). The water exchange is defined by the volume change corresponding to the sea level changes in the bay. The model bay is shown in the figures 5.1 and 5.2.

The momentary sea level variations in the bay are then described by

$$\frac{dH_i}{dt} = \frac{H_o - H_i}{\sqrt{|H_o - H_i|}} \cdot \frac{A_s}{A_i} \cdot \sqrt{2\frac{g}{1+\lambda}} + \frac{Q_f}{A_i} \quad (5.1)$$

where

$$\lambda = 2 \cdot \kappa \cdot \frac{B \cdot L}{A_s} \quad (5.2)$$

describes the effect of friction in the modelled entrance area. g is the acceleration of gravity and $\kappa$ is an empirical bottom drag coefficient. The parameters Ho, $H_i$, $A_s$, $A_i$ and $Q_f$ are defined in Figure 5.1 and Figure 5.2 below.

### 5.1.2 Wind-driven water-exchange model

In the case when the wind is blowing into the bay, it is assumed that an instant wind-setup is caused in the bay due to the wind-driven surface currents. The steady state solution is then described by a wind-driven surface current and a frictionally balanced barotropic outflow caused by the sea level difference induced by the wind-setup. In the case when the wind is blowing out of the opening of the bay, the wind speed is reduced by a user defined fraction WRED ($0 \le WRED \le 1$) in order to simulate the shelter of the bay. The equations describing the wind-driven water exchange of a shallow bay are described below.

**Equations:**

$$0 = -\frac{1}{\rho} \cdot \frac{\partial P}{\partial X} + \nu \cdot \frac{\partial^2 U}{\partial Z^2} \quad (5.3)$$

$$\frac{\partial P}{\partial X} = \rho \cdot g \cdot \frac{\partial \eta}{\partial X} \quad (5.4)$$

Here X is the horizontal coordinate positive towards the bay, Z the vertical coordinate positive upwards, $\eta$ is the sea level, $\nu$ the vertical eddy

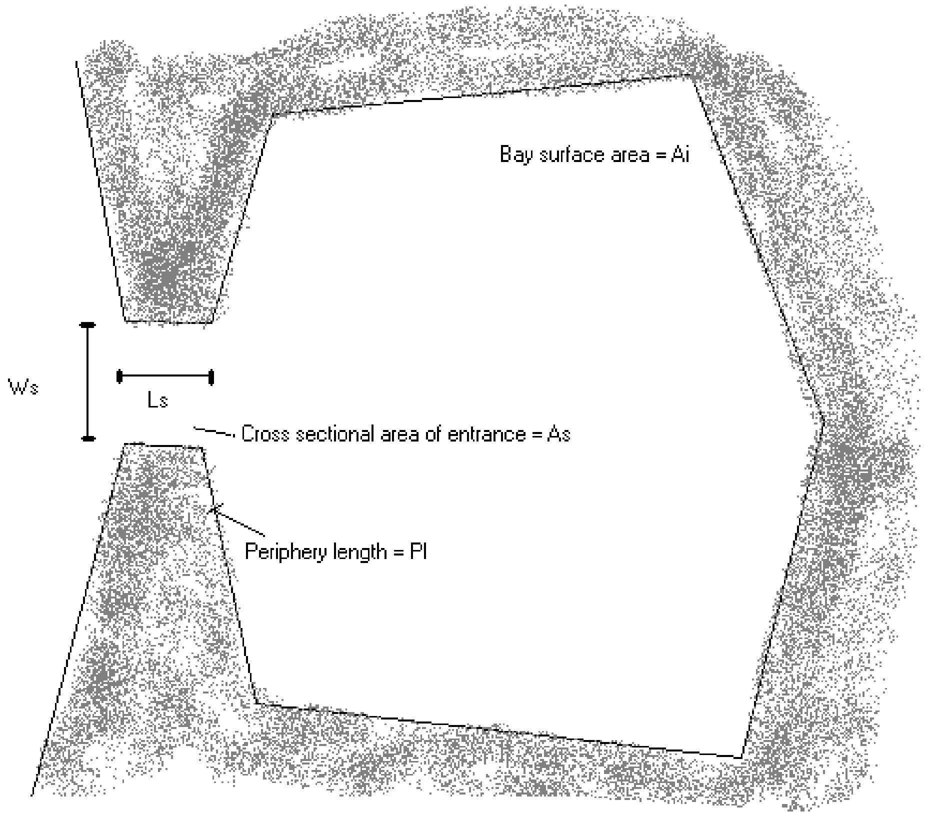


**Figure 5.1**. *Top view of a shallow bay. The surface area of the bay is $A_i$ and the length of the periphery Pl. The cross sectional area, the length, and the width of the entrance are $A_s$, $L_s$ and $W_s$, respectively.*

viscosity, ρ a reference density, g the gravity, P pressure and U is the velocity towards the bay.

**Boundary conditions:**

At the surface Z=b: $\nu \frac{\partial U}{\partial Z} = \frac{\tau}{\rho}$ (5.5)

At the bottom Z=0: U=0. (5.6)

where τ is the wind stress in the direction of U at the sea surface.

The solution is shown in Figure 5.3 below. The figure shows the net result of the wind driven surface current and the barotropic return current. One may observe that the wind driven surface current rapidly decreases with depth and that the velocity U becomes zero when Z=2b/3. Below this depth the velocity changes direction and the return current may be observed.

A vertical integration of Equation (5.7) from $Z=\frac{2}{3}b$ to Z=b gives an estimation of the wind driven transport in the surface layer.

We also assume that there is no net transport through the section $0 \le Z \le b$.

**Solution:**

$$U = \frac{\tau}{\nu \cdot \rho}\left(\frac{3}{4}\frac{Z^2}{b} - \frac{1}{2}Z\right) \quad (5.7)$$

$$q = \frac{5 \cdot b^2}{36} \cdot \frac{\tau}{\nu \cdot \rho} \quad (5.8)$$

where q is the transport per unit width of the opening of the bay.

The wind generated surface stress is in the model computed from equation (5.9) using the wind component (W) in the X-direction.

$$\tau = \rho_a \cdot C_d \cdot W^2 \quad (5.9)$$

Here $\rho_a$ is the density of air and $C_d$ the friction coefficient of wind above the sea surface.

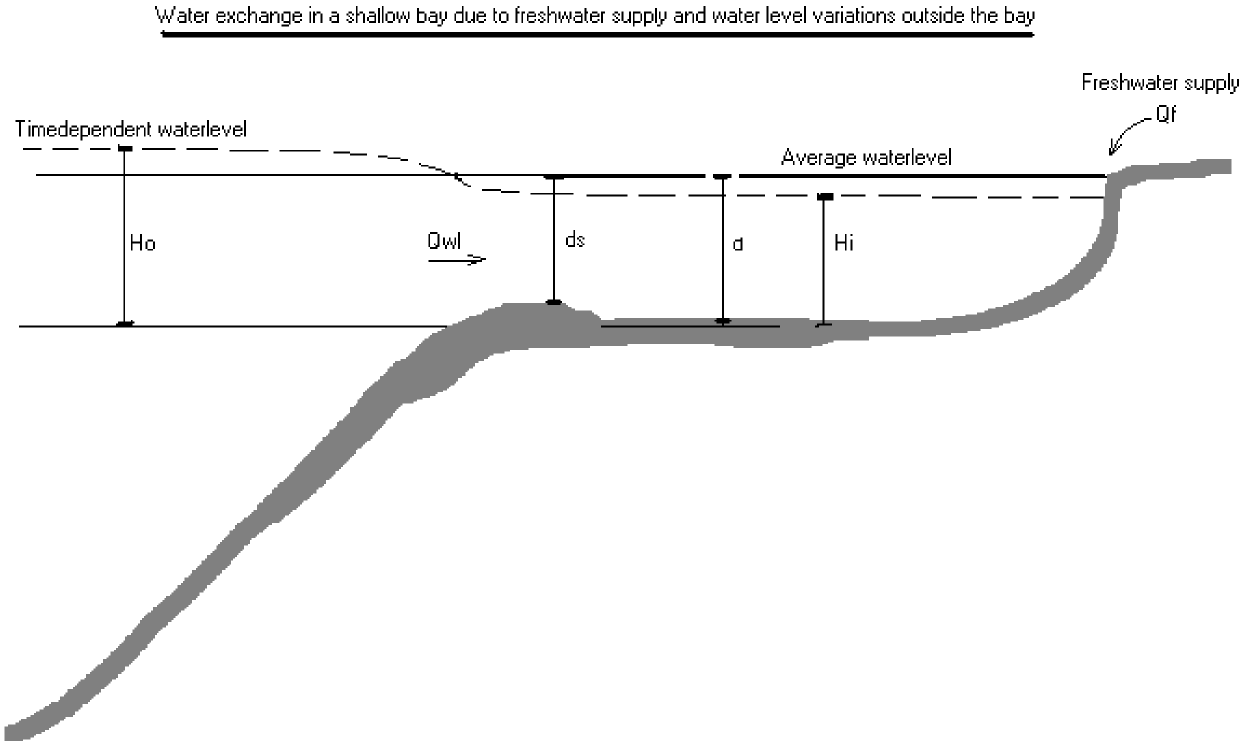


**Figure 5.2**. *Vertical cross section of a shallow bay. The depth of the bay and the entrance of the bay, at an average sea level, are denoted d and ds, respectively. The momentary sea levels inside and outside the bay, $H_i$ and $H_o$, are defined relative to the bottom of the bay. The water exchange due to sea level differences is $Q_{wl}$ and the freshwater supply $Q_f$.*

The eddy viscosity is in the model at present computed from a simple formula simulating the fact that the eddy viscosity increases with increasing turbulence intensity (i.e. with wind speed). Cf. discussion by Neumann and Pierson (1966).

$$\nu = (1+W)\cdot 10^{-4} \qquad (m^2s^{-1}) \qquad (5.10)$$

This should be compared with the molecular viscosity of water which is about $10^{-6}$ $m^2s^{-1}$ while the vertical eddy viscosity usually is about $10^2$ till $10^3$ times larger than the molecular viscosity (Gill,1982). The wind driven water exchange model derived above is in Figure 5.4 below compared with a model presented by Söderkvist (1997). To investigate the importance of ν the present model is tested both with a constant and a varying eddy viscosity according to Equation (5.10). The formulation of Equation (5.10) gives similar results as Söderkvist (1997). However, both models should be furter tested and verifyed against field data in the future.

### 5.1.3 Gravity-density-driven water-exchange model

Varying densities in the bay and on the coast causes gravity-driven currents where the lighter water will flow at the surface and the heavier water in an opposite direction below. The density-driven water exchange is in the model estimated from a two layer critical flow assumption at the entrance of the bay in accordance with Stigebrandt (1989). This assumption implies that the density-driven transport capacity is determined by the internal wave speed. The equations describing the density-driven water exchange of a shallow bay are described below.

**Internal wave speed:**

$$C_W = \frac{1}{2}\sqrt{g' H_i} \qquad (5.11)$$

where

$$g' = g\frac{\Delta\rho}{\rho} \qquad (5.12)$$

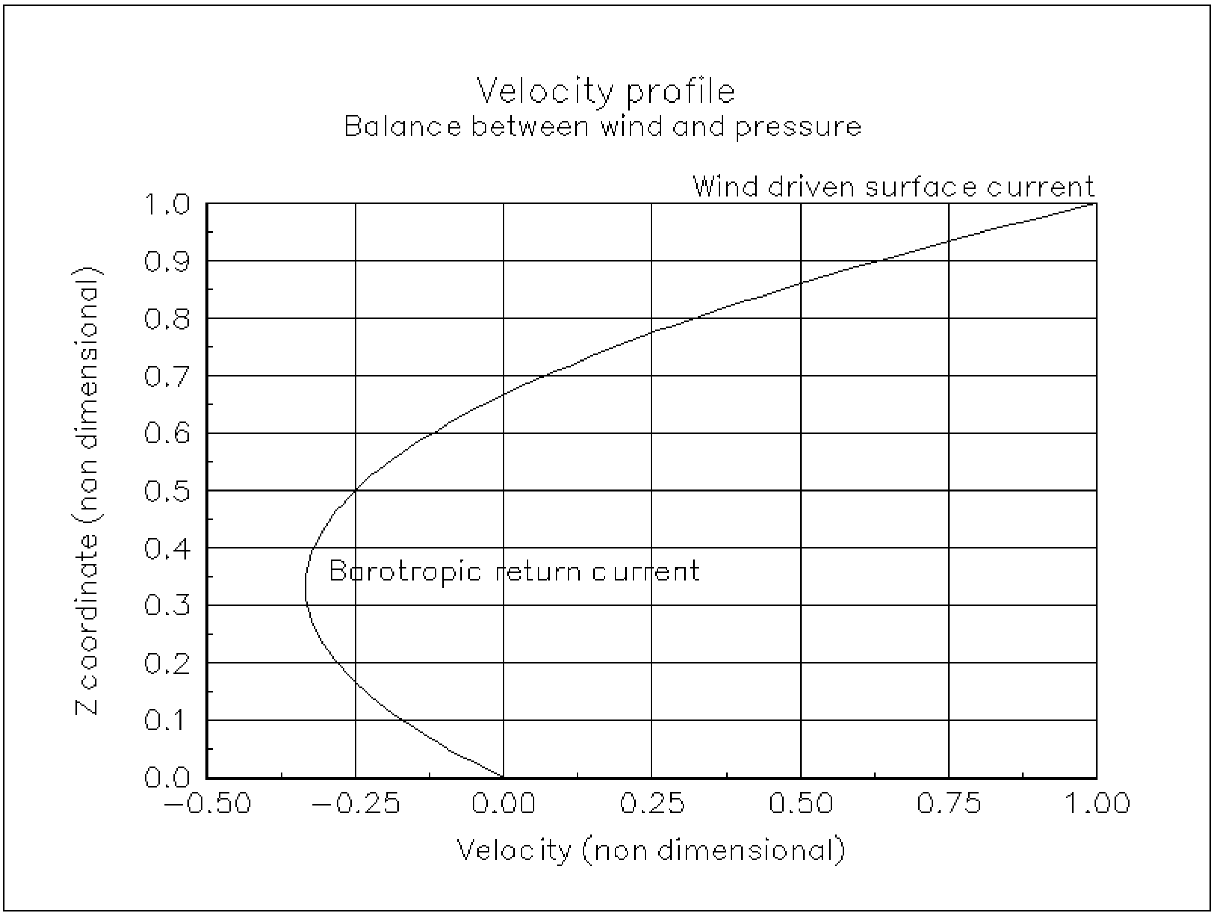


**Figure 5.3.** *Solution to the equations above. The velocity is normalized to the surface current* $U_o$ *and the vertical coordinate to b.*

Here Δρ is the density difference between the upper and lower water layers.

**Transport capacity of the critical flow:**

$$q = \frac{1}{2} H_i C_w \qquad (5.13)$$

where q is the upper and lower layer transport per unit width of the opening of the bay. Here it is assumed that the transport capacity of the upper and lower layers are equal and that the depth of each layer is $0.5H_i$.

### 5.1.4. Water exchange caused by large scale circulation

The large scale circulation may of course vary a lot between different localities. Because of this, the present model is simply implemented with the possibility to define a constant water exchange in the bay caused by the large scale circulation off the bay. This formulation may of course be better described in a specific case if found necessary, see also Söderkvist (1997).

### 5.1.5 Surface heat fluxes

The present model of surface heat fluxes follows the concept described by Stigebrandt (1985) where the net heating of the water body $Q_{in}$ is

$$Q_{in} = Q_s - Q_b - L \cdot E - Q_c \qquad (5.14)$$

where $Q_s$ is the absorbed solar radiation, $Q_b$ the effective longwave back radiation, L•E is the heat loss due to evaporation, L is the latent heat of evaporation, and $Q_c$ the sensible heat exchange. The parametrizations of $Q_b$, $Q_c$ and E below are from Krauss (1972) and Gill (1982).

$$Q_b = \varepsilon \sigma T_s^4 \left(0.39 - 0.05\sqrt{e_a}\right)\left(1 - 0.75nc^2\right) \qquad (5.15)$$

$$Q_c = \rho_a C_{pa} C_h W \left(T_s - T_a\right) \qquad (5.16)$$

$$E = \rho_a C_e W \left(q_s - q_a\right) \qquad (5.17)$$

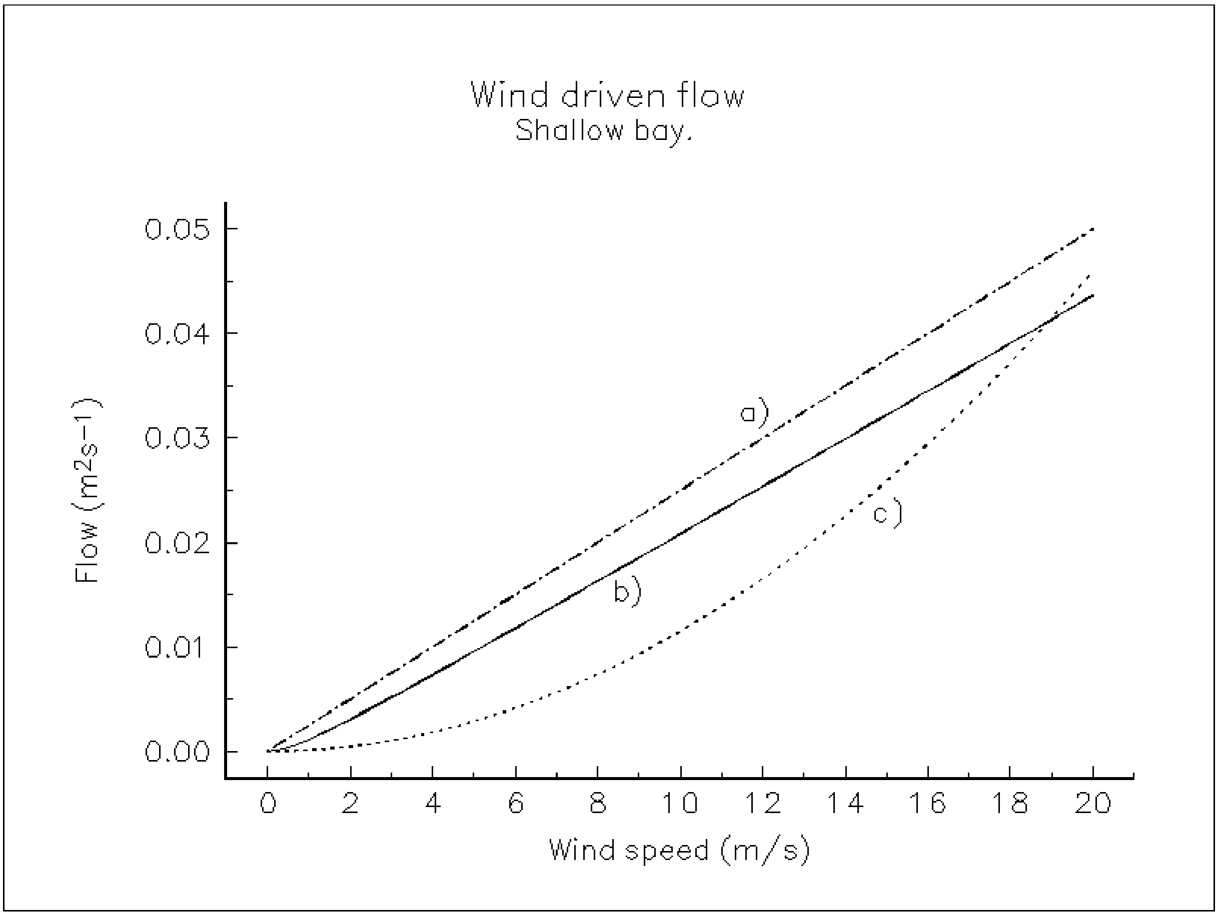


**Figure 5.4.** *Computation of wind driven flow to a shallow bay (1 m depth).*
*a). According to model by Söderkvist (1997).*
*b). The present model with variable* $\nu$ *according to Equation (10) above.*
*c). The present model with* $\nu = 2 \cdot 10^{-3}\ m^2 s^{-1}$.

Here ε is the emissivity of the sea surface, σ is the Stephan's constant, $\rho_a$ the density and $C_{pa}$ the heat capacity of air, $T_s$ is the absolute sea surface temperature (degrees Kelvin) computed by the model, $T_a$ the absolute air temperature, $q_a$ the specific humidity of air, $q_s$ the specific humidity at the air-sea interface, $e_a$ the vapor pressure of air, nc the fraction of sky covered by clouds and W the wind speed.

$Q_s$ is parametrisized in accordance with Stigebrandt (1990)

$$Q_s = Q_{ins}(1 - ref_{ins}) + Q_g(1 - ref_g) \qquad (5.18)$$

where $Q_{ins}$ is the direct solar irradiance at the sea surface

$$Q_{ins} = S_0 \cdot sin(h) \cdot (1 - 0.71nc) \cdot e^{-C_a \cdot m} \qquad (5.19)$$

and $Q_g$ is the global diffuse irradiation computed from $Q_g = 0.52 \bullet Q_{ins} \bullet nc$. Ca is the integrated attenuation coefficient of a clear atmosphere, m the optical pathlength, h the solar elevation, ref is reflectance of solar radiation at the sea surface and $S_0$ the solar constant.

### 5.1.6 Long term temperature, salinity and density data

The long term annual variations of the coastal sea surface salinity and temperature are first shown as a background data set to be compared with the modelled time period. Here we present an overwiev of simultaneously sampled sea surface (0m) temperature and salinity data in the period 1959 to 1992 on the Swedish west coast (N5800-N5850, E1100-E1110). The number of data in each plot is 524 (Figure 5.5, 5.6 and 5.7). Data are provided by the Department of Systems Ecology, Stockholm University. The values of the corresponding computed water density are also presented. The

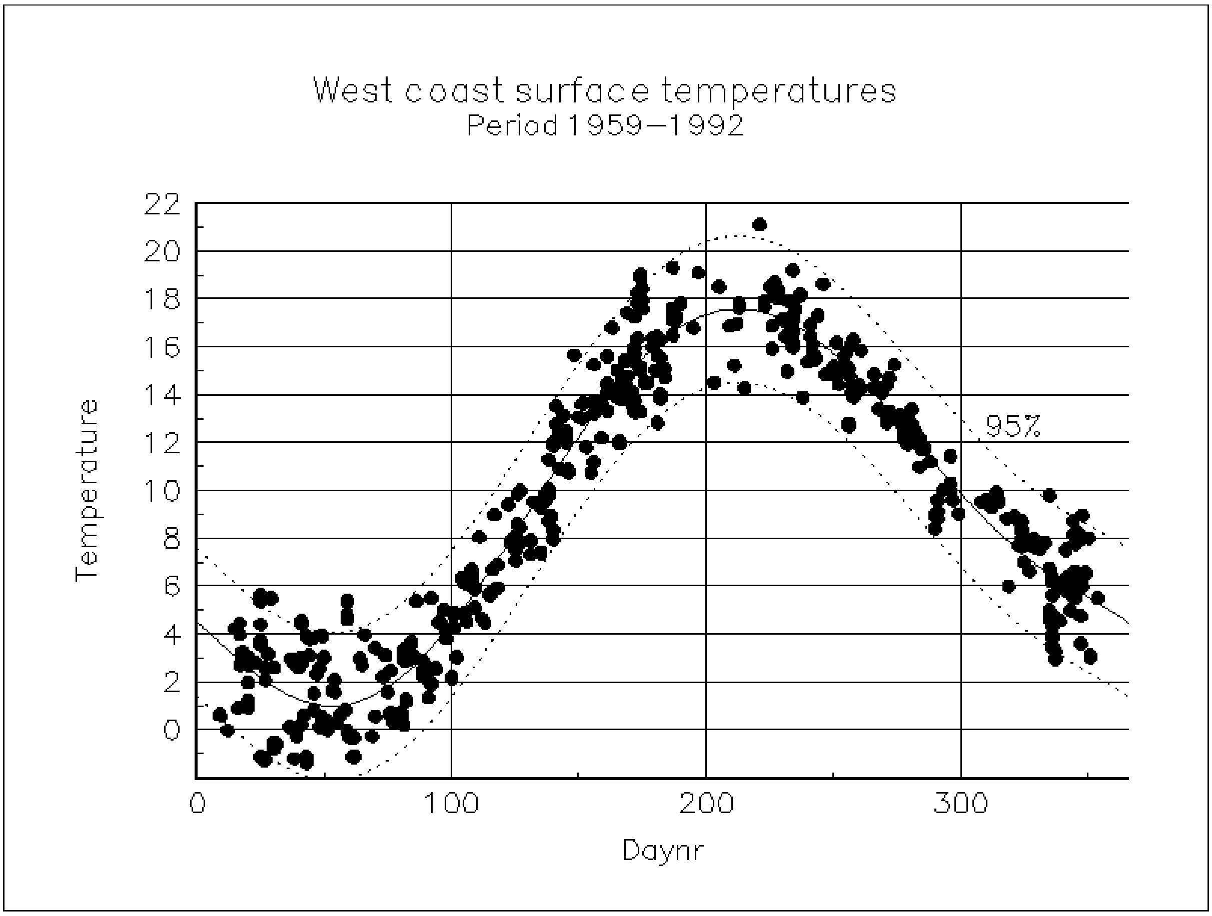


**Figure 5.5.** *Sea surface temperatures.*

fitted polynomials and the 95% confidence bounds are shown in the figures.

### 5.1.7 Monthly temperature and salinity data 1992-1994

The test period of the model was chosen to coinside with the period 1992-1994 when extensive studies of ephemeral algae in a large nuber of bays were made in Bohuslän by Pihl et al. (1996). The forcing of the hydrographic conditions off the coast of Bohuslän were obtained from sea surface data collected by the coastal monitoring program (Bohuskustens Vattenvårdsförbund). The data were linearly interpolated between the months to obtain the daily values used in the model. In Figure (5.8) and (5.9) the data from the period 1992-1994 are presented though the present model period presented in this section covers only the year 1992.

### 5.1.8 Model results of water and heat exchange

The water exchange model described above was run in the period from January 1:st 1992 to the end of the year with actual atmospheric data of wind speed and direction, humidity, cloudiness and air temperature measured three times daily at the weather station Måseskär. Sea level variations outside the bay were forced by weak tides (0.1m amplitude, 12.4h period) and the freshwater supply to the bay was neglected. In cold winters when the water may freeze this is simulated in the model by simply keeping the water at the freezing temperature until solar heating or water exchange increase the temperature again. Thus, this causes a faster melting of ice in the model as compared with the melting of real ice.

The dimension of the bay was assumed to be $4 \bullet 10^4 m^2$ with an average depth of 1m. The width of the entrance was 200m and the length of the entrance was chosen to 1m to avoid effects of bottom friction in the entrance area. The depth of the entrance is assumed to be equal to the average depth of the bay. The sheltering effect on winds blowing out of the bay was assumed to reduce the wind speed to 10% of the wind speed measured at Måseskär. In order to study the effect of sheltering on the water exchange of the bay four cases were run with the model. The entrance of the bay was assumed to be open to wind directions within an angle of ±30° from north, east, south and west respectively. However, since the largest differences occurred between the northern and western bays

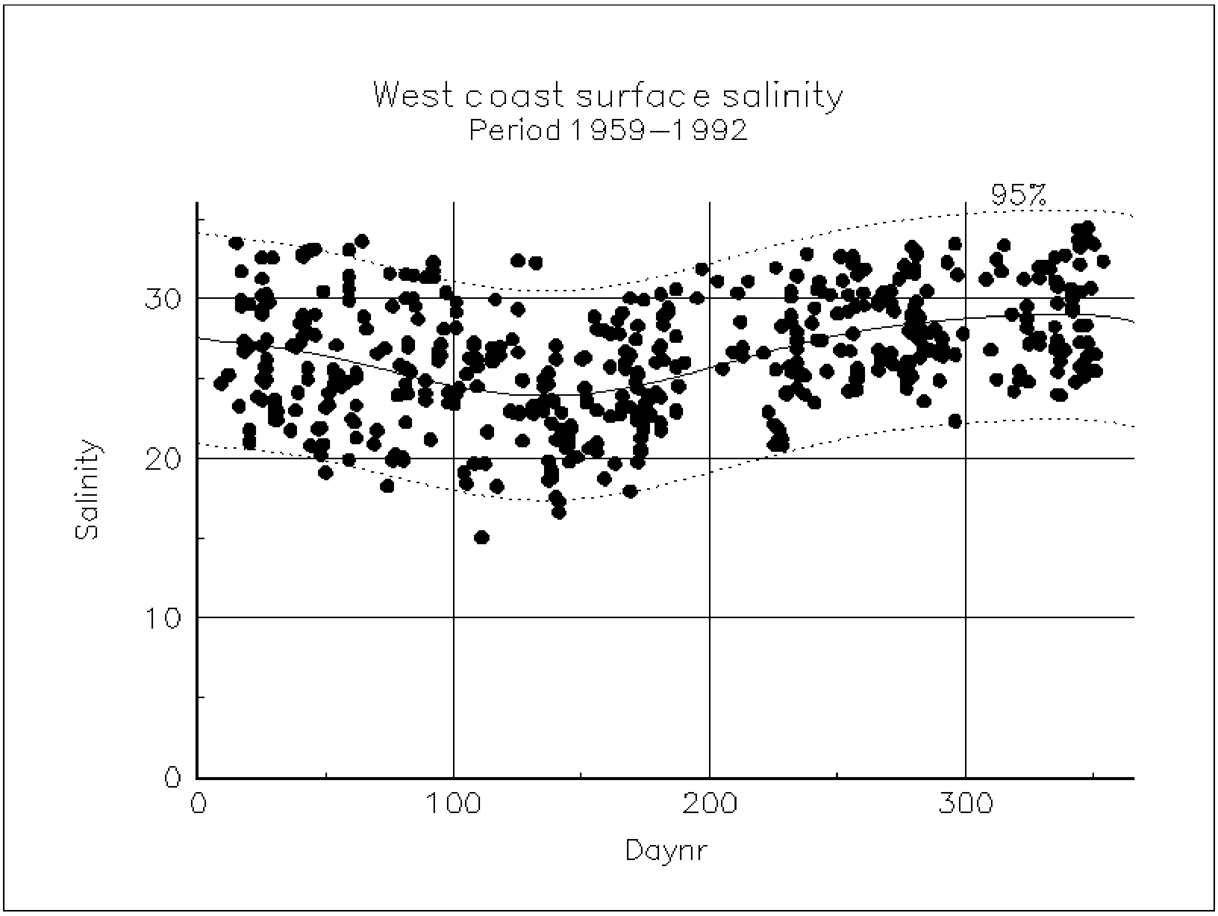


**Figure 5.6.** *Sea surface salinity.*

only the results from these cases are presented below.

The main characteristics of the temperature of the bay (Figure 5.10 and 5.11) are of course following the coastal temperature. However, daily variations in heating and cooling modify the temperature in the bay relative to the coastal surface temperatures. In summers the day time temperature is higher in the bay because the surface heat flux is trapped in a shallower layer relative to the deeper surface layers of the coastal waters. There are of course daily variations also in the coastal surface layer, however these are not resolved in the present data set. In winter and during nights the opposite situation occurs when cooling is more effective in lowering the temperature of the shallow bay relative to the coastal waters. No great differences seem to exist between the northern and western bay.

The annual average flow in the northern shallow bay was 1.29 $m^3s^{-1}$ ($\sigma$=0.86 $m^3s^{-1}$) and 1.75 $m^3s^{-1}$ ($\sigma$=1.5 $m^3s^{-1}$) in the western bay. One may note from Figure (5.12) and (5.13) below that both the frequency and amplitude of in-flows in the surface layer is larger in the western bay. This anomaly is caused by the westerly winds which usually dominate on the Swedish west coast. In periods with low wind speeds the water exchange is mainly driven by the density difference between the bay and the coastal waters.

## 5.2 Oxygen concentrations of a shallow bay

The oxygen concentration of a shallow bay is determined by the oxygen concentrations outside the bay, the gas exchange with the atmosphere and by biological production and decomposition of organic matter.

The oxygen exchange with the adjacent coastal waters is in the model taken care of by the water exchange model described above. However, since it is of our interest to model the oxygen conditions in the shallow bay we also have to introduce an oxygen air-sea flux model. The impact of biological processes on the oxygen concentrations will be discussed below.

### 5.2.1 The air-sea oxygen exchange model

The oxygen exchange with the atmosphere is thought to be driven by differences in the partial pressure of oxygen in the atmosphere and in the

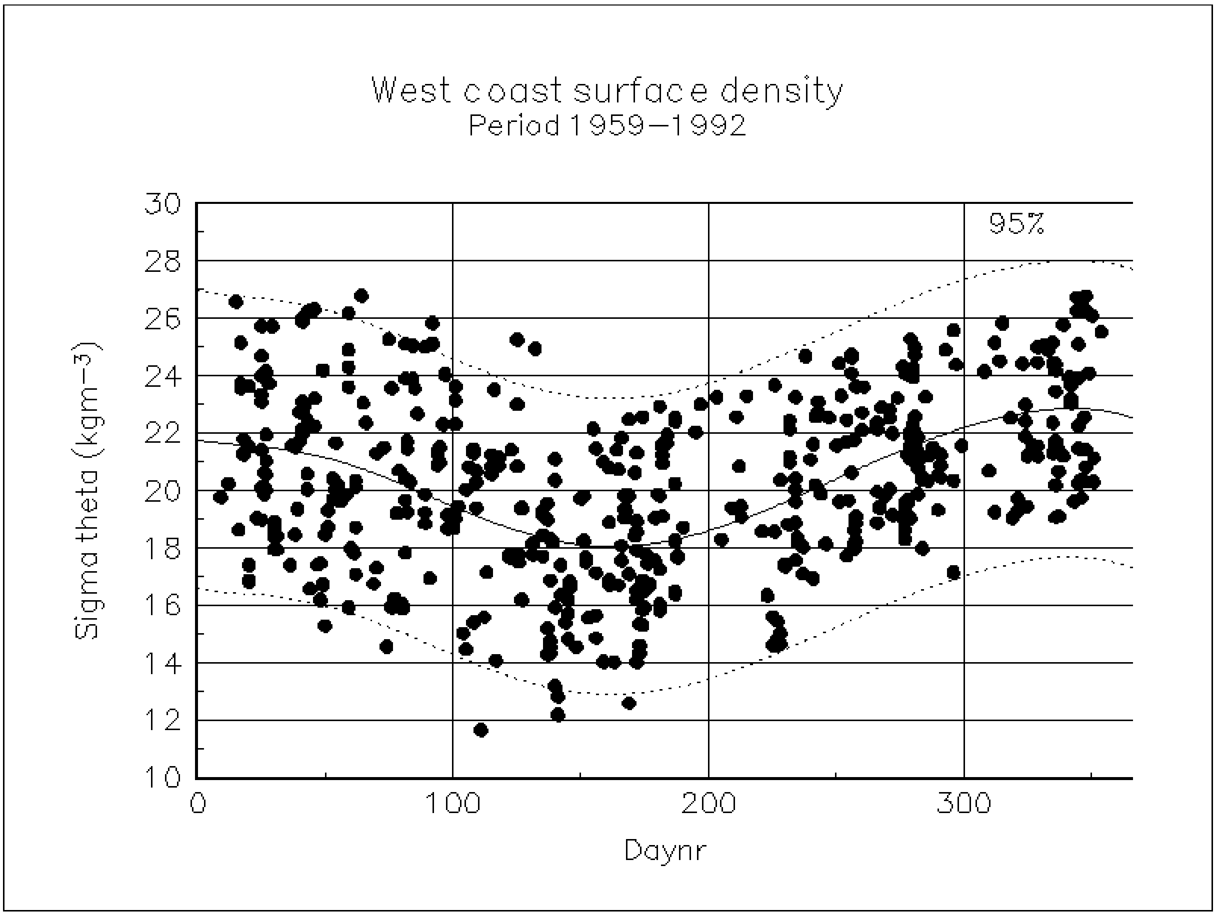


**Figure 5.7.** *Sea surface density expressed as sigma theta defined by the difference Density-1000 kgm*$^{-3}$.

water, respectively. The velocity of the gas transfer is mainly dependent on the wind speed and the water temperature. Mixing of air bubbles into the surface waters by breaking waves may cause super saturation of oxygen in the water. The model of air-sea oxygen transfer that will be used here is mainly based on the model described by Stigebrandt (1991). However, his model used an annually averaged constant super saturation factor due to air bubbles. Since breaking waves and the corresponding penetration of air bubbles into the water are largely wind dependent we introduce the wind dependent bubble factor by Woolf and Thorpe (1991) in the present model.

Oxygen exchange with the atmosphere ($F_{ot}$) is in the model described by

$$F_{ot} = V_{tr} \cdot \left( O_2 - \left( 1 + \beta \right) \cdot O_2 S \right) \qquad (5.20)$$

where $O_2$ is the actual oxygen concentration of the surface water, $O_2S$ is the oxygen saturation concentration computed from a formula given by Weiss (1970), $V_{tr}$ is the gas transfer velocity given by Liss and Merlivat (1986) and β the bubble super saturation factor as described by Woolf and Thorpe (1991).

### 5.2.2 Model results of oxygen exchange model

The model was run for the year 1992 with air-sea oxygen fluxes computed from Equation (5.20) and oxygen exchange with the adjacent coastal waters given from the water exchange model described above. The main characteristics of the oxygen concentrations of the bay (Figure 5.14) are of course largely determined by the oxygen concentrations outside the bay. However, in summer the oxygen concentrations are found to be lower in the bay than outside because the coastal waters are super saturated by biological production of oxygen in the surface layers. The air-sea oxygen flux of the bay tends to keep the bay at the much lower saturation concentration which is determined by the temperature and salinity of the bay. Higher temperatures and lower salinities tends to retain lower oxygen concentrations than lower temperatures and higher salinities do. The impact of biological processes will be discussed in sections 5.3.3 and 5.4.1 below.

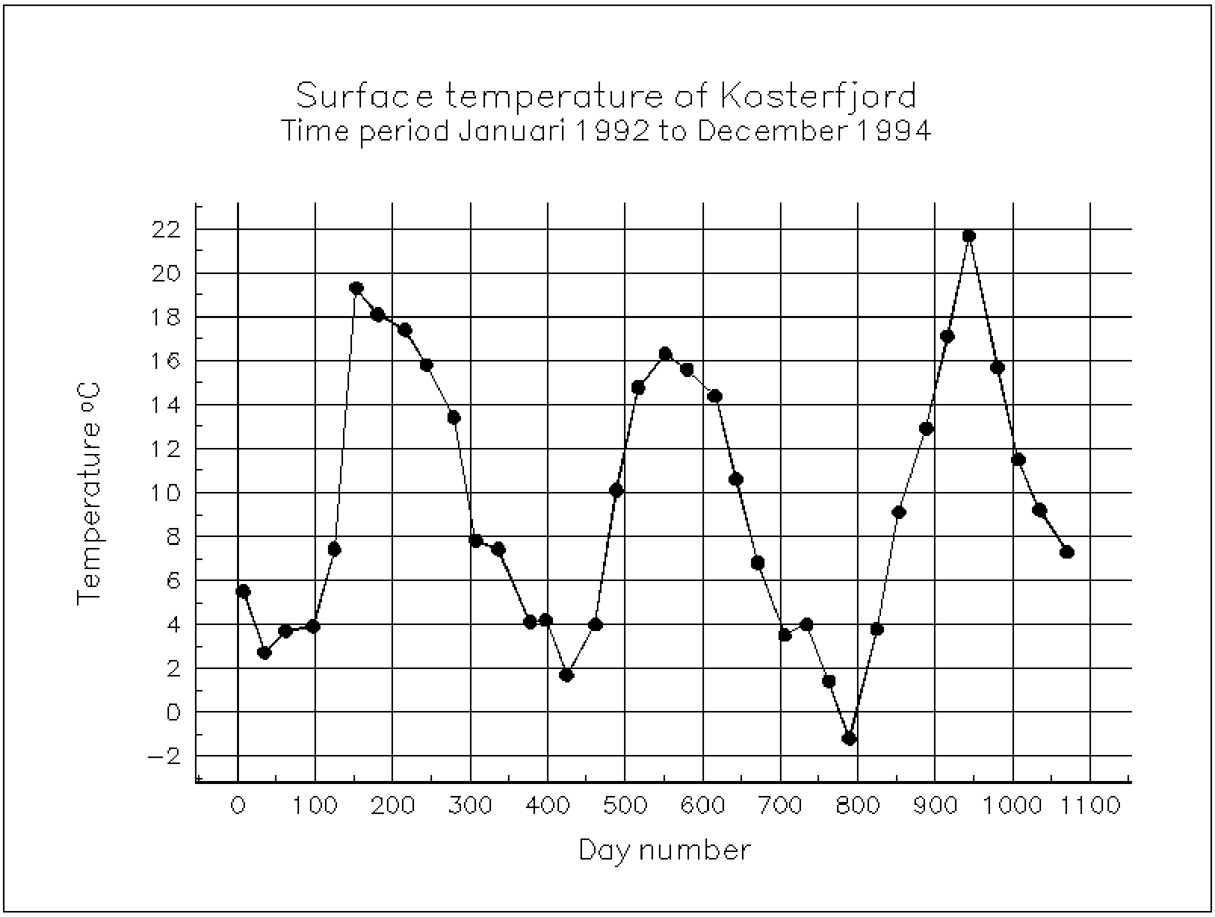


**Figure 5.8.** *Monthly values of sea surface temperatures.*

## 5.3 Nutrient concentrations of a shallow bay

The nutrient concentrations of a shallow bay are mainly determined by the nutrient concentrations outside the bay, the benthic fluxes of nutrients, and by biological production and decomposition of organic matter in the bay. Atmospheric deposition of nutrients and nutrients supplied by freshwater runoff may of course also have some importance in the bay.

The nutrient import to the bay in the form of particulate organic matter produced in the coastal waters outside the bay, and the benthic exchange of nutrients will be modelled in this section. The exchange of nutrients with the coastal waters and nutrients supplied by freshwater runoff are determined by the water exchange model described above. The production and the decomposition of organic matter in the bay will be discussed below. Atmospheric deposition of nutrients is not accounted for in the present model.

### 5.3.1 The supply of nutrients with imported particulate organic matter

The growth of the pelagic phytoplankton community in the bay is severely hampered by the sinking velocity of the plankton and the shallowness of the bay as discussed in section 3.1 above. The plankton community growing in the surface layers of the coastal waters assimilates inorganic nutrients and increases the concentration of particulate organic matter POM in the inflowing water to the bay in spring and summer. Some of the inflowing plankton are decomposed and mineralized in the water of the bay. However, a relatively larger fraction of POM may sink out from the water and eventually become decomposed and mineralized or permanently deposited on the bottom of the bay. This process is of course highly dependent on the turbulence intensity of the water in the bay. The stoichiometric relation of POM in the model is assumed to be given by the molar ratio described by Redfield et al. (1963) $O_2$:C:N:P=138:106:16:1.

In the model it is assumed that POM has a constant sinking velocity (Wp) which together with the actual POM concentrations defines the rate of nutrient supply to the bottoms of the bay. The rate of nitrogen supply ($F_{PON}$) from POM to the bottoms are therefore described by

$$F_{PON} = Wp \cdot PON \qquad (5.21)$$

where PON is the concentration of particulate organic nitrogen in the water. The rate of phosphorus supply ($F_{POP}$) is computed in a similar way.

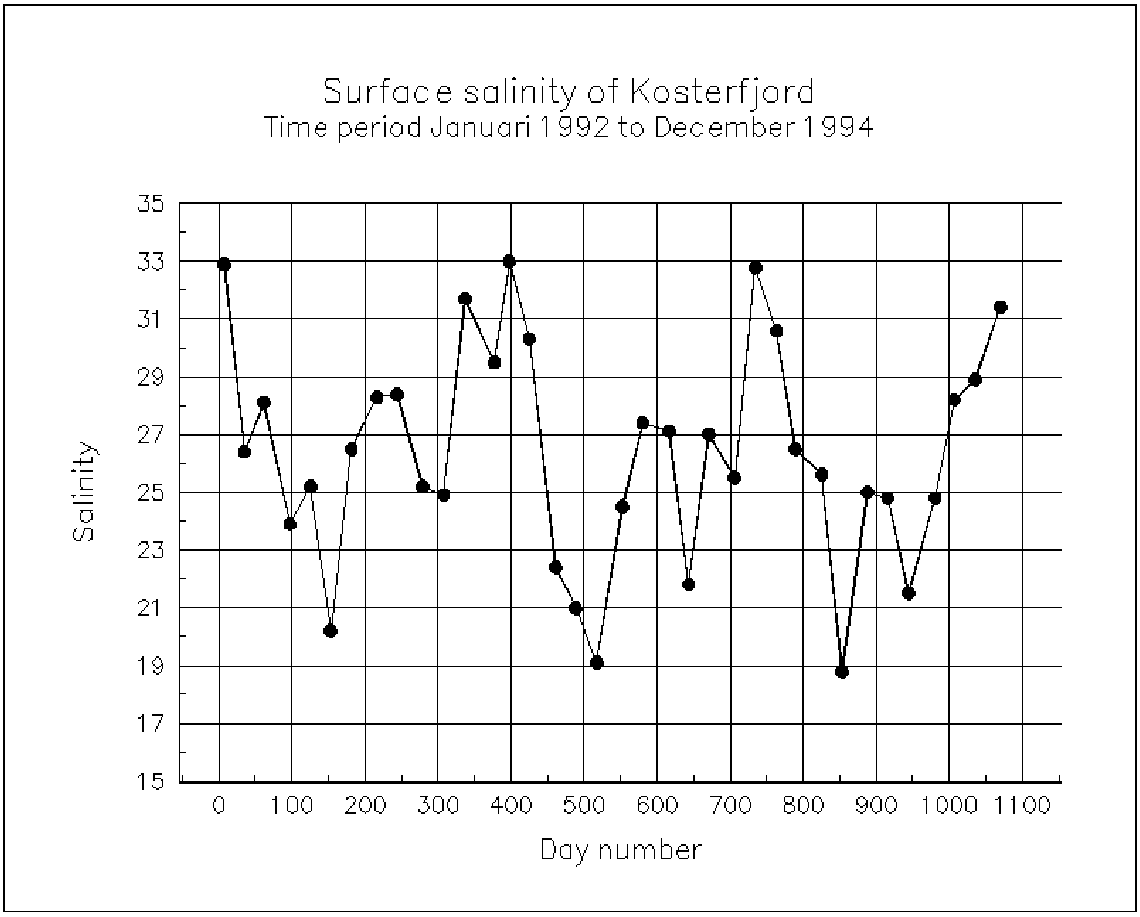


**Figure 5.9.** *Monthly values of sea surface salinity.*

### 5.3.2 The benthic model

In the model it is assumed that a fraction β of the PON (POP) deposited on the bottoms is labile LABN (LABP) and relatively rapidly decomposed and remineralized back to the water column again. The rest REFN (REFP) is assumed "refractory" and more resistant to degradation and remineralization. See eg. Billen and Lancelot (1988) for discussion. Benthic remineralization of labile nitrogen is in the model described by

$$RLABN = C_{LAB} \cdot e^{C_{T1} \cdot Temp} \cdot LABN \qquad (5.22)$$

where $C_{LAB}$ is the first order degradation constant of labile organic matter and $C_{T1}$ the benthic constant of temperature dependency. LABN is the area concentration of labile nitrogen in the active top layer of the sediment. The benthic remineralization of labile phosphorus is computed in a similar way using the concentration of labile phosphorus (LABP) in Equation (5.22). The remineralization of the refractive parts of N and P are also computed from Equation (5.22) however using a ten times smaller coefficient of organic matter degradation, i.e. $C_{LAB}$=10•$C_{REF}$ (Cf. Billen and Lancelot, 1988). A constant fraction DEN (0≤DEN≤1) of the nitrogen remineralized in the sediments is assumed to become denitrified and removed as nitrogen gas in the model. Oxygen consumption in the overlying water of the model is estimated according to the Redfield ratio of the remineralized organic matter in the sediments (Section 5.3.1).

In order to account for the effect of wind-forced waves (se section 3.4 above) on the resuspension (RS) of organic nutrients from the sediments we have introduced the following simplified description of the rate of resuspension in the model.

$$RS_{LABN} = WF_{LIM} \cdot W_{RS} \cdot LABN / SD \qquad (5.23)$$

Here SD is the depth of the active top layer of the sediment. SD is assumed constant in the model. $W_{RS}$ is the maximum rate of resuspension. This equation describes the resuspension of labile nitrogen, though nutrients from all nutrient sediment pools are resuspended in a similar way. $WF_{LIM}$ describes the limiting effect of wind and fetch on the rate of resuspension. $WF_{LIM}$ (≤1) is computed from

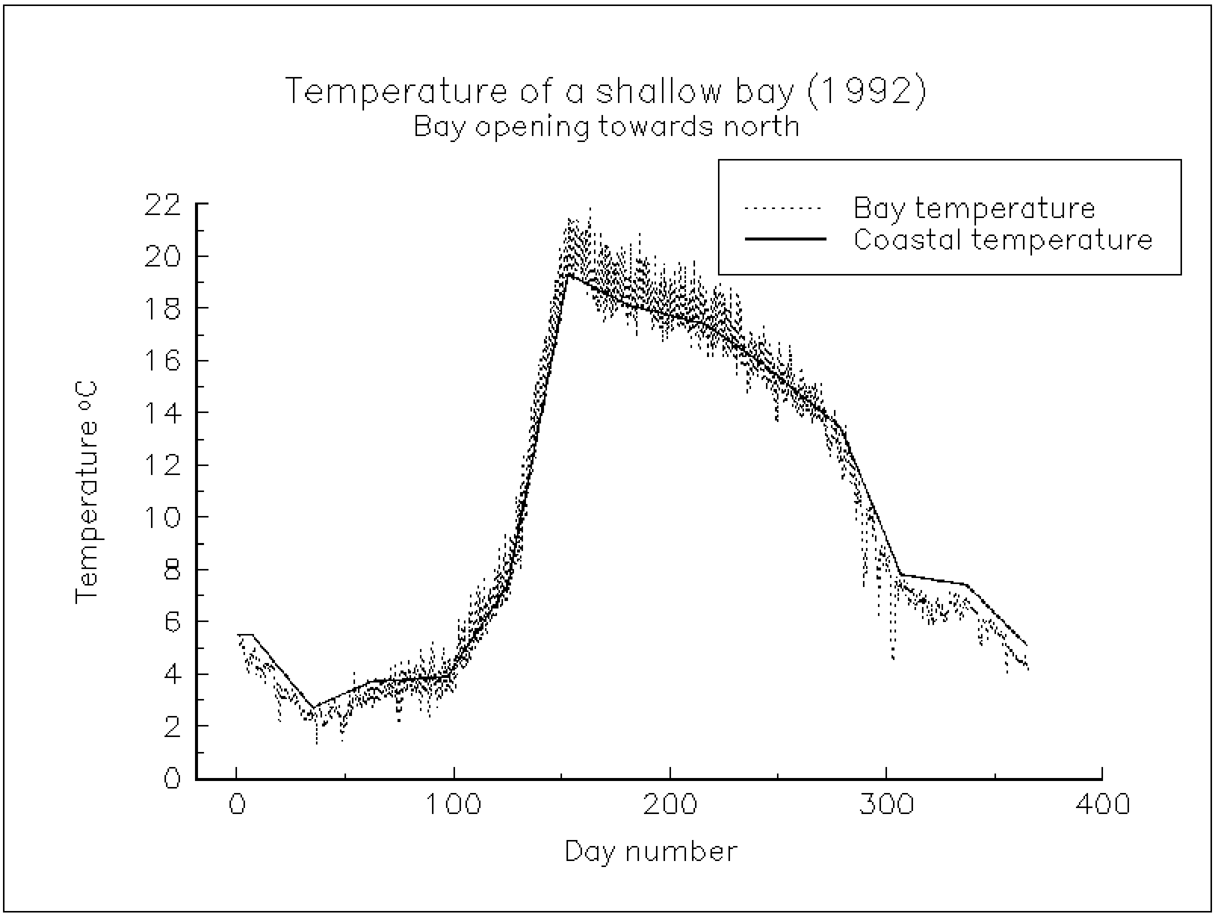


**Figure 5.10.** *Model results (dotted line) of sea surface temperature in the bay having an opening towards north. Also shown is the temperature of the coastal water (solid line).*

$$WF_{LIM} = W^2 \cdot F / \psi \tag{5.24}$$

where W is the wind speed component and F the fetch length in the direction giving the maximum effect of the actual wind driven wave energy to the bay. $\psi$ is a limit where the combination of wind speed and fetch length causes the resuspension of nutrients to achieve an assumed maximum constant rate in the model. The actual values of $W_{RS}$ and $WF_{LIM}$ are however relatively unknown at present and therefore chosen relatively arbitrary in section 5.3.4 below.

## 5.3.3 Pelagic decomposition of POM

Decomposition and remineralization of PON in the watercolumn is described in the model by

$$PEL_{REMN} = C_{PEL} \cdot e^{C_{T2} \cdot TEMP} \cdot PON \tag{5.25}$$

where $C_{PEL}$ is the pelagic degradation constant of POM and $C_{T2}$ the pelagic constant of temperature dependency. The corresponding remineralization of POP and the pelagic oxygen consumption are in the model computed from $PEL_{REMN}$ using the stoichiometric relations of POM described above.

## 5.3.4 Results of the nutrient exchange model

The nutrient exchange model described above was run for an extended period of 1000 days beginning on January 1:st 1992. The forcing of the model was similar to that in section 5.1.8 above. Two cases were investigated;

Case 1) one bay with an opening of about 90° directed towards east and having a fetch length of about 250m

Case 2) one bay with an opening of about 90° directed towards west and having a fetch length of about 5000m

The values of parameters used in the test cases below were

| | | |
|---|---|---|
| Wp= 1 | $mday^{-1}$ | |
| β | = 0.6 | dimensionless |

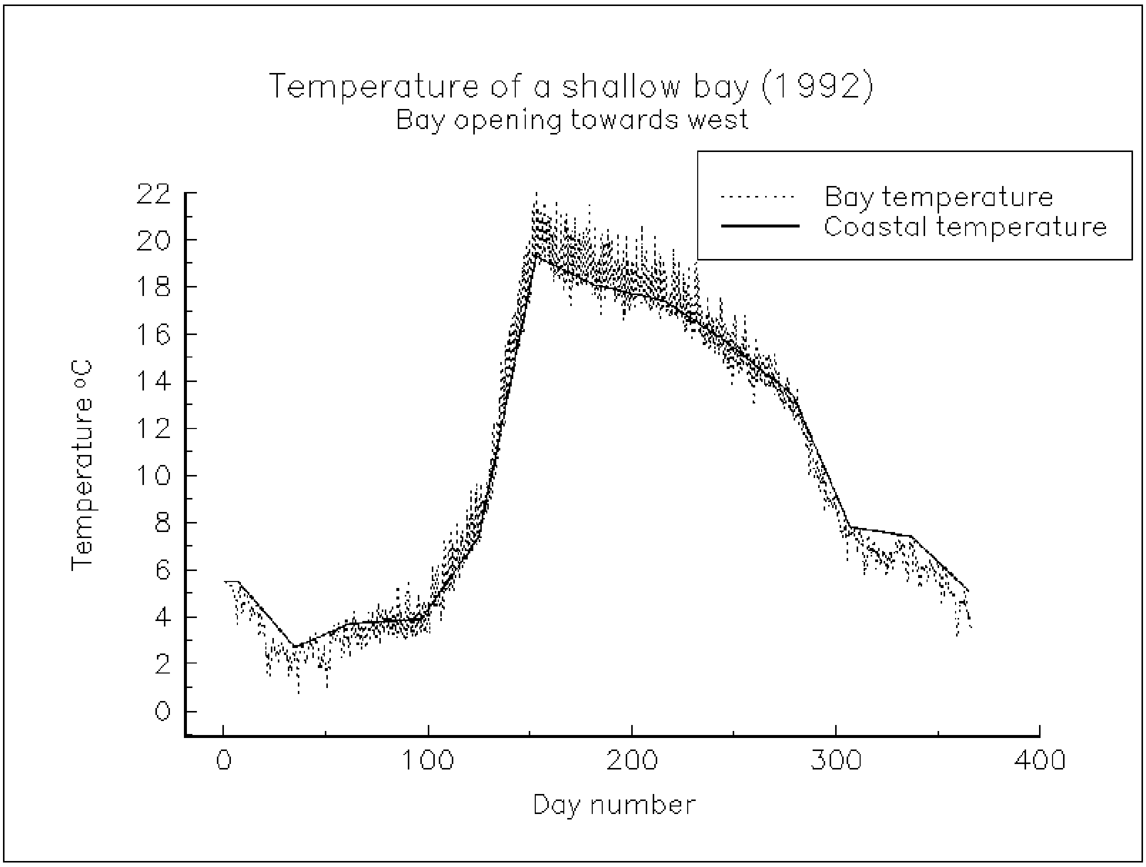


**Figure 5.11.** *Model results (dotted line) of sea surface temperature in the bay having an opening towards west. Also shown is the temperature of the coastal water (solid line).*

| | | |
|---|---|---|
| $C_{LAB}$ | = 0.002 | $day^{-1}$ |
| $C_{REF}$ | = 0.0002 | $day^{-1}$ |
| $C_{PEL}$ | = 0.03 | $day^{-1}$ |
| $C_{T1}$ = 0.15 | $°C^{-1}$ | |
| $C_{T2}$ = 0.11 | $°C^{-1}$ | |
| DEN | = 0.5 | dimensionless |
| SD | = 0.02 | m |
| $W_{RS}$ | = $10^{-9}$ | $ms^{-1}$ |
| $\psi$ | = $2\times10^{5}$ | $m^3s^{-2}$ |

One might mention that the value of $\psi$ corresponds to a situation when the wind speed is e.g. 10 $ms^{-1}$ and the fetch length is 2km. This value is at the moment set arbitrary but should of course in the future be tuned against observations. The maximum rate of resuspension $W_{RS}$ is also set relatively arbitrary at about 2.5 mm per month. However, this value was choosen after some numerical experiments with the present model.

A few test runs were made before the initial conditions of the nutrient pool in the sediment were set in accordance with the measurements described in section 3.3 above. The sediment pool of nitrogen was assumed to be about 0.2% of the sediment dry weight in the sheltered easterly bay and a factor 10 times less in the more exposed western bay. The pool of refractive organic matter was assumed to be a factor 10 times larger than the pool of labile matter in the eastern bay. The phosphorus pool was assumed to be about factor 10 times less than the nitrogen pool.

The initial values used in the tests were:

| | | EAST BAY (mol $m^{-2}$) | WEST BAY (mol $m^{-2}$) |
|---|---|---|---|
| LABN | = | 0.1 | 0.05 |
| REFN | = | 0.9 | 0.05 |
| LABP | = | 0.01 | 0.004 |
| REFP | = | 0.09 | 0.004 |

Coastal concentrations of DIN, DIP and POC were obtained in the same manner as the description of monthly salinity and temperature data in section 5.1.7. The values of POC were transformed to PON and POP using the Redfield ratio described in section 5.3.1 above. In order to focus the present investigation on the nutrient supply to the bay from the coastal waters, the nutrient supply by freshwater runoff was set at zero.

The main characteristics of the PON concentrations of the eastern bay (Figure 5.15) is that the concentrations usually are lower than the

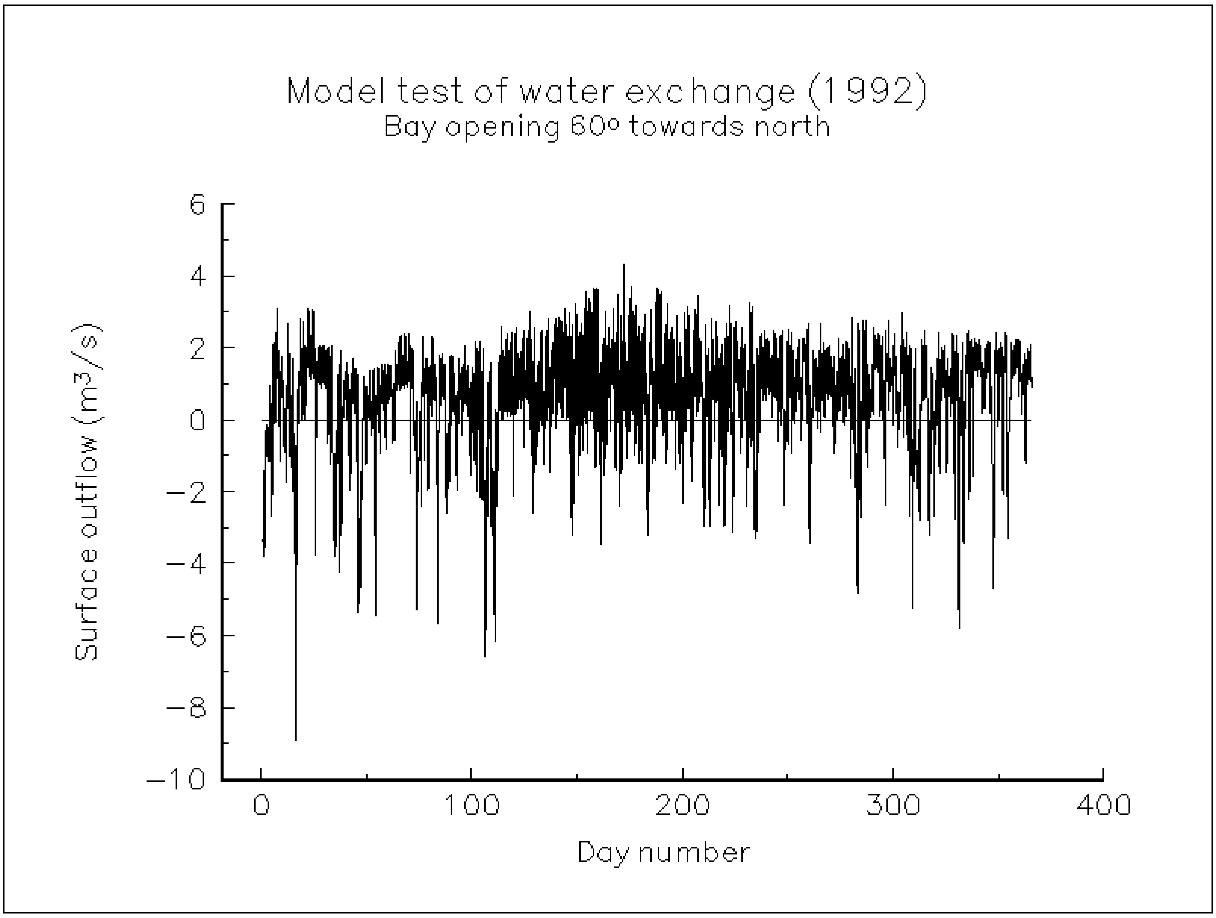


**Figure 5.12.** *Model results showing surface out flow from the bay having an opening towards north. Surface out flow is defined positive.*

concentrations found on the coast. This indicates an almost permanent situation with a sedimentation of PON in the bay. The western bay (Figure 5.16) on the other hand often show higher PON concentrations than found on the coast. This is especially true during the winter. This indicates that sedimentation of nutrients in the summer are counteracted by an entrainment of PON from the sediments to the water column in the model, and an export of PON from the bay in the winter.

These conditions are of course also reflected in the concentrations of nutrients found in the sediments (Figure 5.17 and 5.18). The nutrient accumulation is about ten times larger in the sediments of the sheltered eastern bay than in the more exposed western bay. However, one may note that the nitrogen pool of the sheltered eastern bay declines from the initial conditions. Experiments with the model show that the refractive part of nitrogen in the eastern bay continues to decline from the initial values to about 450 $mmolNm^{-2}$ where a more or less steady state situation occurs. This indicates that there may be additional sources supplying nutrients to the sediments of the bay besides the external supply of POM, or that the remineralization and resuspension rates are too high in the model. This issue will be further investigated in the future when the model is run with real forcing from a specific bay and the results may be compared against field data obtained from the bay.

The pools of labile and refractive nitrogen in the sediments of the exposed western bay have equal magnitude. This is due to the fact that the physically forced entrainment of nutrients from the sediments to the water column in the model determines the sediment concentrations of nutrients in this bay. In the sheltered bay on the other hand, the ratio between the pools of refractive and labile nutrients are determined by their different rates of remineralization in the model.

The fluxes of nutrients from the sediments to the water column in the sheltered eastern bay are much larger than in the western bay (Figure 5.19 and 5.20). The maximum summer values of remineralized DIN in the modelled period amounts to about 250 $\mu molNm^{-2}h^{-1}$ in 1992 and about 150 $\mu molNm^{-2}h^{-1}$ in 1993 and 1994 respectively in the eastern bay, and less than 100 $\mu molNm^{-2}h^{-1}$ in the

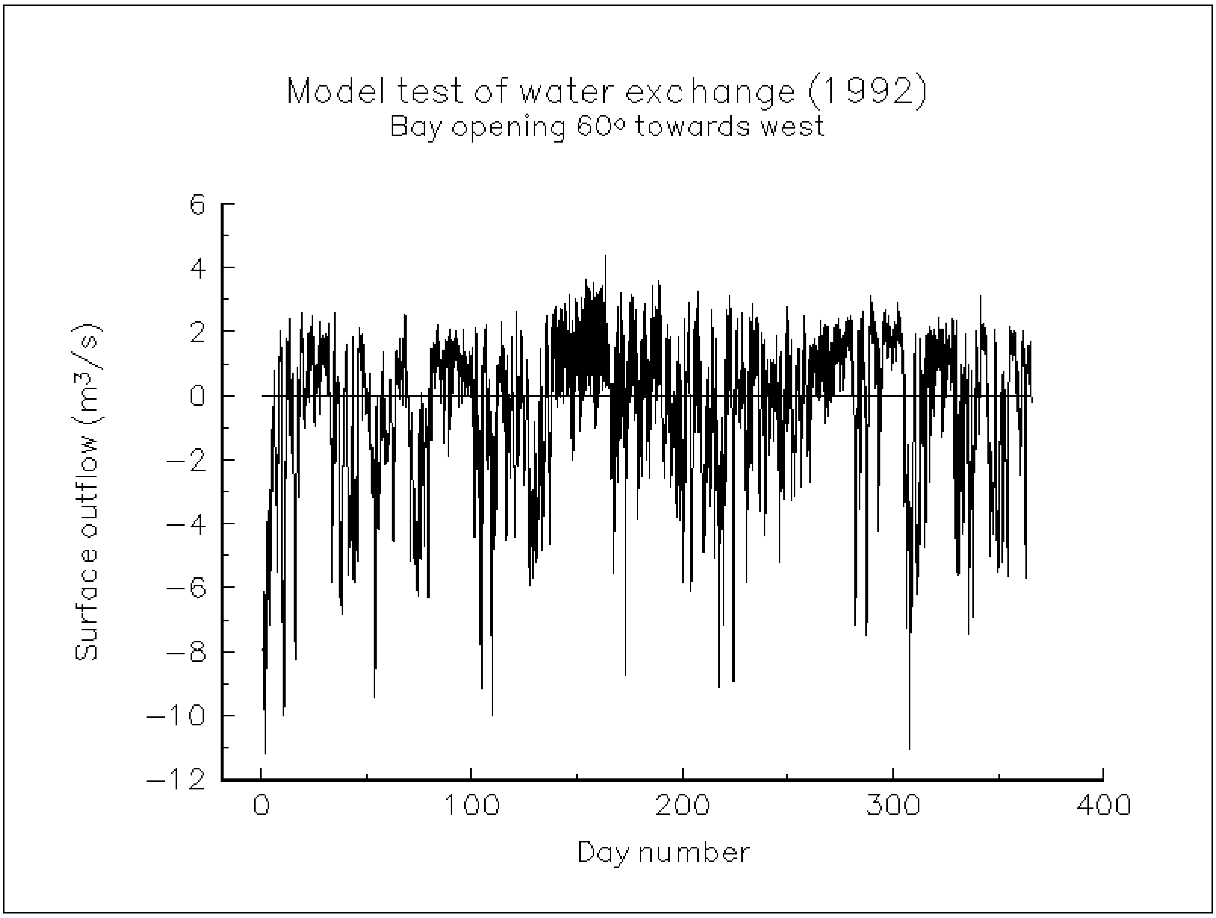


**Figure 5.13.** *Model results showing surface out flow from the bay having an opening towards west. Surface out flow is defined positive.*

western bay. The corresponding maximum summer values of remineralized DIP in the model amounts to about 50 µmolPm$^{-2}$h$^{-1}$ in 1992 and about 20 µmolPm$^{-2}$h$^{-1}$ in 1993 and 1994 in the eastern bay, and less than about 10 µmolPm$^{-2}$h$^{-1}$ in the western bay. One may note that these values fall within the range of observations of sediment-water fluxes of nutrients reported in the literature by eg. Cowan et al. (1996a, 1996b).

The fluxes of nutrients from the sediments in the shallow bays of course also have impact on the concentrations of nutrients in the water column as can be seen in Figure 5.21, 5.22, 5.23 and 5.24 below. The summer values of DIN and DIP concentrations are always higher in the bays than on the coast with the highest concentrations found in the sheltered eastern bay. These differences in nutrient concentrations between bays are one of the preconditions that we expect to have importance on the varying growth of e.g. filamentous algae in different shallow bays on the Swedish west coast (section 3.2). One may also note that the modelled DIN values of about 1-3 mmolNm$^{-3}$ and DIP values of about 0.1-0.5 mmolNm$^{-3}$ agree well with the nutrient concentrations measured in Trälebergskile during 1993 and 1994 (Pihl et al., 1996).

## 5.4 Concentrations of filamentous algae in a shallow bay

The growth of filamentous algae in a shallow bay is mainly determined by the light and nutrient concentrations in the bay and the exposure to waves of the bay as mentioned earlier (section 3). The decay of algae biomass in autumn and the general absence of algae in winter are however still poorly understood.

The light conditions on the Swedish west coast are sufficient for growth throughout the year and the nutrient concentrations are high in late autumn and winter. So the decay and absence of algae in winter may not be explained by these factors. Model experiments also show that this may not be explained by a natural harvest by the increased winds in autumn and winter. It has also been observed that the algae may have a rapid growth at quite low temperatures (~3 °C) in spring. Thus, a pure temperature dependency of the algae growth doesn’t seem to be the explanation neither. In the present model we have simply introduced an increased temperature dependency of the growth

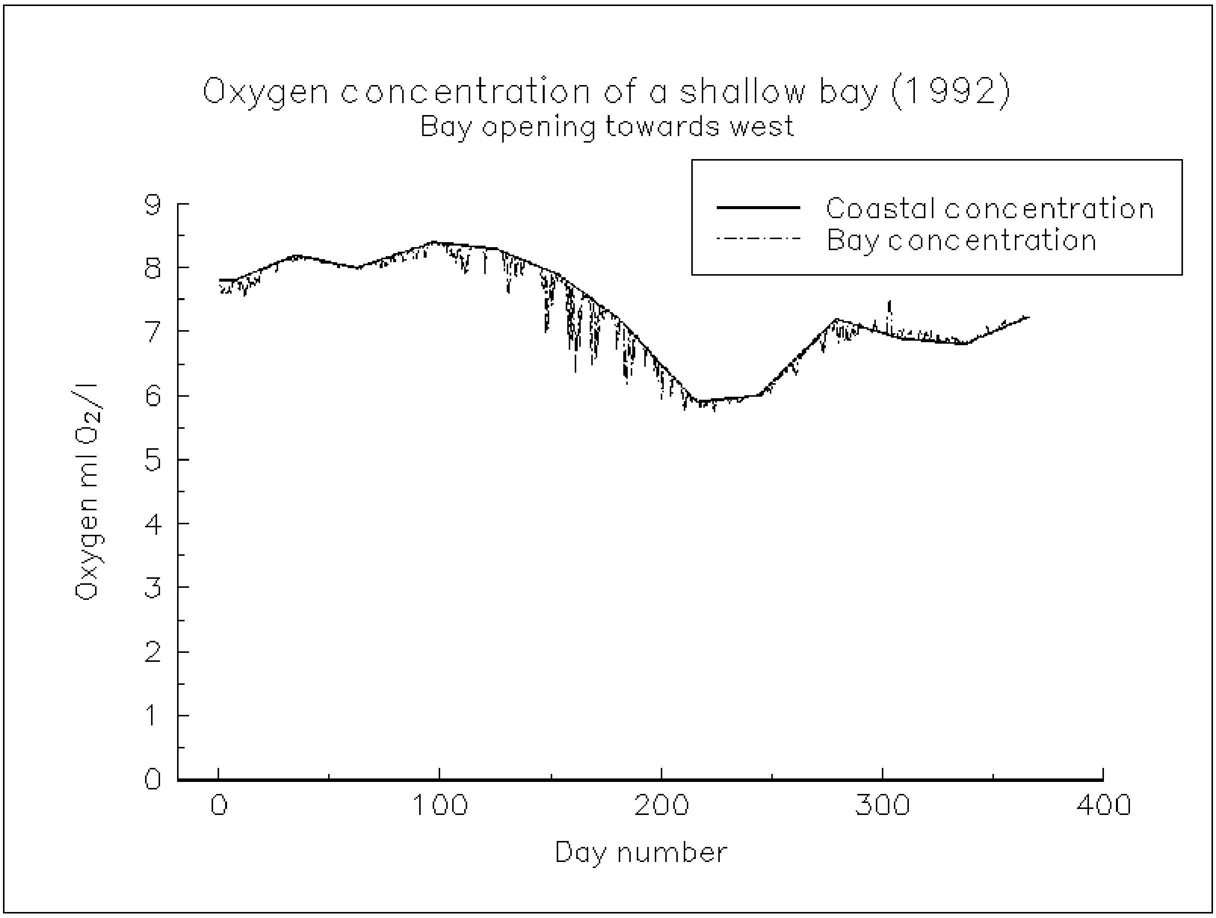


**Figure 5.14.** *Model results showing oxygen concentrations of the modelled bay and the surface layer of the coastal waters. The bay is open towards west.*

rate of algae in autumn and winter to simulate a seasonal variation in the "age" of the algae. Thus, the growth of algae from juvenile sprouts in spring is in the model assumed to be potentially greater at a given temperature than the growth of mature older algae in late summer and autumn in the model.

The growth and decay of filamentous algae, and the natural and man made harvest of algae in a shallow bay will be modelled in this section. The concentrations of nutrients and oxygen in the bay are determined by the oxygen and nutrient exchange models described in section 5.2 and 5.3, and by the growth and remineralization rates of filamentous algae in the bay. The possibility of an import or export of drifting mats of macroalgae through the entrance of the bay is not included in the present model.

### 5.4.1 The growth of filamentous algae in the model of a shallow bay

The growth of filamentous algae is in the model determined by the uptake rate of nutrients from the surrounding bay water. The growth rate is however limited by the available light and nutrients as well as by the water temperature. The maximum coverage of algae (MAXCOVER) in the modelled bay is limited by a literature value of the maximum biomass density of filamentous algae observed on the west coast. A fraction of the algae biomass in the model is lost according to a mortality rate to a pool of dead algae in the water called detritus. Another fraction is in the model permanently lost due to the harvest of algae by wind-waves or by man. A minor fraction of the detritus is incorporated into the sediments and the rest is either remineralized back to the water or lost at the harvest of algae. The stoichiometric relation of filamentous alga in the model is assumed to be given by molar ratios described in accordance with Atkinsson and Smith (1983) and Pihl et al. (1996) by C:N:P=310:22:1. It is further assumed that 354 moles of oxygen are produced at the photosynthetic production of one mol phosphorus in algae and equally much consumed at the decomposition of dead algae in the water column. However, oxygen consumption at decomposition of dead algae accumulated in the sediments is similar to the decomposition of PON described above. This will slightly under estimate benthic oxygen consumption in the model. Though, this has small

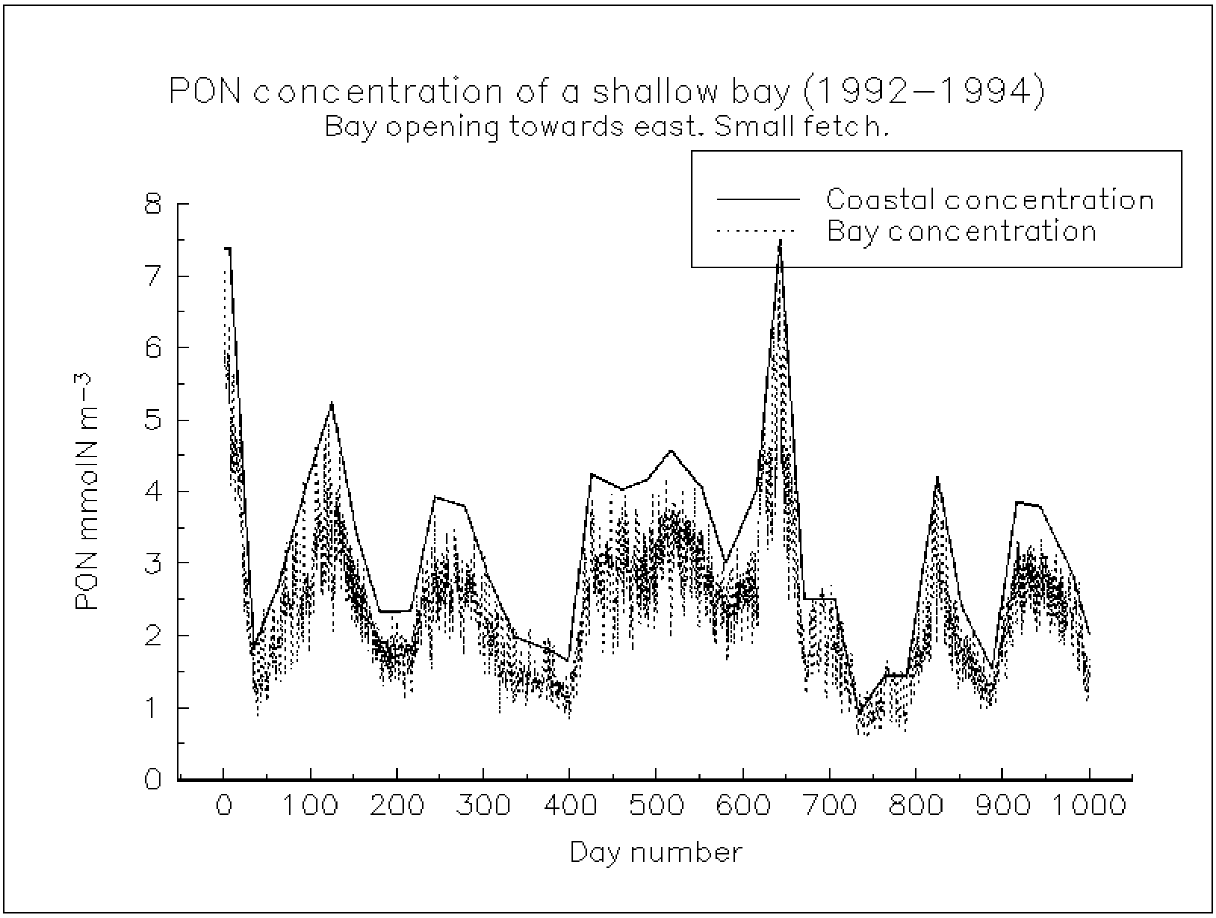


**Figure 5.15.** *Model results showing PON concentrations of the modelled bay (dotted line) and of the surface layer of the coastal waters (solid line). The bay is open towards east.*

importance for the results since the sedimentation of filamentous algae is quite small according to the present model formulation. The carbon content of algae in the model is described in accordance with Pihl et al. (1996) by 0.2 gram carbon per gram dry weight of algae.

## 5.4.2 The growth rate of filamentous algae

The uptake rate of nutrients by filamentous algae is in the model described by the Michaelis-Menten half saturation constant ($K_h$) and the maximum uptake rate (Vmax). The increased activity of biological processes at higher temperatures is in the model simulated by a temperature dependent maximum growth rate. The temperature dependence of the growth rate is defined to obtain a doubled growth rate of algae for a temperature increase of 10 degrees. The growth of algae is in the model negligible for light irradiance (Irr) levels below $Irr_{min}$. The growth limitation by light decreases linearly for an increasing Irr to a point $Irr_{opt}$ where the maximum photosynthesis of the algae is obtained. Photoinhibition occurs in the model if the light irradiance exceeds $I_{opt}$. The photosynthetically active fraction (PAR) of the solar radiation is in the model defined by half of the absorbed solar radiation $Q_s$ described in section 5.1.5.

Thus, the production of algae (ALGGROW) is in the model described by

$$ALGGROW = NLIM \cdot LLIM \cdot GMAX \cdot ALG \quad (5.26)$$

where NLIM is the nutrient limitation ($0 \le NLIM \le 1$), LLIM the light limitation ($0 \le LLIM \le 1$), GMAX the maximum growth rate of algae and ALG the biomass of living algae in the bay.

The nutrient limitation is described by

$$NLIM = MIN\left(\frac{DIN}{K_{DIN} + DIN}, \frac{DIP}{K_{DIP} + DIP}\right) \quad (5.27)$$

where Din and DIP are the concentrations of inorganic nitrogen and phosphorus in the bay. $K_{DIN}$

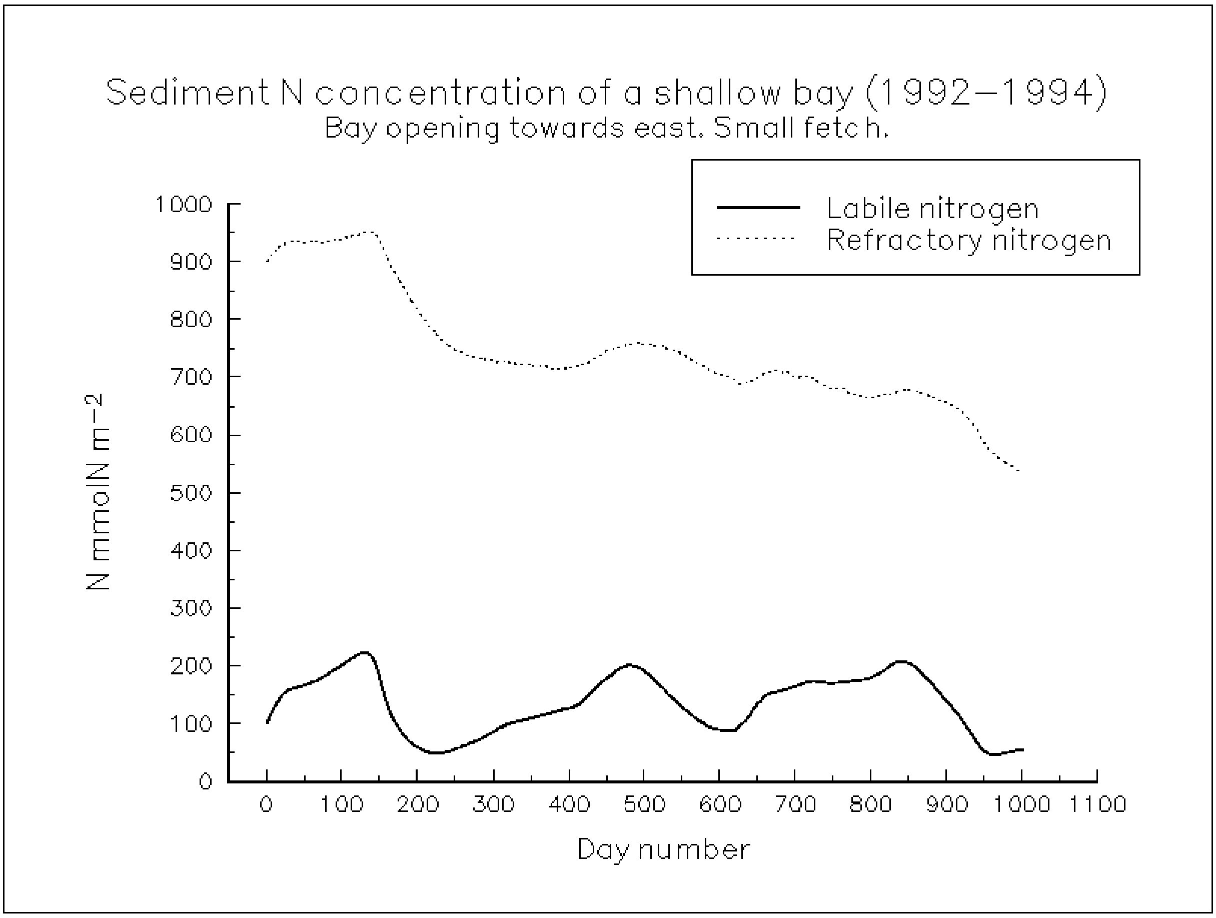


**Figure 5.17.** *Model results showing nitrogen concentrations of the bay sediments. The solid line represents the labile fraction and the dotted line the refractory fraction of nitrogen. The bay is open towards east.*

and $K_{DIP}$ are the half saturation constants of DIN and DIP respectively.

The light limitation for an irradiance greater than $Irr_{min}$ is described by

$$LLIM = \frac{Irr - Irr_{min}}{Irr_{opt} - Irr_{min}} \qquad (5.28)$$

and

$$LLIM = 1 - C_x \cdot \frac{Irr - Irr_{opt}}{Irr_x - Irr_{opt}} \qquad (5.29)$$

if Irr is greater than $Irr_{opt}$. Here $C_x$ (=2/5) and $Irr_x$ (=482Watt) are tuned to values obtained from the litterature (cf. Öberg,1999). The value of Irr is computed from Irr=0.5•$Q_s$.

The maximum growth rate is described by

$$GMAX = GMAX_0 \cdot e^{C_{TG} \cdot TEMP} \cdot (1 - AGERED) \qquad (5.30)$$

where $GMAX_0$ is the maximum growth rate at 0° Celsius, $C_{TG}$ the temperature constant of the growth rate and AGERED the algae age reduction factor (0≤AGERED≤1) of growth rate discussed above.

The growth of algae from juvenile sprouts in spring is in the model assumed to begin when the 5 day average of water temperature in the bay have been increasing for a period of 10 days in a row. When this happens the factor AGERED is set to zero. Similarly, in autumn when the average water temperature decreases below 10° Celsius the factor AGERED increase linearly from 0 to 0.95 below 8° Celsius. Thus, in this way the potential growth rate of old algae is reduced to only 5% of the growth rate of juvenile algae. A minimum concentration of algae (ALGMIN) is introduced in the model to simulate the huge potential of algae growth in spring due to the spores passing the winter in the sediments (see section 3.5). These formulations in the model are at the present set relatively arbitrary and should of course be tuned against observations in the future.

The maximum growth rate at 0° Celsius is in the model defined by $GMAX_0$=0.5•$VMAX_{10}$ where $VMAX_{10}$ is the maximum uptake rate of the limiting nutrient at 10° Celsius. A rough estimate of $VMAX_{10}$ and $K_{DIN}$ and $K_{DIP}$ was obtained using literature values (Wallentinus, 1984) of the half saturation constants and the corresponding

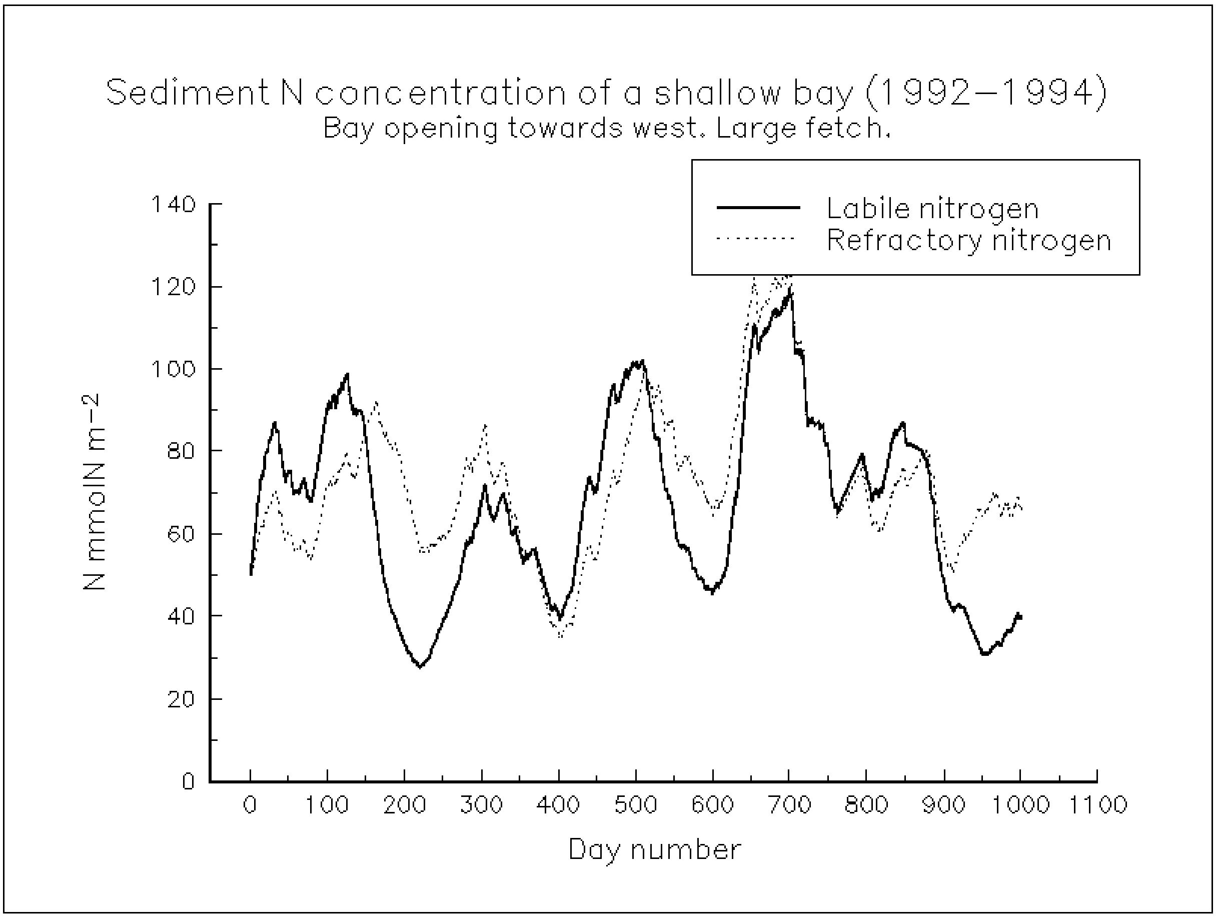


**Figure 5.18.** *Model results showing nitrogen concentrations of the bay sediments. The solid line represents the labile fraction and the dotted line the refractory fraction of nitrogen. The bay is open towards west.*

maximum uptake rates of nitrate, ammonium and phosphorus. These values were obtained from some species of fast growing algae, e.g. Cladophora and Enteromorpha, at largely varying water temperatures. The average values obtained here are presented in Table 5.1 below.

| | PO4 | NO3 | NH4 |
|---|---|---|---|
| $K_h$ (µM) | 1.6 | 6.9 | 17.7 |
| Vmax (µmolg$^{-1}$dw$^{-1}$h$^{-1}$) | 3.9 | 77.0 | 159.0 |
| Vmax (day$^{-1}$) | 1.68 | 1.55 | 3.21 |

**Table 5.1.** *Michaelis-Menten half saturation constant ($K_h$) and the maximum uptake rate (Vmax). Average temperature was 10°Celsius. The last row is computed using the stoichiometric values presented in section 5.4.1.*

There are only small differences between the net uptake rates of nitrate and ammonium especially at N concentrations below 5µM if the effect of NLIM is accounted for. Thus, since the specific uptake rates of phosphate and nitrate are quite similar we use a value of $VMAX_{10}$=1.6 day$^{-1}$ together with the half saturation constants $K_{DIN}$=6.9µM and $K_{DIP}$=1.6µM in the model.

### 5.4.3 The mortality, remineralization and sedimentation rates of filamentous algae

The model description of mortality, remineralization and sedimentation rates of the filamentous algae and detritus are here directly imported from Öberg (1999). A fraction (ALGMORT) of the biomass of algae is lost at a constant rate Ω to a pool of detritus in the model. Öberg (1999) also define an increased "toxic" mortality rate at temperatures above 25° Celsius which, however, is not incorporated in the present model. A fraction (DETREM) of the biomass of detritus is remineralized in the water at the constant rate REM and a small fraction (DETSED) is lost to sediments at a constant rate SED. Thus,

$$ALGMORT = \Omega \cdot ALG \qquad (5.31)$$
$$DETREM = REM \cdot DET \qquad (5.32)$$
$$DETSED = SED \cdot DET \qquad (5.33)$$

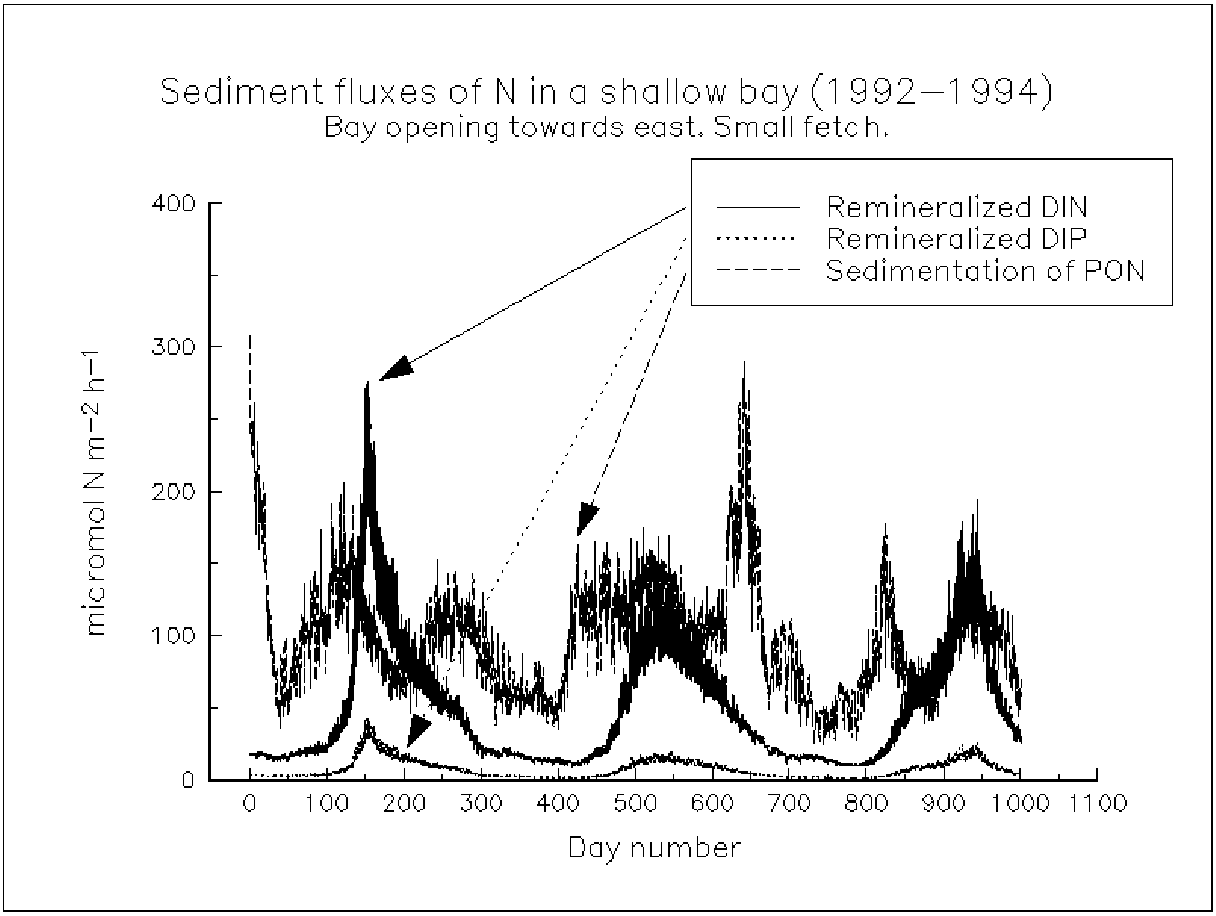


**Figure 5.19.** *Model results showing sediment-water fluxes of inorganic nitrogen DIN and phosphorus DIP, and sedimentation of PON in the bay. The solid line represents the flux of remineralized DIN, the dotted line the flux of remineralized DIP. The dashed line represents sedimentation of PON. The bay is open towards east.*

where DET is the biomass of dead algae in the bay. We also defined SED in accordance with the model description used by Öberg (1999) SED=0.01•REM. These formulations should however be further studied in the future to account for e.g. varying water temperatures.

## 5.4.4 The natural and man made harvest of filamentous algae

The natural harvest of filamentous algae (ALGHARV) and detritus (DETHARV) by wind-waves in a shallow bay are accounted for in the model by the following simplified description.

$$ALGHARV = HARV \cdot ALG / ( ALG + DET ) \quad (5.34)$$

$$DETHARV = HARV \cdot DET / ( ALG + DET ) \quad (5.35)$$

where HARV is computed from

$$HARV = HARVLIM \cdot HARVMAX \quad (5.36)$$

HARVMAX is the maximum rate of algae harvest discussed below. HARVLIM ($0 \le HARVLIM \le 1$) is a factor limited by wind speed and fetch length in a similar way as described in Equation 5.24 in section 5.3.3. HARVLIM is computed from the following expression.

$$HARVLIM = \frac{W^2 \cdot F - W2F_{low}}{W2F_{high} - W2F_{low}} \quad (5.36)$$

Here $W2F_{low}$ is the minimum limit where the combination of wind speed and fetch length may begin to harvest the algae. $W2F_{high}$ is the upper limit where the maximum rate of harvest is achieved.

HARVMAX and $W2F_{high}$ are determined from an observation in the shallow bay of Trälebergskile on the west coast of Sweden. Pihl et al. (1996) made extensive studies of the distribution of ephemeral algae in this bay and found that all of the biomass of algae, about 240 gdw$^{-1}$m$^{-2}$, was harvested within less than one week with strong winds (15-20m/s) in late June 1994. The fetch length of the bay corresponding to winds blowing into the bay is about 2 km. Thus, in accordance with this

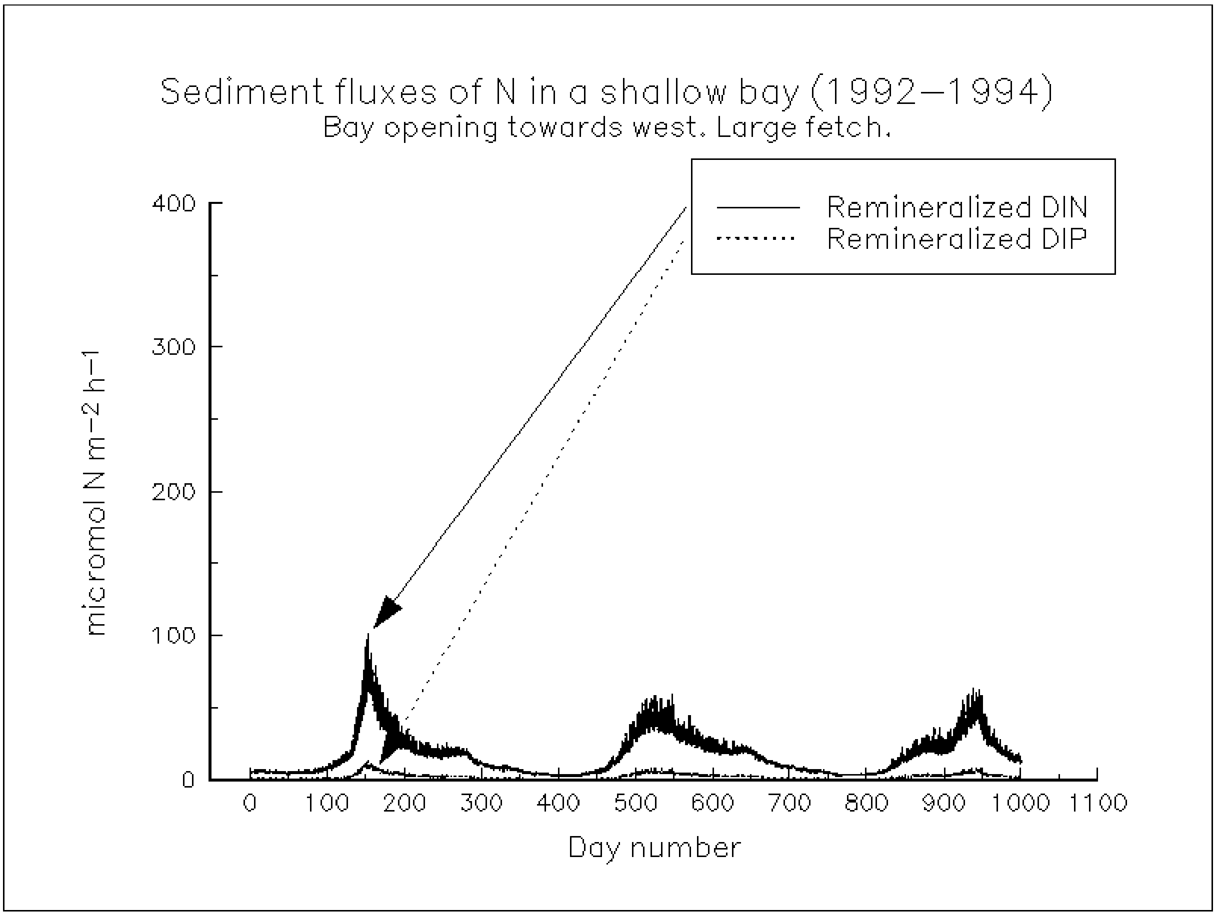


**Figure 5.20.** *Model results showing sediment-water fluxes of inorganic nitrogen DIN and phosphorus DIP. The solid line represents the flux of remineralized DIN, the dotted line the flux of remineralized DIP. The bay is open towards west.*

HARVMAX was set to 240 $gdw^{-1}m^{-2}$ per 5 days in the model and $W2F_{high}$ was set to 650000 $m^3s^{-2}$ ($\approx 18^2 \bullet 2000$ $m^3s^{-2}$). The value of $W2F_{low}$ was set relatively arbitrary at 300000 $m^3s^{-2}$. However, this value was chosen after some numerical experiments with the present model.

The man made harvest in the model was simply introduced as an opportunity to specify a number of days when all of the algae and detritus should be harvested from the bay in each year of the model run.

## 5.4.5 Results of the filamentous algae model

The filamentous algae model described above was run for a period of 1000 days beginning on January 1:st 1992. The set up of the nutrient exchange model was set equal to that of the eastern bay described in section 5.3.4, except that the initial value of REFN was set to 0.4 $molNm^{-2}$. Results from five different test cases are first presented below. Thereafter a simple test of the model is performed on a random collection of a large number of shallow bays on the Swedish west coast.

The degree of algae cover in the model results are compared to observations of algae area coverage in the bays.

The five test cases investigated are;

Case1)

Case2) One bay with an opening of about 90° directed towards east and having a fetch length of about 250m. Bay depth 1m.

Case3) One bay with an opening of about 90° directed towards west and having a fetch length of about 5000m. Bay depth 1m.

Case4) Similar to case 1 but with bay depth 0.5m.

Case5) Similar to case 1 but with manual harvest on day number 180 each year.

Case6) Similar to case 3 but with manual harvest on day number 180 each year.

The values of parameters used in the test cases below are:

| | | |
|---|---|---|
| $GMAX_0$ | =0.8 | $day^{-1}$ |
| $C_{TG}$ | =0.07 | $°C^{-1}$ |
| $K_{DIN}$ | =6.9 | µM |
| $K_{DIP}$ | =1.6 | µM |
| $Irr_{opt}$ | =60 | watt |
| $Irr_{min}$ | =1 | watt |
| $Irr_x$ | =482 | watt |

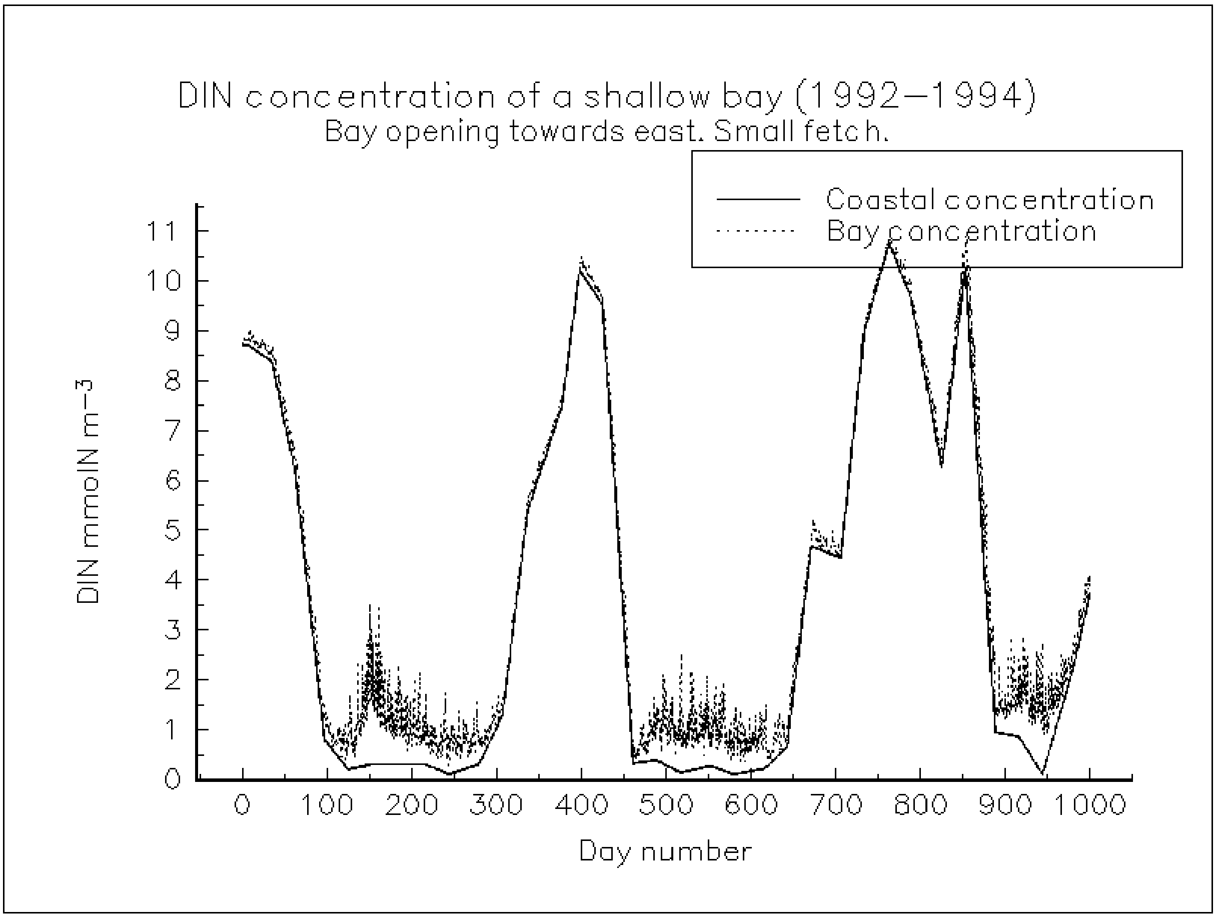


**Figure 5.21.** *Model results showing DIN concentrations in the modeled bay (dotted line) and of the surface layer of the coastal waters (solid line). The bay is open towards east.*

| | | |
|---|---|---|
| $C_x$ | =2/5 | dimensionless |
| Ω | =0.04 | $day^{-1}$ |
| REM | =0.04 | $day^{-1}$ |
| SED | =0.01•REM | $day^{-1}$ |
| HARVMAX | =48 | $gdw^{-1}m^{-2}$ $day^{-1}$ |
| $W2F_{high}$ | =650000 | $m^3s^{-2}$ |
| $W2F_{low}$ | =300000 | $m^3s^{-2}$ |
| MAXCOVER | =600 | $gdw^{-1}m^{-2}$ |
| ALGMIN | =0.84 | $gdw^{-1}m^{-2}$ |

The stoichiometric relations and the ratio of dry weight to carbon of algae used in the model are described in section 5.4.1 above. Note that the freshwater supply to the bay is zero (section 5.1.8).

The first important note regarding the model results is that there is no observed increased accumulation of nutrients in the sediments relative to the results in section 5.3.4. Intuitively one would expect that this might be the case. Observations from a large number of shallow bays on the Swedish west coast (Pihl et al., 1999) have indeed showed that sediments covered by algal mats have higher contents of carbon and nitrogen than unvegetated sediments. This may of course at least partly be due to the deposition of filamentous algae in the sediments. However, the maximum summer concentration of nitrogen obtained in the sediments of the modelled sheltered and exposed bays correspond to about 0.14% and 0.04% of dry weight, respectively (compare with Figure 5.17 and 5.18). These results are quite similar to the average observations of nitrogen content in the sediments in locations with and without filamentous algae mats made by Pihl et al. (1999). Thus, it seems that a major fraction of the nutrients found in the sediments of the shallow bays can be explained by an import of nutrients with PON from the coastal waters outside the bay.

The main characteristics of the modelled growth of filamentous algae in the sheltered bay is that a slow growth begins in early spring followed by a rapid increase of algae and detritus biomass from late May to the beginning of August (Figure 5.24).

The maximum biomass obtained in the modelled period is about 170 $gdw^{-1}m^{-2}$. For comparison one may mention that the growth in the bay of Trälebergskile started in mid May and ended at an average cover of about 240 $gdw^{-1}m^{-2}$ in the end of June as mentioned above. The average algae biomass in the years 1994 to 1996 varied from 11

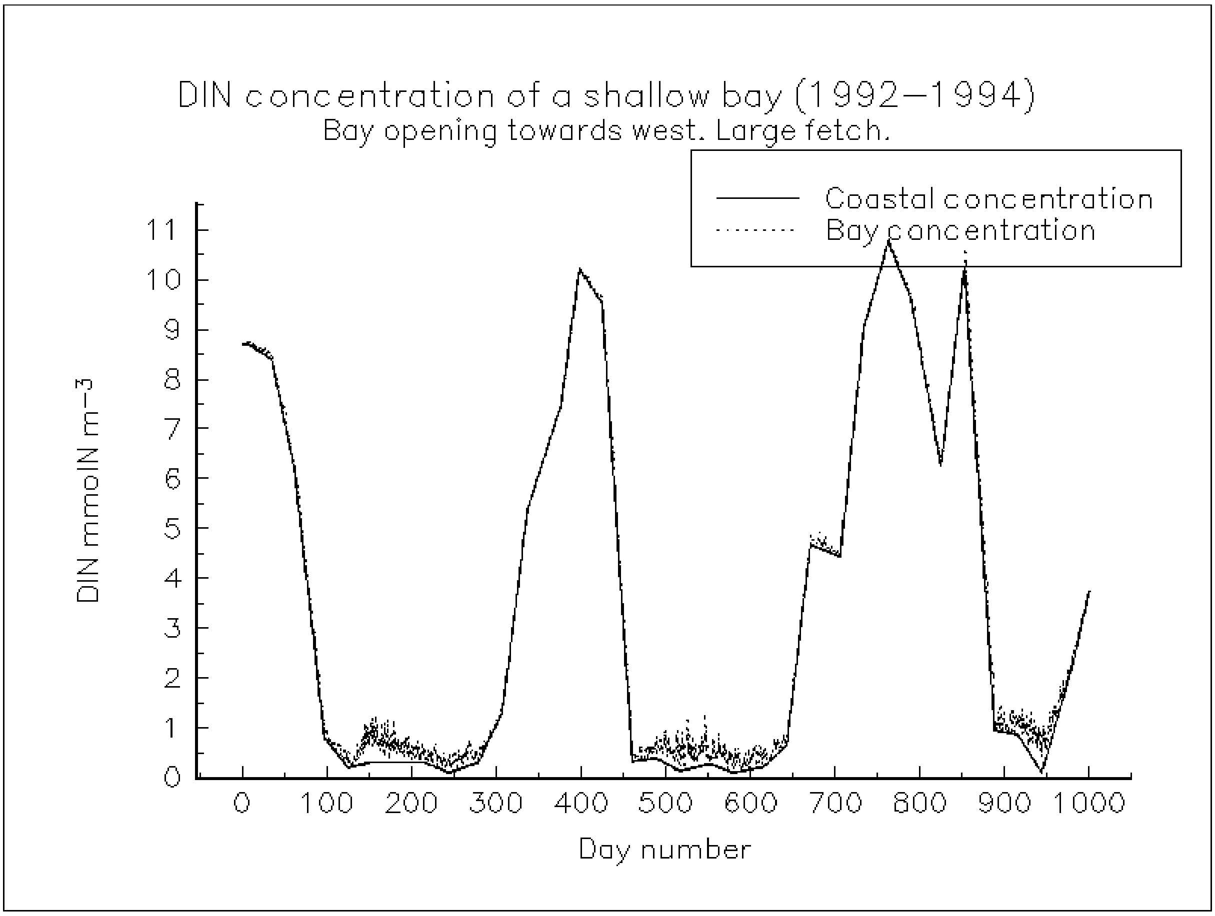


**Figure 5.22.** *Model results showing DIN concentrations in the modeled bay (dotted line) and of the surface layer of the coastal waters (solid line). The bay is open towards west.*

$gdw^{-1}m^{-2}$ and 286 $gdw^{-1}m^{-2}$ on algae-covered parts of this region on the Swedish west coast (Pihl et al., 1999). Thus, it seems that the model may produce relatively realistic results regarding the growth of filamentous algae.

The more exposed westerly opened bay shows only small traces of growth of filamentous algae above the minimum allowed algae concentration in the model (Figure 5.25). This is due to the relatively low concentrations of nutrients in the bay (section 5.3.4) and the relatively frequently occurring natural harvest of algae by winds in the model.

Reducing the depth of the bay by half causes an increased biomass of algae in the bay (Figure 5.26). This biomass increase may be explained by an increased availability of nutrients in the bay due to a reduced water exchange of the bay. Thus, more of the nutrients released from the sediments and from decaying algae are trapped in the bay and may be used for the production of algae. A look at the oxygen concentrations of the same bay shows that the growth of algae during day time in the model may increase concentrations in the bay relative to the coastal concentrations of oxygen. On the other hand, the night time respiration by decomposition of decaying algae causes an oxygen consumption and oxygen concentrations reaching below 5 $mlO_2l^{-1}$.

The effect of a manual harvest once a year may reduce the maximum amount of biomass covering the bay by about 50% in the model results (Figure 5.28 and 5.29). The results of course depend on which day the harvest is done. However, the harvest of algae in the model have no effect on the potential growth of the algae in the following year since the nutrients used to increase the accumulated biomass in the bay are mainly supplied from the sediments. These nutrients are in turn supplied by the sedimentation of externally supplied PON in the model.

The model was finally used to predict the maximal area coverage of algae in 1994 in a large number of randomly sampled shallow bays on the Swedish west coast. The geometry of the modelled bay was however the same as used in case 1 and 2 above. The results are compared with observations of the degree of algae coverage from the bays made at some occasions in the period 1994-1996 (see section 3.4). The model results from the bay with an average depth of one meter are normalized to the maximum degree of algae cover obtained in the modelled sheltered bay, i.e. a 100% degree of modelled algae cover in Figure 5.30 represents 170

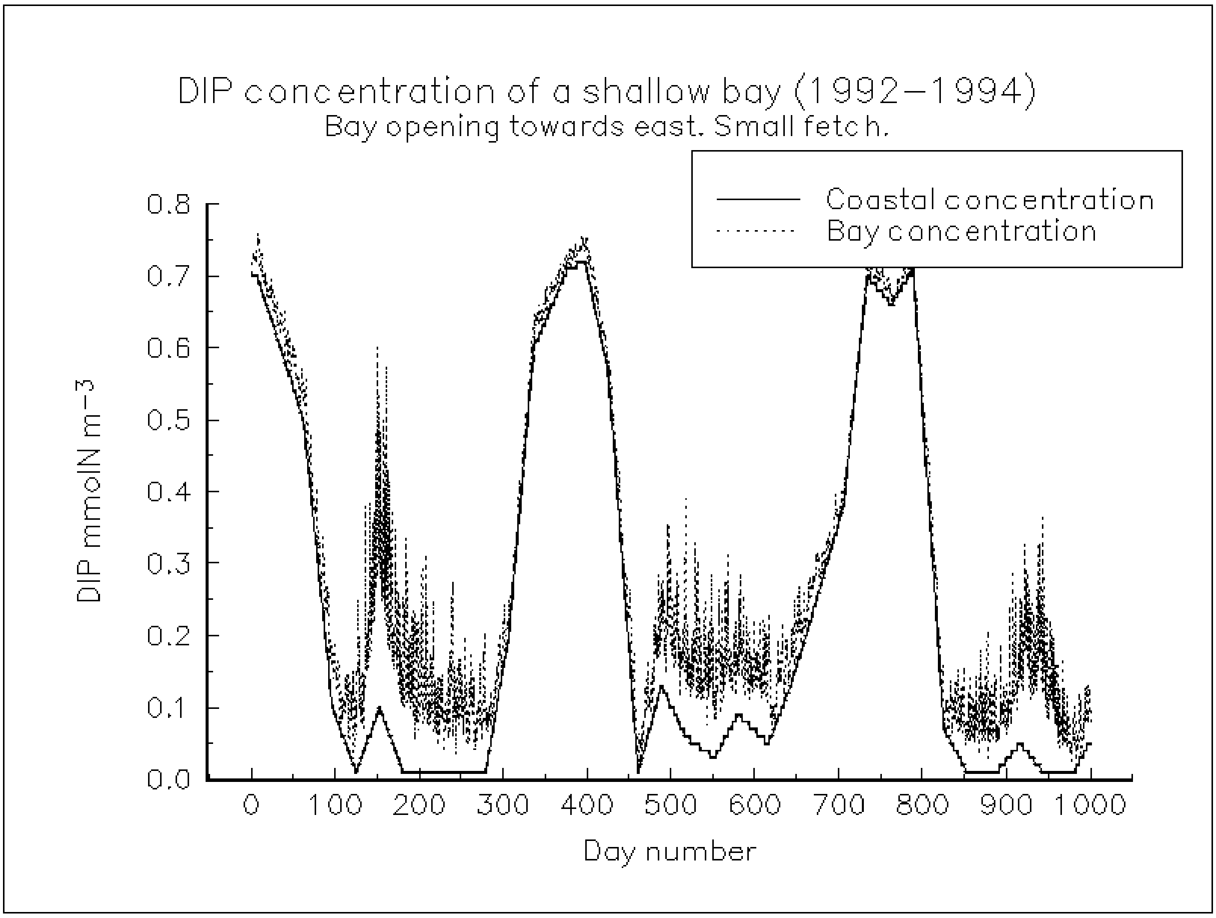


**Figure 5.23.** *Model results showing DIP concentrations in the modeled bay (dotted line) and of the surface layer of the coastal waters (solid line). The bay is open towards east.*

gdw$^{-1}$m$^{-2}$. The results are plotted as a function of the estimated exposure index discussed in section 3.4 above.

The model results show a fair deal of similarity with the observations from the real bays. The functional dependence between the degree of algae cover and the degree of exposure of the bay becomes clear in the figure. It seems from the figure (5.30) that the the degree of exposure may be exaggerated by the model. This may partly be due to the rough estimates of the parameters used to tune the  harvest of algae in the model. Though, one has to bear in mind that the real bays may differ a lot from the modelled bay in their geometrical dimensions. There may also be some influences from freshwater supply as well as from atmospheric exchanges to the real bays which were not included in the model run. The nutrient concentrations in the adjacent waters of the different bays may differ from the coastal values used in the present model run. Further, the depth of the fetch area outside the bay and the ratio of the width of the bay entrance and the bay peripheral length have been used at the computation of the exposure index. These parameters are not accounted for in the present model but should in the future be implemented to the model to more accurately describe the acual wave climate of a specific shallow bay.

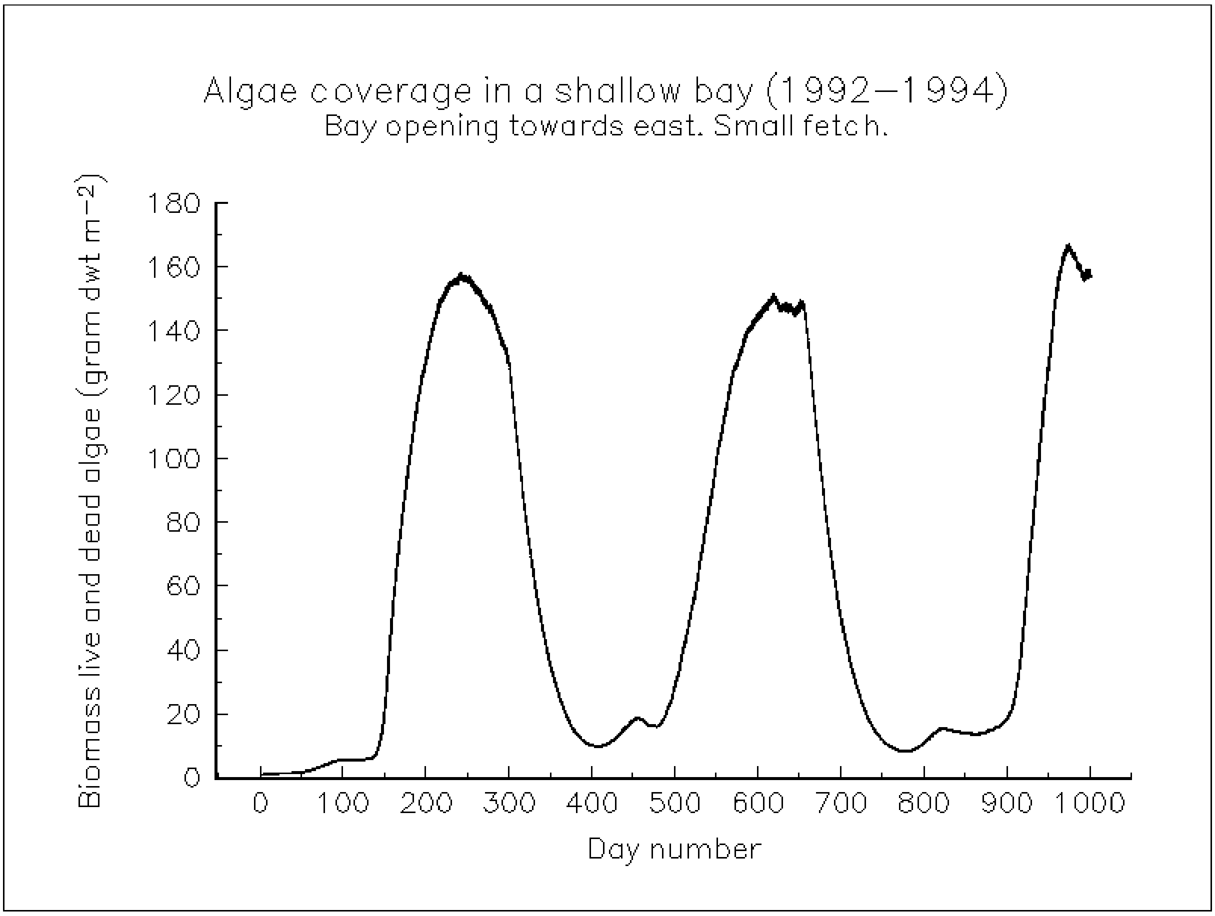


**Figure 5.24.** *Model results showing area concentrations of the sum of live and decaying filamentous algae in the modeled bay. The bay is open towards east with a small fetch. The average depth of the bay is one meter.*

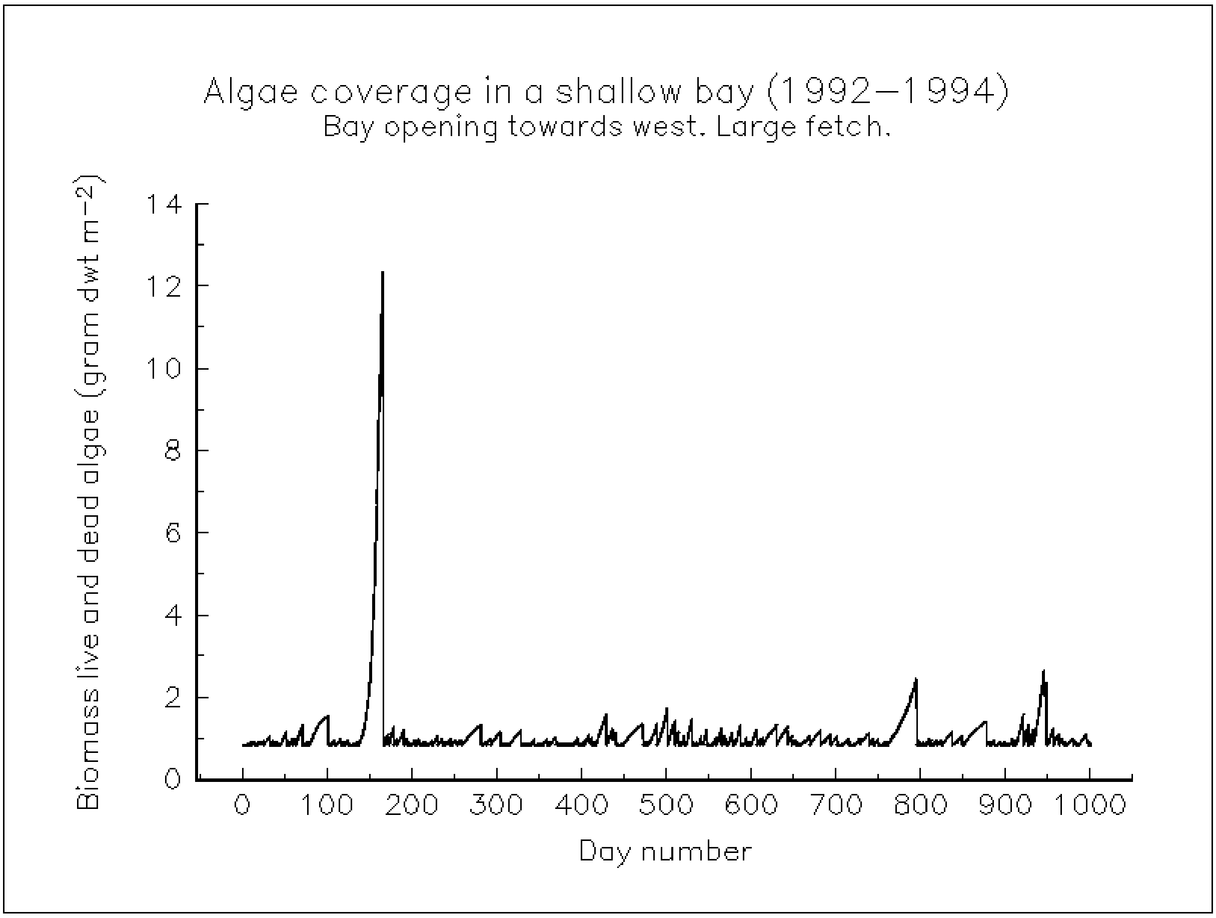


**Figure 5.25.** *Model results showing area concentrations of the sum of live and decaying filamentous algae in the modeled bay. The bay is open towards west with a large fetch. The average depth of the bay is one meter.*

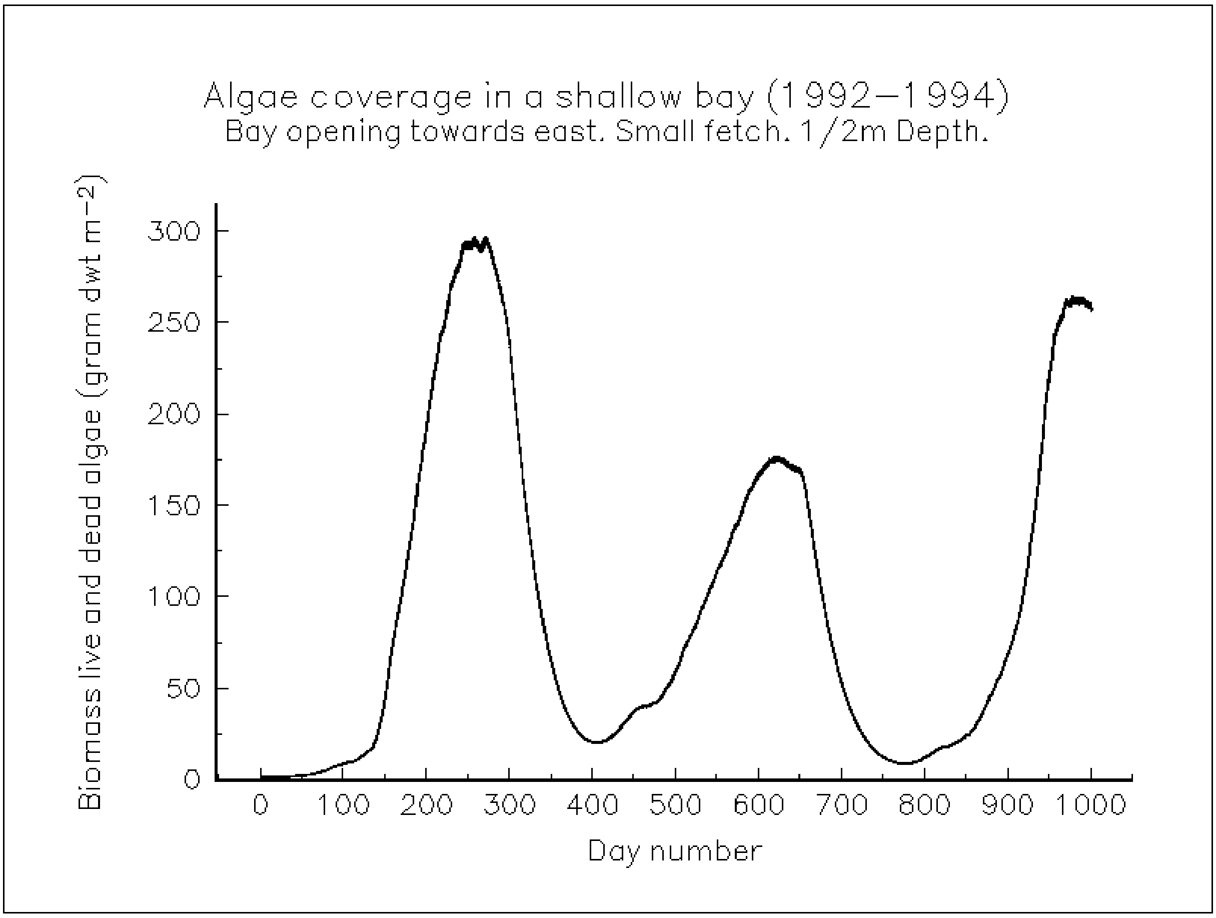


**Figure 5.26.** *Model results showing area concentrations of the sum of live and decaying filamentous algae in the modeled bay. The bay is open towards east with a small fetch. The average depth of the bay is a half meter.*

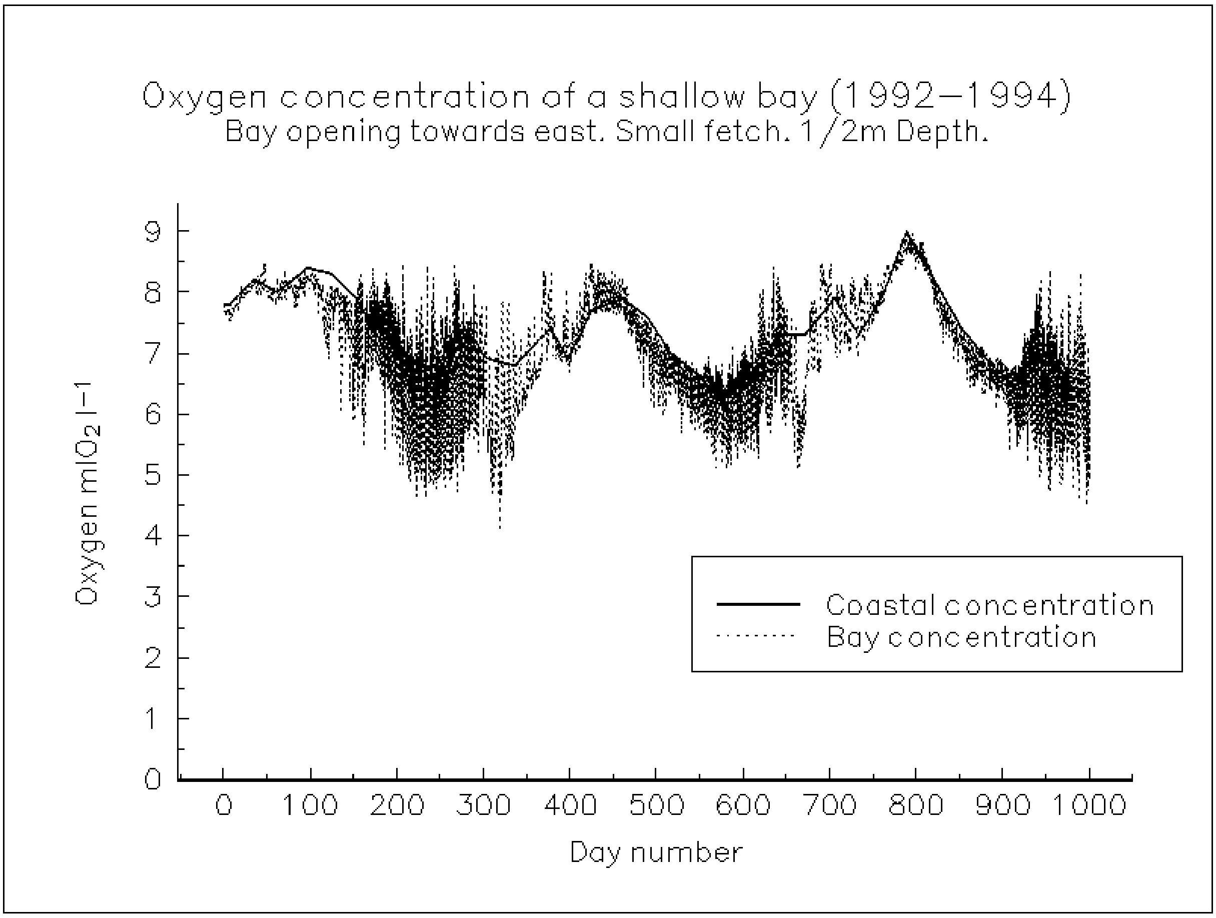


**Figure 5.27.** *Model results showing oxygen concentrations in the modeled bay (dotted line) and in the surface layer of coastal waters (solid line). The bay is open towards east with a small fetch. The average depth of the bay is a half meter.*

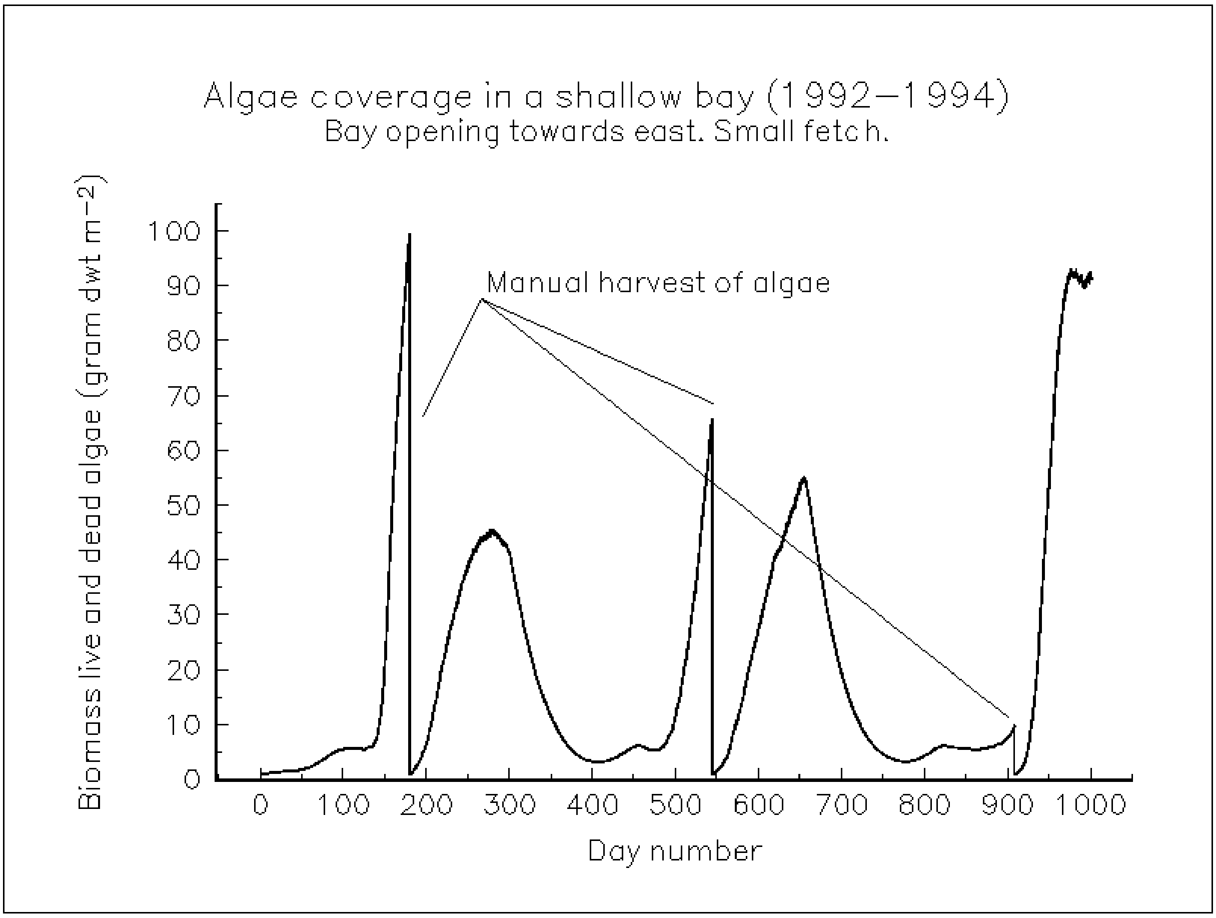


**Figure 5.28.** *Model results showing area concentrations of the sum of live and decaying filamentous algae in the modeled bay. The bay is open towards east with a small fetch. The average depth of the bay is one meter. Algae is manually harvested on day number 180 each year.*

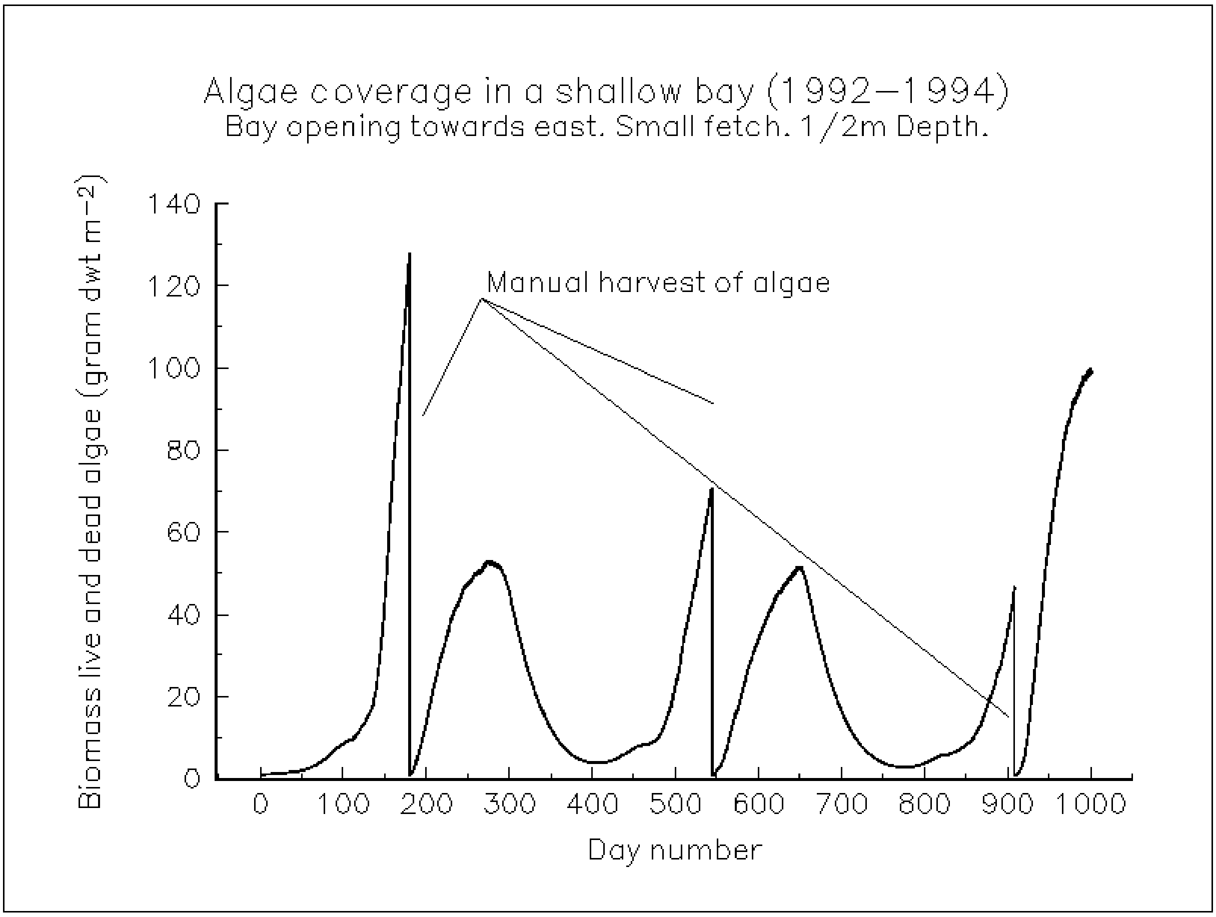


**Figure 5.29.** *Model results showing area concentrations of the sum of live and decaying filamentous algae in the modeled bay. The bay is open towards east with a small fetch. The average depth of the bay is a half meter. Algae is manually harvested on day number 180 each year.*

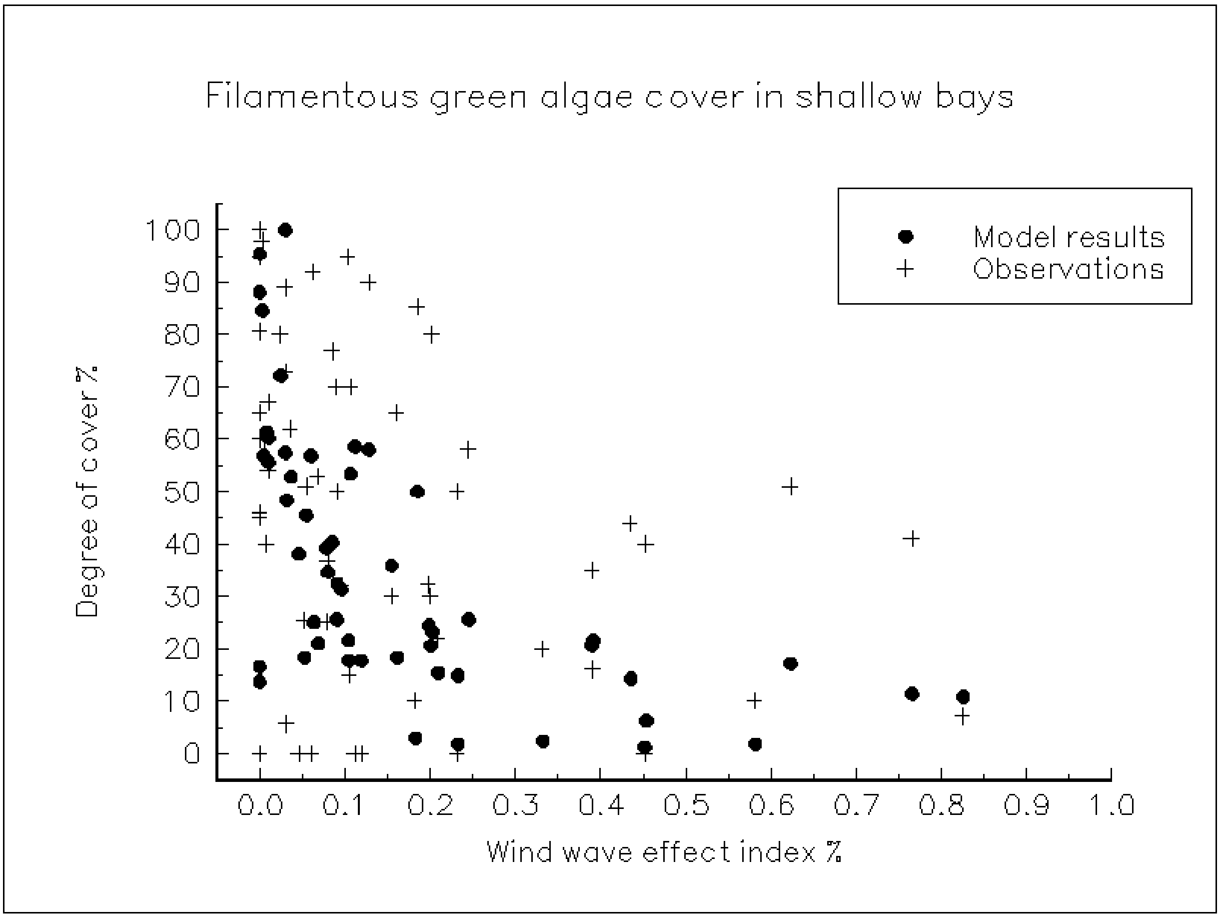


**Figure 5.30.** *Model results from 1994 (solid circles) and observations from the period 1994-1996 (plus) showing the degree of algae cover as function of an exposure index in a random collection of shallow bays on the Swedish west coast.*

# 6. Acknowledgements

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We also want to thank the staffs of the county administration, the Kristineberg Marine Research Station and the Dept. Of Oceanography at Göteborg University for their assistance during the project.

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# 8. Appendix

## 8.1 Field investigation in the Tjärnö archipelago and the Kosterfjord, spring 1999

During preliminary investigations foregoing the modelling effort it was recognized that there was a lack of information about the temporal changes during spring of nutrient concentrations in the water and in the sediments of the shallow bays. Therefore a series of simple investigations were performed in four shallow bays in the Tjärnö Archipelago. Two of the bays (Dynäs and Kingeleran) were chosen from the sheltered inner archipelago where large amounts of filamentous algae usually causes problems in summer. The other two (Lindholmen Nord and Syd) were chosen from the outer archipelago were no filamentous algae had been observed before. Five cylindrical samples, about 2cm diameter, were randomly collected from the surface sediment of each bay. The samples were saved in freezer for the analysis of the content of carbon and nitrogen in the upper 0.5 cm of the sediment. The analysis was performed on the carbon/nitrogen analyzer at the Kristinebergs Marina Forskningsstation. Only the results from the nitrogen analysis is presented here since these are most interesting for the present task. Water bottle samples were collected in connection with each sediment sample. The water samples were saved in darkness and transported as quick as possible to an autoanalyzer at the Kristinebergs Marina Forskningsstation. Later it was decided that five water samples should be collected as reference samples from a reference station in Kosterfjorden and from a station located outside the bays in the inner archipelago. Unfortunately the timelag was too large between the sampling and the analysis at the three first occasions. The ammonium analysis from these samples could therefore not be used. Sampling and analysis was performed by personnel from the Kristinebergs Marina Forskningsstation. The raw data is saved by Anders Svensson at Kristineberg.

The inner archipelago was covered with a thin ice sheet and the nutrient concentrations were quite high relative to the coastal waters at the first sampling occasion. The spring phytoplankton bloom had already started earlier in the Kosterfjord. Some filamentous algae could be observed at the outer northern bay where this had not been observed before by Anders Svensson. Maybe because they always have visited the location later in the spring. The filamentous algae disappeared rapidly and was substituted by Fucus seaweed which covered about 50% of the bottoms of the northern bay in early June.

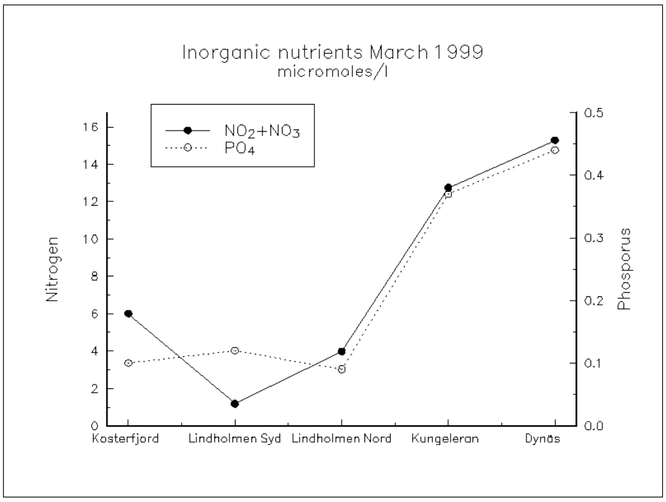
Two weeks later the ice was gone and relatively large amounts of filamentous algae were observed in one bay in the inner archipelago. The nitrate concentrations were much lower than two weeks earlier though the phosphate concentrations were still high. In the end of April the shallow bays of the inner archipelago were completely covered by some kind of aggregated forms ”filamentous like” brown microalgae. Clusters of these algae were also found free drifting in the deeper waters of the inner archipelago. Spots with hydrogen sulphide could be found among the brown microalgae in the bay Kingeleran. Inorganic nutrients were depleted in the shallow inner bays while the deeper reference station in the inner archipelago still had relatively high nutrien concentrations. In the beginning of May an increase of phosphate concentrations were observed in the shallow bays while the coastal waters were totally depleted of phosphate. The brown microalgae in the inner bays had changed to a coverage of filamentous algae. Towards the end of May the phosphate in the waters of the inner archipelago were emptied and the filamentous algae almost gone. The ammonium concentration seems to be relatively constant around 2 $mmolNm^{-3}$ in the shallow bays and in the deeper waters of the inner archipelago. The Kosterfjord however is almost completely emptied of all inorganic nutrients in June. Phosphate concentrations had slightly increased in the shallow bays and the inner archipelago in June while the nitrate was gone everywhere. The filamentous algae covered about 10% of the bottoms of the inner shallow bays in June while another ephemeral algae, Ulva species, covered about 40% of the outer southerly bay.

Since the sampling of sediment data started after the spring bloom had started, we do not know how much newly produced organic matter that already had been deposited on the bottoms of the shallow bays at the beginning of the sampling period. Though we may observe that the concentrations of gram nitrogen per gram sediment dry weight (gN/gdwt) vary from about 0.05% in the northern outer bay to about 0.9% in Dynäs in the inner archipelago. We may also observe a relatively strong increase of the concentrations, about 0.1-0.2% from the beginning of April to the end of May in three of the bays. Dynäs show a decrease from April to May but a rapid increase back to initial conditions again in the end of May. The data from March and June are missing at the time of the report.

The results from the investigation are presented below in figures together with brief comments to the observations.

**24 March 1999**

- On-going spring bloom in Kosterfjorden (10/3-99).
- Decrease of inorganic nutrients in Kosterfjord.
- Coastal winter values ~ 10 µmolNl$^{-1}$, 0.7 µmolPl$^{-1}$.
- Inner archipelago ice covered.
- High nitrogen concentrations in inner archipelago.
- Filamentous algae observed on location Lindh. Nord.

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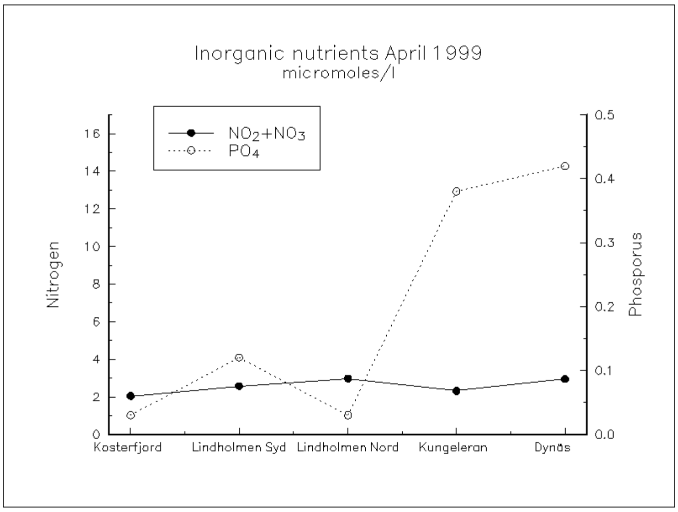
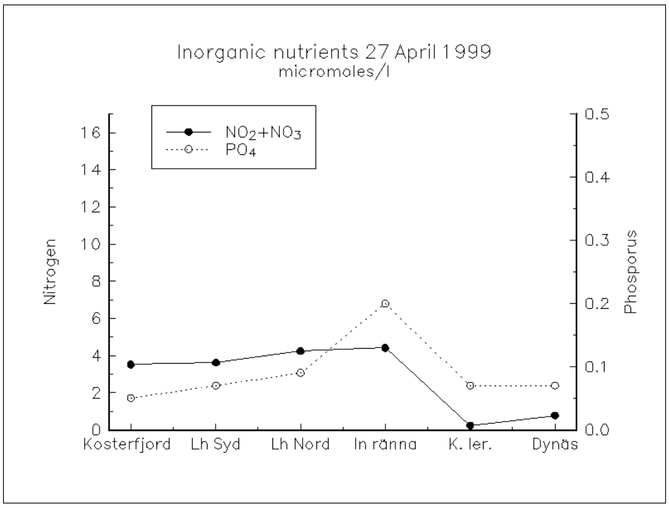
**12 April 1999**



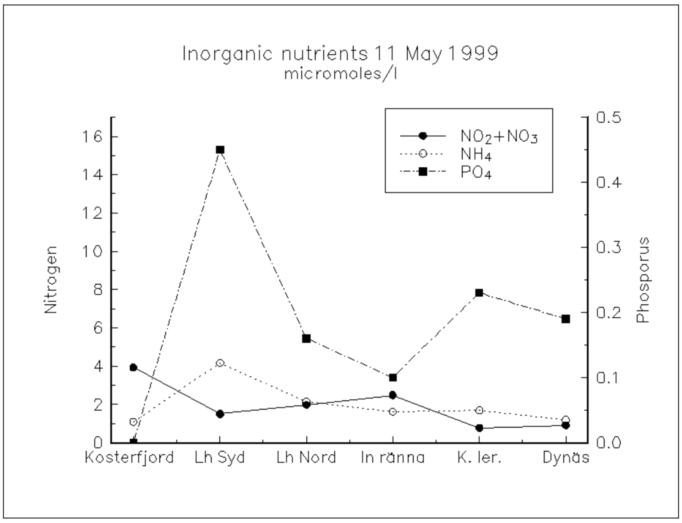

- Phosphate emptied in Kosterfjord.
- Low nitrate concentrations in inner archipelago.
- Relatively high phosphate conc. in inner archipelago.
- Open water in inner archipelago.
- Abundance of filamentous algae on one location in inner archipelago.

**27 April 1999**

- New reference station “in ränna” in deeper waters of the inner archipelago outside the shallow bays.
- Phosphate low, except in ”in ränna”.
- Nitrate emptied in inner shallow bays.
- Large amounts of brown algae in inner archipelago.
- Spots with hydrogen sulphide in Kingeleran.
- Free drifting clusters of brown algae in “in ränna”.
- Low sea level.



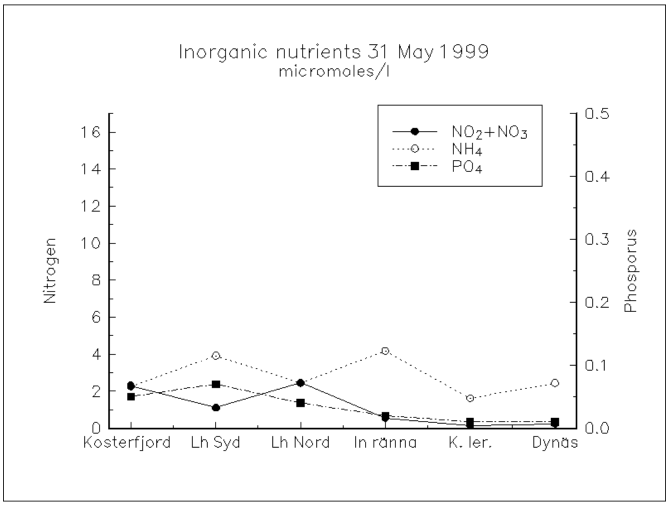

**11 May 1999**



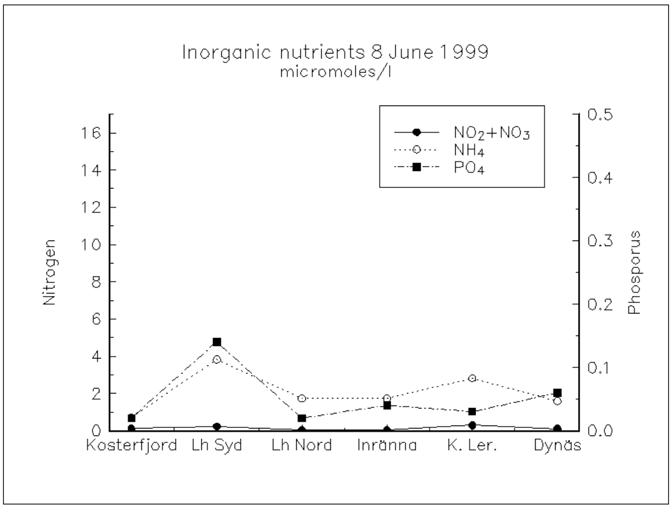

- Coastal phosphate emptied. Increase in shallow bays.
- Nitrate low in inner shallow bays.
- Inner shallow bays covered with filamentous algae.
- No brown algae.
- Growth of Fucus in Lindholmen Nord.
- Very low sea level.

## 31 Maj 1999

- Phosphate low in inner archipelago.
- Filamentous algae almost gone from inner shallow. bays. Seagrass covered the outer parts of the bays.
- Fucus covered about 30% of Lh Nord.
- Low sea level.

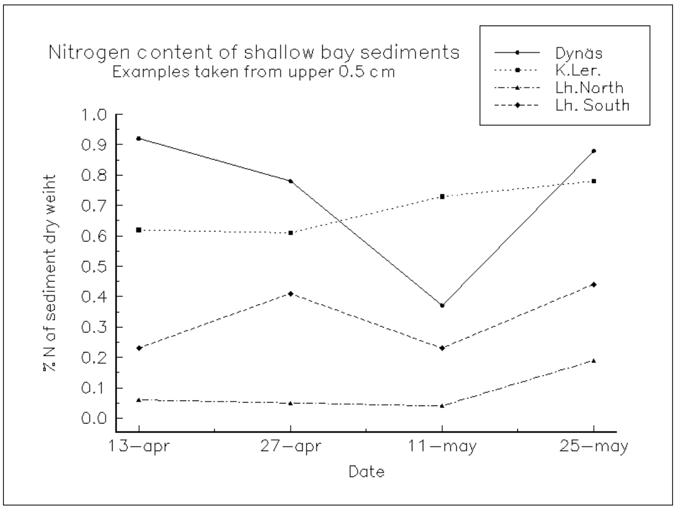



## 8 June 1999




- Nitrate low. No inorganic nutrients in Kosterfjorden.
- Slightly increased phosphate och ammonium in bays especially in Lh Syd.
- Filamentous algae covers about 10% in inner bays. Filamentous algae grow attached to seagrass.
- Fucus plants covers about 50% of Lh Nord. No filamentous algae.
- Lh Syd covered with about 40% Ulva.

**Sediment data spring 1999**




- High nitrogen concentrations in inner bays.
- Ten times lower concentrations in Lh. North.
- Indication of increased concentrations towards end of May.
- Data from March and June is missing at the time of the report.

## 8.2 Sammanställning av datagenomgång

981027
Project: EU Life Algae LIFE96ENV/S/380 (Task 10)
MODELLING FILAMENTOUS ALGAE MATS IN SHALLOW BAYS

Vi har i denna första rapportdel ställt oss frågan varifrån näringsämnen till produktionen av algmattor kommer. För att svara på detta formuleras en hypotetisk modell där näringsämnen tillförs sedimenten genom sedimentation av lokalt producerade plankton samt plankton som transporteras till viken från omgivande yttre vattenområden. Dessa näringsämnen kan senare frisläppas till vattnet genom biologisk nedbrytning av organiskt material i sedimenten.

För att erhålla grova uppskattningar på flöden av näringsämnen har siffror från litteratur och rapporter använts för 1994 då ett intensivt mätprogram på algmattor i Bohuslän utfördes. Dessa siffror och utförda beräkningar redovisas nedan tillsammans med aktuella slutsatser och en preliminär modell beskrivning.

### 8.2.1. Biomassa och näringsämnen

Först undersöks fosfor (P) innehållet i algmattorna i Göteborgs och Bohusläns kustområden under den varma och soliga sommaren 1994 (tabell 1). Nedan används förkortningen ha för ytan en hektar 100m•100m.

Dessa värden jämförs med den maximala fosfor koncentrationen i vattnet i de respektive kustområdena på vårvintern 1994 (tabell 2).

Siffrorna i tabell 1 och 2 indikerar att fosforinnehållet i algmattorna i genomsnitt är av samma storleksordning som det maximala fosforinnehållet lokalt i vattenmassan.

**Tabell 1.**

| **Område** | **Biomassa**(1) | **Fosforinnehåll**(2) |
|---|---|---|
| Göteborg | 207 kg torrvikt per ha | 350 gram P per ha |
| Tjörn-Orust | 74 kg torrvikt per ha | 130 gram P per ha |
| Gullmaren-Sotenäset | 109 kg torrvikt per ha | 180 gram P per ha |
| Fjällbacka-Idefjorden | 399 kg torrvikt per ha | 670 gram P per ha |

*(1) [Moksnes and Pihl, 1995]*
*(2) Beräkningar för blandning av Cladophora och Enteromorpha baserade på; Kolinnehåll c:a 0.2 gram kol per gram biomassa torrvikt [Pihl et al., 1996], stökiometriskt förhållande C:P=120 gram kol (C) per gram P [Atkinson and Smith, 1983].*

**Tabell 2.**

| **Område** | **TOT-P**(1) | **Fosforinnehåll**(2) |
|---|---|---|
| Göteborg | 0.76 mmol P per $m^3$ | 236 gram P per ha |
| Tjörn-Orust | 0.90 mmol P per $m^3$ | 279 gram P per ha |
| Gullmaren-Sotenäset | 1.06 mmol P per $m^3$ | 329 gram P per ha |
| Fjällbacka-Idefjorden | 1.02 mmol P per $m^3$ | 316 gram P per ha |

*(1) Medelvärden av maximala TOT-P koncentrationer på 5m djup beräknade från data insamlat för kustvattenkontrollen i Göteborgs och Bohusläns Vattenvårdsförbund, Årssammanfattning 1994*
*(2) Maximala fosfor innehållet i vattnet på ett område med medeldjup 1m.*

## 8.2.2. Tillväxt av Biomassa och flöden av näringsämnen

Intensiva undersökningar av algmattornas dynamik gjordes i nio grunda vikar under åren 1992-1994 [*Pihl et al., 1996*]. Här nedan görs en studie av Trälebergskile som ligger precis norr om Lysekil. Viken undersöktes varje vecka under perioden april till oktober 1994. Studien är koncentrerad till perioden Maj till Juni därför att algmattan blåste upp på land den sista veckan i juni. Beräkningarna baserade på kolinnehåll och stökiometri enligt Tabell 1.

En snabb tillväxt av algmattorna observerades med början i Maj. Vid denna tidpunkt var vårblomningen i kustvattnet förbi och fosfat halterna i kustvattnet utanför viken mycket låga redan i April, ~0.05 mmol P $m^{-3}$ (Kustvattenkontrollen, 1994). Under en sex veckors period tillväxte algbiomassan till c:a 626 gram torrvikt per kvadratmeter algmatta vilket motsvarar c:a 1 gram P per kvadratmeter algmatta eller totalt c:a 4 kg P per ha då algmattans täckningsgrad var c:a 40% per ha. Detta är mer än tio gånger mer än genomsnittet i Tabell 1. D.v.s. dessa siffror indikerar att mycket mer fosfor har använts för algmattans tillväxt i Trälebergskile än vad som finns lokalt tillgängligt per ha i vattnet (Tabell 2). Det bör dock påpekas att det stökiometriska förhållandet C:P behöver studeras vidare för att kunna uttala sig noggrannare om siffrornas storlek.

Den genomsnittliga tillväxten av algmatta per ha under sex veckors perioden var 6 gram torrvikt per kvadratmeter och dygn vilket motsvarar ett upptag av $Alg_P$ med c:a 0.3 mmol P per kvadratmeter och dygn. Fosfatflöden från sedimenten av denna storleksordning (~0.1 mmol P per kvadratmeter och dygn) har vi observerat i litteraturen från Skagerraks djupa bottnar [*Hall et al., 1996*] och från ett algblomningsexperiment där färska planktonalger (Skeletonema costatum) tillfördes ett antal sediment prover tagna från Laholmsbukten i Kattegat [*Enoksson, 1993*].

Under sommaren upprätthölls en fosfat koncentration i vattnet på c:a 0.20 mmol P $m^{-3}$ i Trälebergskile medan koncentrationen i kustvattnet utanför var endast 0.05 mmol P $m^{-3}$. Ett vattenutbyte på c:a 0.2 $m^3s^{-1}$ per ha skulle upprätthålla den observerade fosfat koncentrationen när algmattans nettotillväxt avstannat under antagandet om fortsatta fosfatflöden på 0.3 mmol P per kvadratmeter och dygn från sedimenten (och/eller tillförsel från land). Eventuellt färskvattenflöde har försummats.

Generellt visar resultaten från Pihl et al. *[1996]* att tillväxten av algmattor 1994 påbörjas efter att fosfatförråden i kustvattnet (kustvattenkontrollen, 1994) tömts efter vårblomning av planktonalger. Ovanstående undersökning antyder att tillförsel av färskt organiskt material från t.ex. algblomningar kan ha stor betydelse för påfyllningen av nya näringsämnen i sedimenten i de grunda vikarna.

## 8.2.3. Första modellansats:

**Beskrivning av tillförsel av näringsämnen till grund havsvik.**

En grund havsvik står i förbindelse, genom ett vattenutbyte (Q), med ett yttre havsområde som är oberoende av tillståndet i havsviken. Modellen beskriver koncentrationen av plankton i viken, uttryckt som partikulärt organiskt fosfor POP, som funktion av vattenutbytet och planktons fallhastighet ($W_p$).

$$\frac{dPOP}{dt} + \left(\frac{w_p}{h} + \frac{Q}{A \cdot h}\right) POP = \frac{Q}{A \cdot h} POP_o \qquad (1)$$

Här är POPo koncentrationen av plankton i det yttre havsområdet, h djupet och A ytarean i viken.

Flödet av fosfor bundet i organiskt material till havsvikens botten ($F_{POP}$) kan beräknas från fallhastigheten och koncentrationen av plankton.

$$F_{POP} = POP \cdot W_p \qquad (2)$$

Om POPo förändras långsamt relativt responsen i viken kan vi anta ett stationärt tillstånd i ekvation 1. Under förutsättningen att $Q \neq 0$ fås att

$$POP = POP_o / \left(1 + \frac{W_p \cdot A}{Q}\right) \qquad (3)$$

$$F_{POP} = POP_o / \left(\frac{1}{W_p} + \frac{A}{Q}\right) \qquad (4)$$

## 8.2.4. Uppskattning av fosforflöden $F_{POP}$ till sediment med modellen:

Första uppskattning av flödet av organiskt fosfor till sedimenten görs för ett 1ha stort område med vattenutbytet Q=0.5 $m^3s^{-1}$ och planktons fallhastighet $W_p$=1 meter per dygn (Referens ....?). Beräkningarna baseras på plankton uppbyggda enligt den så kallade ”Redfield kvoten” med C:P=106 mol kol per mol fosfor. Koncentrationen av partikulärt kol i April är c:a 25 mmol per $m^3$ (Tabell 3) vilket ger en sedimentation av $F_{POP}$= 0.2 mmol P per kvadratmeter och dygn (Ekvation 4). Man kan observera att detta flöde av fosfor till sedimenten är av samma storleksordning som det ovan uppskattade flödet av fosfor från sedimenten.

Kontroll av totalmängden fosfor TOT-P i vattnet i April och på sommaren jämförd relativt partikel koncentrationen POP beräknad från Redfield kvoten (Tabell 4) visar att det finns tillräckligt med fosfor observerat i vattnet i April. På sommaren däremot överskattas mängden fosfor i partiklarna i Göteborg och Tjörn-Orust området då andelen kol i partiklarna i genomsnitt måste vara större än förväntat från Redfield kvoten. Orsaken till den observerade genomsnitts skillnaden mellan Göteborg-Orust området relativt Gullmaren-Idefjorden området där fosfor verkar finnas i tillräckliga mängder är för närvarande oförklarad. Sommar koncentrationen av oorganiskt fosfor (fosfat) är generellt av storleksordningen 0.05 mmol P per $m^3$ eller mindre fr.o.m April. Tyvärr saknas mätningar på löst organiskt fosfor.

Koncentrationen av partikulärt organiskt kol POCo för Göteborgs och Bohusläns kustvatten 1994.

**Tabell 3**

| **Område** | **Minimum Januari-Mars**(1) | **April**(1) | **Maximum Juni-Juli**(1) |
|---|---|---|---|
| Göteborg | 16 mmol C per $m^3$ | 24 mmol C per $m^3$ | 43 mmol C per $m^3$ |
| Tjörn-Orust | 10 mmol C per $m^3$ | 29 mmol C per $m^3$ | 55 mmol C per $m^3$ |
| Gullmaren-Sotenäset | 9 mmol C per $m^3$ | 20 mmol C per $m^3$ | 37 mmol C per $m^3$ |
| Fjällbacka-Idefjorden | 8 mmol C per $m^3$ | 31 mmol C per $m^3$ | 26 mmol C per $m^3$ |

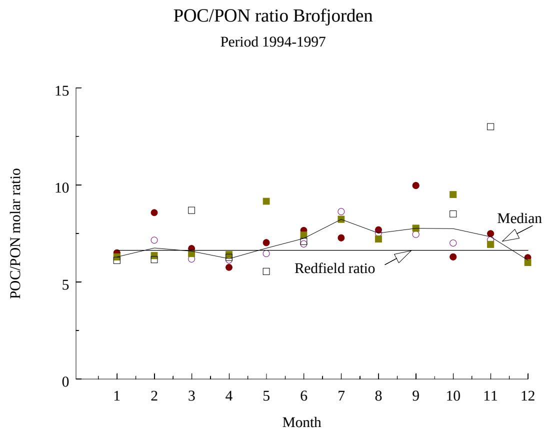
*(1) Medelvärden av POCo koncentrationer på 5m djup beräknade från data insamlat för kustvattenkontrollen i Göteborgs och Bohusläns Vattenvårdsförbund, Årssammanfattning 1994*

**Tabell 4**

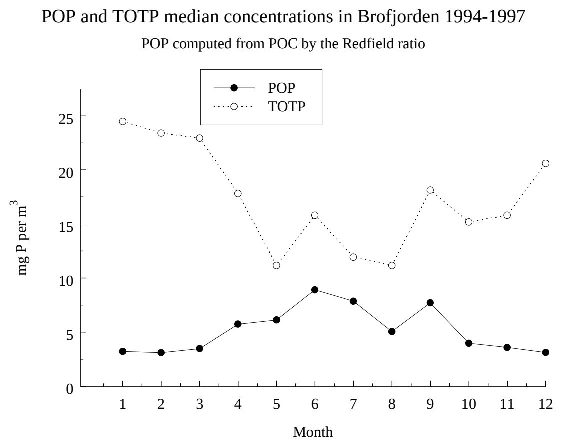
| **Område** | **POC** mmol C per $m^3$ | | **POP** mmol P per $m^3$ | | **P-TOT** mmol P per $m^3$ | |
|---|---|---|---|---|---|---|
| | April | sommar | April | sommar | April | sommar |
| Göteborg | 24 | 43 | 0.22 | 0.41 | 0.55 | 0.28 |
| Tjörn-Orust | 29 | 55 | 0.27 | 0.52 | 0.65 | 0.23 |
| Gullmaren-Sotenäset | 20 | 37 | 0.19 | 0.34 | 0.43 | 0.45 |
| Fjällbacka-Idefjorden | 31 | 26 | 0.29 | 0.25 | 0.63 | 0.47 |

*POC från tabell 3. POP beräknat från Redfield kvoten. Medelvärden på P-TOT koncentrationer på 5m djup i April beräknade från data insamlat för kustvattenkontrollen i Göteborgs och Bohusläns Vattenvårdsförbund, Årssammanfattning 1994.*

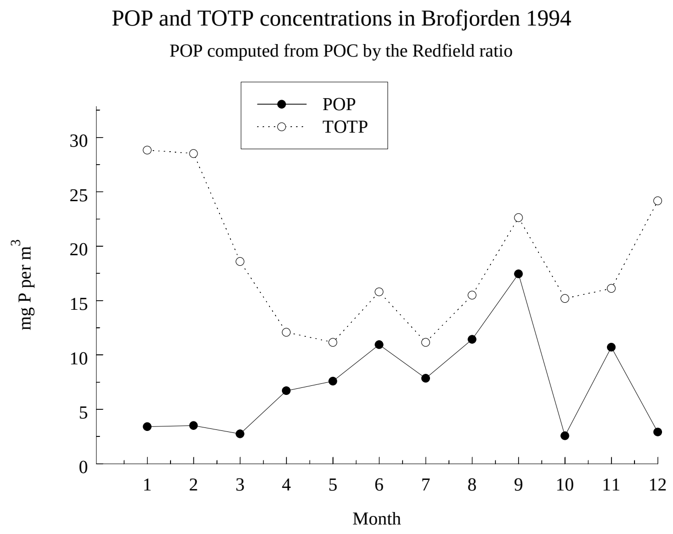
En undersökning av tillståndet utanför Brofjorden som kan representera tillståndet utanför Trälebergskile visar att uppmätta POC/PON kvoten (Figur 1) beskrivs relativt bra med Redfield kvoten, speciellt under våren och försommaren. Man ser dock även här att andelen kol i partiklarna ökar under sommaren. Tyvärr saknas mätningar på partikulärt fosfor, men vi kan observera från Figur 2a och 2b att mängden fosfor i Brofjorden under hela året överstiger den fosformängd i partiklarna som kan förväntas från Redfield kvoten. D.v.s. det är sannolikt att vi får en relativt bra uppskattning av POPo beräknat från POCo i detta fall (Trälebergskile).




**Figur 1**. *Molekylär POC/PON kvot på 5m djup utanför Brofjorden under perioden 1994-1997.*




**Figur 2a**. *Medianvärdet av POP beräknat från POC samt på uppmätt TOTP på 5m djup utanför Brofjorden under perioden 1994-1997.*




**Figur 2b**. *Koncentrationen av POP beräknat från POC samt uppmätt TOTP på 5m djup utanför Brofjorden under 1994.*

### 8.2.5. Beskrivning av koncentrationen av oorganiska näringsämnen i vattnet

Makroalger kräver i genomsnitt mer än tio gånger så höga koncentrationer vattnet som mikroalger för att växa bra, beskrivet av halvmättnadskoncentrationerna av kväve för algerna [*Hein et al., 1995*]. Här ignorerar vi effekter av betning, respiration, temperatur, ljus m.m. tillsvidare. Möjligheten att uppnå höga näringsämneskoncentrationer (C) i vattnet i viken bestäms huvudsakligen av vattenutbytet och flödet av regenererade näringsämnen från bottnarna ($F_{BC}$) till vattnet. Vid ett stationärt tillstånd utan färskvattentillförsel till viken beskrivs C av

$$C = C_o + \frac{A}{Q} \cdot F_{BC} \qquad (5)$$

där Co är koncentrationen i vattnet utanför viken.

Om vi tar hänsyn till effekten av färskvattentillförsel $Q_f$ till viken fås att

$$C = C_O + \frac{A}{Q_2} \cdot F_{BC} + \frac{1}{P}[C_f - (\frac{A}{Q_2} \cdot F_{BC} + C_O)]$$

(5a)

där $P=Q_1/Q_f$. $Q_1$ är utflöde från viken, $Q_2$ inflöde och $Q_f$ färskvatten tillflöde till viken. $C_f$ är koncentrationen i färskvattnet.

Om vi för enkelhetens skull antar att $C \approx 10C_o$ vid ett stationärt tillstånd med P>>1, d.v.s. litet färskvatten flöde till viken får vi att

$$\frac{Q}{A} = \frac{1}{9} \frac{F_{BC}}{C_o} \qquad (6)$$

Detta visar att flödeshastigheten Q/A för vattnet måste i genomsnitt vara mindre än c:a en niondel av $F_{BC}/C_o$ för att C skall bli 10 gånger större än Co vilken huvudsakligen bestäms av mikroalgerna som blommar i vattnet utanför viken på våren och sommaren. Större vattenflöden drar ner koncentrationerna i viken och hämmar därigenom tillväxten av algmattor.

### 8.2.6. Beskrivning av nettoflödet av näringsämnen till viken.

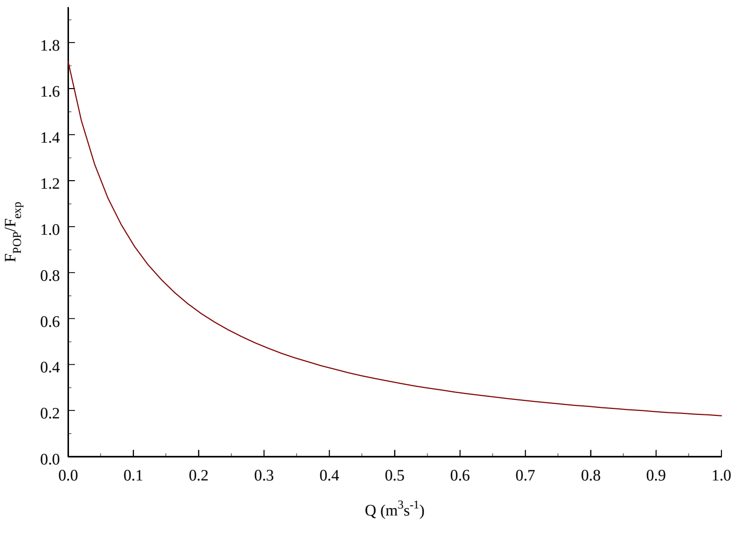
Export av näringsämnen från viken, nedan angivet per ytenhet, beskrivs av vattenutbytet och näringämneskoncentrationerna i vattnet

$$F_{exp} = \frac{Q}{A}(C - C_o) = (stationärt) = F_{BC} \qquad (7)$$

d.v.s. kvoten $F_{POP}/F_{exp}$ nedan beskriver då nettoutbytet av näringsämnen i viken.

$$\frac{F_{POP}}{F_{exp}} = \frac{POP_o}{(1 + \frac{Q}{W_p \cdot A})(C - C_o)} = (stationärt) = \frac{POP_o}{(\frac{1}{W_p} + \frac{A}{Q}) \cdot F_{BC}} \qquad (8)$$

Som belysande exempel i Figur 3 nedan använder vi sommarvärden från Brofjorden och Trälebergskile 1994 med POPo=8 mg P per $m^3$, C=0.2 mmol PO4-P per $m^3$, Co=0.05 mmol PO4-P $m^3$, Wp=1 m per dygn och A=10000$m^2$. I detta fall exporteras näringsämnen ut från viken om Q är större än c:a 0.1 $m^3s^{-1}$ medan ackumulering av näring i sediment eller biomassa sker för mindre vattenflöden. Det bör noteras att färskvatten flöden och eventuellt nettoflöde av löst organiskt P (DOP) ej tagits med i beräkningarna ovan.




**Figur 3**. *Nettoimport av näringsämnen beskrivet av kvoten mellan importerat och exporterat fosfor som funktion av vattenutbytet på en hektar i viken.*

## 8.2.7. Uppskattning av ackumulation av näringsämnen i viken.

För att uppskatta ackumuleringen av fosfor i Trälebergskile görs en integrering av $F_{POP}$ över året (ACCPOP) med start i April då vårblomningen kommit igång. ACCPOP i Figur 4 beräknas från ekvation 4 med $W_p$= 1m per dygn och Q/A=0.2 $m^3s^{-1}$ $ha^{-1}$. Denna jämförs med upptaget av fosfor i fintrådiga alger AlgP som ökade från 0 till 4 kg P per ha under tidsperioden April till slutet på Juni. Eventuell nettoeffekt av vattenutbytet har försummats under denna period, d.v.s. Fexp=0. Från och med Juli antas Fexp=2.4 kg per månad och hektar, d.v.s. Q/A=0.2 $m^3s^{-1}$ $ha^{-1}$, C=0.2 mmol P $m^3$ och Co=0.05 mmol P $m^3$. Man kan notera att kurvorna sammanfaller väl under sommaren vilket indikerar ett starkt samband mellan tillförseln av näringsämnen med POP och ackumulation i biomassa och/eller export genom vattenutbytet.

Man skall dock minnas att Q/A har trimmats till med avseende på koncentrationerna utanför och inne i viken. D.v.s. vi får en balanserad fosforbudget under våren och sommaren för Trälebergskile om vi antar att;

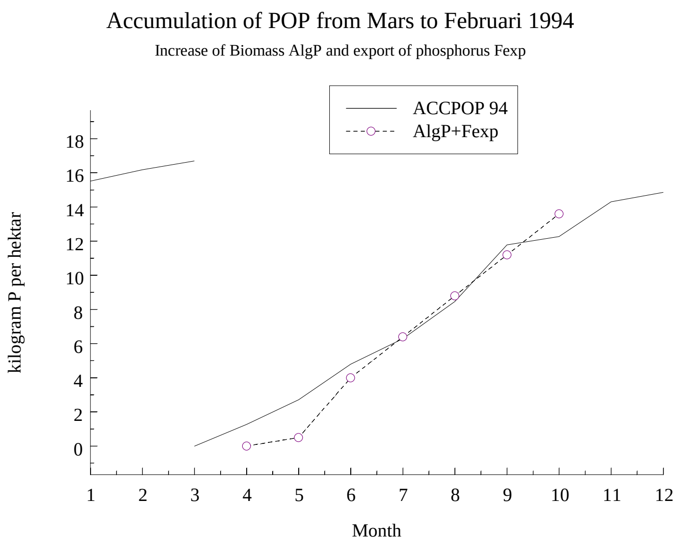
-Färskvattentillförseln har liten betydelse

-Nettoutbytet av näringsämnen mellan viken och Brofjorden är liten innan vårblomningen startar

-Exporten av näringsämnen från viken är liten under försommaren då biomassan tillväxer i Trälebergskile

-Flödet av regenererade näringsämnen från sedimenten är relativt konstant under sommaren med värden givna från tillväxten av algbiomassa

-Vattenutbytet är relativt konstant och givet av att vattenutbytet upprätthåller koncentrationsskillnaden mellan viken och Brofjorden under sommaren




**Figur 4**. *Ackumulering av fosfor genom sedimentation av POP på en hektar i viken (ACCPOP). Upptag av P i fintrådiga alger AlgP och export av P genom vattenutbytet Fexp.*

### 8.2.8. Summering av studien

Den ansatta modellen för tillförsel av näringsämnen till de grunda vikarna ser ut att vara en god början på vår förståelse av grunda vikars näringsämnesdynamik.

Det är intressant att bottendjupet inte har någon betydelse för denna studie. Endast flöden av vatten och näring per ytenhet av viken har betydelse för koncentrationerna i vattnet och för mängden näring som lagras i bottnarna viken. Höga koncentrationer i vattnet ger möjlighet till blomning av makroalger och stora mängder deponerat färskt organiskt material ger möjlighet till stora mängder biomassa.

Självklart är studien mycket grov men den kan användas som bas för att ge oss kunskap om de processer som bör studeras vidare.

## 8.3 Sammanställning av vågmodell

981027
Project: EU Life Algae LIFE96ENV/S/380 (Task 10)

MODELLING FILAMENTOUS ALGAE MATS IN SHALLOW BAYS

Vi har i denna andra rapportdel arbetat med en beskrivning av vind och vågklimat i en grund vik.

Tillväxt och utbredning av algmattor bör vara beroende på den fysiska stressen från vind och vågor. Detta är ju självklart i de fall då man finner algerna uppe på land efter ett oväder med kraftiga vindar. Algmattorna kan också rivas loss från bottenförankringen och driva iväg med vindar och strömmar. Vi har därför bl.a. ställt oss frågan vilken vindstyrka och strömhastighet kan få en algmatta att slitas loss från sina fästen. Avsikten med denna rapportdel är att formulera en modell där vi kan jämföra vind – och vågstressens inverkan på algmattan i en grund vik med varandra. Vi beskriver också en modell som kan användas för att uppskatta sannolikheten för vågor med ett olika energiflöde vid mynningen av den grunda viken. Den externa vindgenererade vågenergins uppskattade effekt på en grund vik parametriseras och sannolikhetsfördelningen av effekten kan användas för att studera korrelationen med t.ex. täckningsgrad av fintrådiga alger i ett stort antal grunda vikar efter Bohuskusten.

### 8.3.1. Vind- och vågstress

Vi antar en algmatta som täcker en del av ytan i en grund vik. Algmattan påverkas av vindstress på sin ovansida och/eller av en stress orsakad av strömmar under algmattan. Om stressen blir tillräckligt kraftig kan algmattans fästen vid botten lossna eller gå av. Algmattan kan då driva fritt flytande på ytan och transporteras av vindar och strömmar t.ex. ut från viken eller kastas upp på land. Man kan notera att den vågdrivna horisontella nettotransporten på grund av så kallad Stokes drift är liten utom för brytande vågor eller för vågor som nära att bryta. Vi förväntar oss därför att algmattor kan driva med vinden i alla riktningar medan kraftiga vågor transporterar algerna mot land och upp på land.

Ytstress ($\tau$) beskrivs ofta med kvadratiska funktioner av vindhastigheten (W) respektive strömhastigheten (U).

$$\tau_a = \rho_a C_{da} W^2 \qquad (1)$$

$$\tau_w = \rho_w C_{dw} U^2 \qquad (2)$$

Här betecknar index a luften (air) och w vattnet (water). $\rho$ är densiteten och $C_d$ den så kallade dragkoefficienten. Värdet på $C_d$ varierar huvudsakligen beroende på ytans råhet medan densiteten för havsvatten och luft är relativt konstanta ($\rho_a \approx 1.3 kg/m^3$, $\rho_w \approx 1025 kg/m^3$). Tyvärr känner vi ännu inte exakt vilket värde $C_d$ för en algmatta har, men som första gissning antar vi att $C_{da}=4\times10^{-3}$ vilket motsvarar vinddrag över en gräsyta. Detta värde är beräknat från gränsskikts teori med en så kallad roughness length $Z_o$ på 0.017m [Houghton, 1985]. Motsvarande drag koefficient för vattnet antar vi från isdynamik där $C_{dw} \approx 4\text{-}5\times10^{-3}$ [Göran Björk, Göteborgs Universitet, Pers. Komm.] vilken är av samma storlek som vinddrag över gräsytan.

För att jämföra effekterna av vind- respektive strömstress kan vi uppskatta vilken strömhastighet som behövs i vattnet under algmattan för att erhålla samma stress som för en given vindhastighet genom

$$\frac{U}{W} = \sqrt{\frac{\rho_a C_{da}}{\rho_w C_{dw}}} \qquad (3)$$

Med ovan angivna siffror erhålls då en ekvivalent stress för U=0.036W, så t.ex. stressen från en strömhastighet på c:a 0.5 $ms^{-1}$ motsvarar vindstressen från en kuling på c:a 15$ms^{-1}$. Man bör dock också notera att vind- och strömstress på algmattan kan samverka då stresserna är riktade åt samma håll.

Strömmarna kan vara orsakade av storskaliga strömsystem eller av mer lokala orsaker som t.ex. lokal vind. Här nedan betraktar vi först de våggenererade strömmarna i en grund vik. Förhållandet mellan vågornas amplitud (a) och den maximala strömhastigheten i havsytan kan relativt enkelt beskrivas för två fall av icke brytande vågor [t.ex. Kundu, 1990].

$$U = a_l \sqrt{\frac{g}{d}} \qquad \text{;långa (l) vågor } L_l > 14d \qquad (4)$$

$$U = a_k \sqrt{\frac{2\pi g}{L_k}} \cdot \quad \text{;korta (k) vågor } L_k < 2d \qquad (5)$$

där g är gravitationen, L våglängden och d djupet. Vågorna bryter om a>0.07L eller a>0.38d för korta respektive långa vågor.

Här kan vi t.ex. se att en dyning ($L_l$>14d) med en amplitud på c:a 10cm på en halvmeters djup i en grund vik kan orsaka en strömstress på algmattan som motsvarar stressen från en kuling på 15m/s. Vi kan också notera att vågen bryter om amplituden blir c:a 20cm vid en halvmeters djup. När vinden ligger an mot land kommer vind- och vågstress att samverka och den totala stressen att öka på algmattan under den halva period då strömhastigheten är riktad in mot land. Vågornas hävning av algmattan och impulsen från vågorna kan förstås ytterligare öka påfrestningen på fästpunkterna. Detta visar att vågklimatet bör ha en stor betydelse för tillväxt möjligheterna av en algmatta i en grund vik.

## 8.3.2. Vågklimat

För att klassificera en grund vik med avseende på vågklimatet formulerar vi en model där vi grovt kan uppskatta sannolikheten för vindgenerade vågor med olika amplitud vid mynningen av den grunda viken (exempelvis vid 1m djup). Vågbildningen lokalt inne i den grunda viken samt eventuella effekter av vågrefraktion försummas. För att avgöra hur stor stresseffekt vågorna kan ha inne i viken uppskattar vi vågenergiflödet till viken av en våg med en signifikant våghöjd som representerar medelhöjden av den högsta tredjedelen av vågorna och jämför denna med storleken av det område över vilken energin blir fördelad.

Energiflödet ($E_F$) för en våg med våglängden L vid mynningen beskrivs av

$$E_F = \frac{1}{2} C \cdot E \cdot [1 + \frac{4\pi d / L}{\sinh(4\pi d / L)}] \qquad \text{(Watt/m)} \qquad (6)$$

där vågens fashastighet (C) ges av

$$C = \sqrt{\frac{gL}{2\pi}\tanh(2\pi d / L)} \qquad \text{(m/s)} \qquad (7)$$

och vågens energitäthet (E) ges av

$$E = \frac{1}{2}\rho g a^2 \qquad \text{(Joule/m}^2\text{)} \qquad (8)$$

maximala vågamplituden begränsas av brytande vågor approximativt till den minsta av a=0.07L eller a=0.38d för korta respektive långa vågor.

För att erhålla ett ickedimensionellt mått på storleken av vågenergiflödet vid en given våglängd och amplitud inför vi en parameter $\delta_E$(a,L) som beskriver energiflödet relativt det maximala vågenergiflödet som kan uppnås vid mynningen av viken, d.v.s. $0 \geq \delta_E \leq 1$.

$$\delta_E = E_F / E_{F(max)} \qquad (9)$$

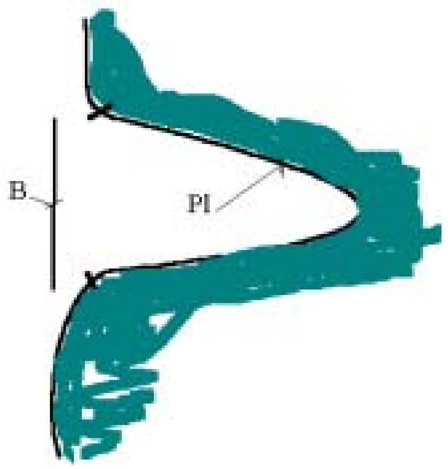
där det maximala energiflödet uppnås för långa vågor vid brytningsamplituden. Man kan visa från ekvationerna (6) (7) och (8) för långa vågor med a=0.38d att

$E_{F(max)}=0.07\rho g^{3/2}d^{5/2}$ (Watt/m) (10)

För att kunna jämföra effekten av ett givet vågenergiflöde på olika vikar måste vi också ta hänsyn till storleken på viken relativt storleken på det totala relativa vågenergiflödet som når viken, d.v.s. $\delta_E \bullet B$, där B är bredden av vikens mynning vid djupet d. Vi beskriver därför effekten av vågenergin med ett vågeffektindex $V_{EI}$ ($0 \geq V_{EI} \leq 1$) som definieras genom

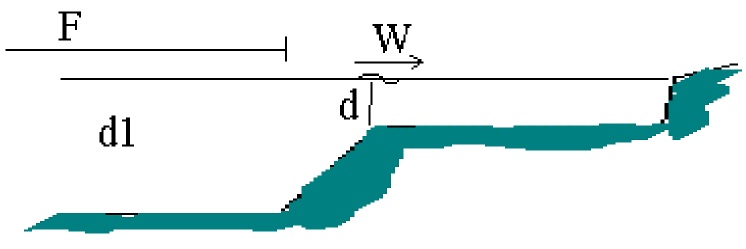
$V_{EI}=\delta_E \bullet B/Pl$ (11)

där Pl är längden på vikens periferi innanför djupet d. D.v.s. effekten av ett givet vågenergiflöde i olika vikar beror i denna modell på mynningsöppningens bredd relativt längden av stränderna i viken (Figur 1).




**Figur 1.** *Vy över en grund vik med mynningsbredden B och periferilängden Pl.*

För att uppskatta vågamplitud och våglängd vid djupet d använder vi empiriska formler som beskriver den signifikanta våghöjden ($H_s$) och vågperioden ($T_s$) som funktion av stryklängden F (s.k. Fetch), och vindhastigheten W i fetchens längdriktning på ett område med djupet d1 utanför den grunda viken (Figur 2).




**Figur 2.** *Tvärsnitt genom en grund vik och dess yttre havsområde med djupet d1. Djupet vid mynningen till viken är d. Stryklängden F från närmaste landområde till viken i vindriktningen är angiven.*

Signifikant våghöjd är medelhöjden av den högsta tredjedelen av vågorna. Signifikanta amplituden $a_s$ är $H_S/2$. Amplituden a vid djupet d blir högre än vid d1 på grund av uppstuvning av vågorna på grundare områden. Amplituden a kan approximativt beräknas under antagandet om bevarande av vågenergiflöde.

För beräkningen av $H_s$ och $T_s$ använder vi SMB (Sverdrup-Munk-Bretschneider) ekvationer modifierade, av U.S. Army Engineer Waterways Experiment Station Coastal Engineering Research Center (1984), för att även kunna användas på grunt vatten (d/L<0.5) med ett konstant djup (d1). Ekvationerna presenteras i Lakhan och Trenhaile [1989]. För vårt ändamål uppskattar vi d1 från medel djupet utanför den grunda viken och antar att vinden är konstant för en tillräckligt lång tidsperiod så ett fullt utbildat vågfält hunnit utvecklas.

$$\frac{gH_s}{W^2} = 0.283 \cdot \tanh[0.530 \cdot (gd_1 / W^2)^{3/4}] \cdot \tanh\left(\frac{0.00565 \cdot (gF / W^2)^{1/2}}{\tanh[0.530 \cdot (gd_1 / W^2)^{3/4}]}\right) \qquad (12)$$

$$\frac{gT_s}{W} = 7.54 \cdot \tanh[0.833 \cdot (gd_1 / W^2)^{3/8}] \cdot \tanh\left(\frac{0.0379 \cdot (gF / W^2)^{1/3}}{\tanh[0.833 \cdot (gd_1 / W^2)^{3/8}]}\right) \qquad (13)$$

Amplituden bestäms av villkoret att energiflödet och perioden T bevaras, d.v.s. $E_F(d)=E_F(d1)$ och $T(d)=T_s(d1)$ vilket ger

$$\left(\frac{a}{a_s}\right)^2 = \left(\frac{\tanh[2\pi \cdot d_1 / L_s]}{\tanh[2\pi \cdot d / L]} \cdot \frac{1 + \frac{4\pi \cdot d_1 / L_s}{\sinh[4\pi \cdot d_1 / L_s]}}{1 + \frac{4\pi \cdot d / L}{\sinh[4\pi \cdot d / L]}}\right) \qquad (14)$$

där den signifikanta våglängden $L_s$ samt våglängden L vid djupet d bestäms från

$$L_s = \frac{gT_s^2}{2\pi} \tanh[2\pi \cdot d_1 / L_s] \qquad (15)$$

och

$$L = \frac{gT_s^2}{2\pi} \tanh[2\pi \cdot d / L] \qquad (16)$$

## 8.3.3. Stryklängd (fetch) och vindfördelning

Från en statistisk långtidsfördelning av vind från en meteorologisk mätstation som kan betraktas som representativ för Bohuslän (se Appendix) kan vi uppskatta sannolikheten för hur vindar av olika styrka och riktning kan påverka en given grund vik i området. För att uppskatta vågklimatet bestämmer vi en medelfetch $\overline{F}_\theta$ för en given vindriktning θ och uppskattar vågeffekten $V_{EI}$ för viken för olika vindhastigheter W med ekvationerna ovan. Från vindstatistiken kan vi då erhålla en sannolikhets fördelning för olika stora vågeffekter i viken. Vi kan sedan undersöka hur sannolikhetsfördelningen av $V_{EI}$ korrelerar med t.ex. täckningsgraden av fintrådiga alger i ett stort antal grunda vikar efter Bohuskusten.

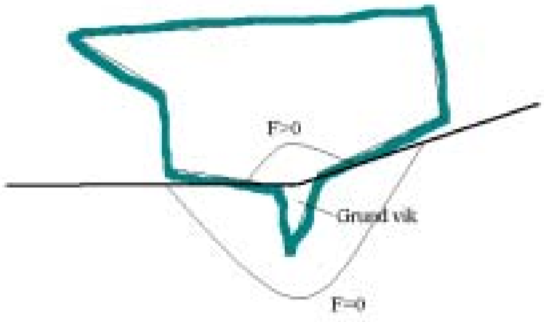
För att enkelt och rationellt kunna få en uppskattning av vågklimatet i många vikar inför vi en standard metodbeskrivning som kan följas för varje vik. För enkelhetens skull definierar vi att den grunda viken börjar vid 1m djup (d=1m).

**Metodbeskrivning:**

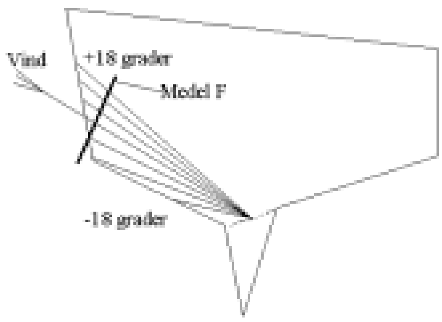
Punkt 1 och 2 bestäms från sjökort och används som indata till dataprogrammet som sedan utför beräkningarna enligt övriga punkter. Notera om man kan misstänka att viken kan vara utsatt för dyningar eller strömmar som ej beskrivs av det direkta vind-fetchdrivna vågfältet.

1. Bestäm periferilängden Pl, bredden B och medeldjupet d1 i fetchområdet.
2. Bestäm stryklängden F i meter till en central punkt på en meters djuplinjen för alla kompassriktningar θ med 6° intervall. Starta från norr med θ=0° och sluta med θ=354°. Stryklängden för vinklar som hamnar innanför 1m djuplinjen sättes lika med 0 (se exempel i Figur 3).
3. Medelvärdesbilda F över 36° (d.v.s. ±18°) kring θ=0°, 45°, 90°, 135°, 180°, 225°, 270° och 315° (se exempel i Figur 4).

$$\overline{F}_\theta = \frac{1}{N}\sum_{i=1}^{N} F_{\theta_i} \qquad (17)$$




**Figur 3.**




**Figur 4.**

Utför punkt 4-6 för alla vindriktningar där $\overline{F}_\theta \neq 0$ och för vindhastigheterna 1, 3, 6, 9 och 12 m/s.

4. Uppskatta största $H_s$ samt tillhörande $T_s$ från ekvationerna (12) och (13). Största vågubildningen fås för den riktning där $H_s$ är störst.
5. Beräkna våglängd Ls och L samt amplituden a från ekvationerna (14), (15) och (16).
6. Beräkna vågenergiflödet $F_E$ från ekvation (6) med hjälp av ekvationerna (7) och (8). Maximala amplituden att användas i ekvation (8) begränsas av brytande vågor till den minsta av a=0.07L eller a=0.38d.
7. Beräkna vågeffektindex $V_{ei}$ från ekvation (11) med hjälp av ekvationerna (9) och (10).
8. Bestäm sannolikheten (P) för $V_{ei}$ , d.v.s. för den antagna vindriktningen och vindhastigheten från vindstatistiken. Ett exempel på vindstatistiken från Måseskär för januari månad finns här nedan.

D.v.s. den slutliga informationen för varje vik beskriver $V_{ei}$ fördelningen samt sanolikhetsfördelningen för varje $V_{ei}$ (se exempel i Tabell 1).

| | 0° | | 45° | | 90° | | 135° | | 180° | | 225° | | 270° | | 315° | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $V_{ei}$ | P | $V_{ei}$ | P | $V_{ei}$ | P | $V_{ei}$ | P | $V_{ei}$ | P | $V_{ei}$ | P | $V_{ei}$ | P | $V_{ei}$ | P |
| 1 m/s | | | | | | | | | | | | | | | | |
| 3 m/s | | | | | | | | | | | | | | | | |
| 6 m/s | | | | | | | | | | | | | | | | |
| 9 m/s | | | | | | | | | | | | | | | | |
| 12 m/s | | | | | | | | | | | | | | | | |

Från detta kan man sedan t.ex. definiera en medel $V_{ei}$ för viken eller avgöra sannolikheten för mycket stora $V_{ei}$.

### Vindstatistik för Bohuskusten perioden 1970 till 1995

Nedan följer en månadsvis sammanställning av vindstatistik för perioden 1970 till 1995 baserad på tre dagliga observationer vid väderstation Måseskär. Sammanställningen visar den procentuella frekvensfördelningen av observationerna uppdelat i olika vindriktningar och vindhastighetsklasser.

Tabell beskrivning:

Month: Månads nummer, Jan=1, Feb=2, .. o.s.v.

Class: Vindhastighetsklasser

| | | |
|---|---|---|
| Klass 1: | 0 | m/s |
| Klass 2: | 1-2 | m/s |
| Klass 3: | 3-5 | m/s |
| Klass 4: | 6-8 | m/s |
| Klass 5: | 9-11 | m/s |
| Klass 6: | ≥12 | m/s |

Acc. freq.: Ackumulerad frekvens, ex. Acc. freq. för klass 6 anger totala procentuella frekvensen av observerade vindar i den angivna vindriktningen.

Frequency: Procentuella frekvensen av vindobservationer i den angivna vindriktningen och hastighetsklassen.

Direction: Vindriktning θ i kompassgrader. Data insamlat från omgivning $\theta \pm 22.5°$.

Nr. of obs.: Totala antalet observationer i den aktuella månaden.

## VINDDATA 1970-1995 from Måseskär

| Month | Class | Acc. freq. | Frequency | Direction | Nr. of obs. |
|---|---|---|---|---|---|
| 1 | 1 | 1.28 | 1.28 | 0 | 2418.00 |
| 1 | 2 | 2.36 | 1.08 | 0 | 2418.00 |
| 1 | 3 | 4.96 | 2.61 | 0 | 2418.00 |
| 1 | 4 | 8.56 | 3.60 | 0 | 2418.00 |
| 1 | 5 | 10.13 | 1.57 | 0 | 2418.00 |
| 1 | 6 | 11.66 | 1.53 | 0 | 2418.00 |
| 1 | 1 | 1.28 | 1.28 | 45 | 2418.00 |
| 1 | 2 | 1.90 | 0.62 | 45 | 2418.00 |
| 1 | 3 | 3.76 | 1.86 | 45 | 2418.00 |
| 1 | 4 | 6.20 | 2.44 | 45 | 2418.00 |
| 1 | 5 | 7.73 | 1.53 | 45 | 2418.00 |
| 1 | 6 | 8.81 | 1.08 | 45 | 2418.00 |
| 1 | 1 | 1.28 | 1.28 | 90 | 2418.00 |
| 1 | 2 | 2.94 | 1.65 | 90 | 2418.00 |
| 1 | 3 | 7.24 | 4.30 | 90 | 2418.00 |
| 1 | 4 | 15.14 | 7.90 | 90 | 2418.00 |
| 1 | 5 | 19.40 | 4.26 | 90 | 2418.00 |
| 1 | 6 | 21.59 | 2.19 | 90 | 2418.00 |
| 1 | 1 | 1.28 | 1.28 | 135 | 2418.00 |
| 1 | 2 | 1.70 | 0.41 | 135 | 2418.00 |
| 1 | 3 | 2.73 | 1.03 | 135 | 2418.00 |
| 1 | 4 | 5.00 | 2.27 | 135 | 2418.00 |
| 1 | 5 | 7.07 | 2.07 | 135 | 2418.00 |
| 1 | 6 | 8.44 | 1.36 | 135 | 2418.00 |
| 1 | 1 | 1.28 | 1.28 | 180 | 2418.00 |
| 1 | 2 | 1.82 | 0.54 | 180 | 2418.00 |
| 1 | 3 | 4.09 | 2.27 | 180 | 2418.00 |
| 1 | 4 | 8.64 | 4.55 | 180 | 2418.00 |
| 1 | 5 | 14.06 | 5.42 | 180 | 2418.00 |
| 1 | 6 | 22.04 | 7.98 | 180 | 2418.00 |
| 1 | 1 | 1.28 | 1.28 | 225 | 2418.00 |
| 1 | 2 | 1.45 | 0.17 | 225 | 2418.00 |
| 1 | 3 | 2.65 | 1.20 | 225 | 2418.00 |
| 1 | 4 | 5.13 | 2.48 | 225 | 2418.00 |
| 1 | 5 | 8.60 | 3.47 | 225 | 2418.00 |
| 1 | 6 | 12.70 | 4.09 | 225 | 2418.00 |
| 1 | 1 | 1.28 | 1.28 | 270 | 2418.00 |
| 1 | 2 | 1.57 | 0.29 | 270 | 2418.00 |
| 1 | 3 | 3.14 | 1.57 | 270 | 2418.00 |
| 1 | 4 | 5.54 | 2.40 | 270 | 2418.00 |
| 1 | 5 | 9.31 | 3.76 | 270 | 2418.00 |
| 1 | 6 | 18.44 | 9.14 | 270 | 2418.00 |
| 1 | 1 | 1.28 | 1.28 | 315 | 2418.00 |
| 1 | 2 | 1.49 | 0.21 | 315 | 2418.00 |
| 1 | 3 | 2.19 | 0.70 | 315 | 2418.00 |
| 1 | 4 | 3.02 | 0.83 | 315 | 2418.00 |
| 1 | 5 | 3.68 | 0.66 | 315 | 2418.00 |
| 1 | 6 | 5.29 | 1.61 | 315 | 2418.00 |

## 8.4 Grund vik

981029
Project: EU Life Algae LIFE96ENV/S/380 (Task 10)

MODELLING FILAMENTOUS ALGAE MATS IN SHALLOW BAYS

Vi har i denna tredje rapportdel arbetat med en beskrivning av en grund vik relativt ett djupare område utanför viken.

Tillväxt och utbredning av makroalger är huvudsakligen kopplat till grundområden och belysta havsbottnar. Avsikten med denna rapportdel är att formulera en modell där vi kan avgöra villkoren för en möjlig tillväxt av makroalger samt algsamhällets sammansättning.

### 8.4.1. Mikro- och makroalger

Den från vår modellerings synpunkt viktigaste skillnaden i egenskaper mellan mikro- och makro alger består i skillnaden mellan deras maximala näringsupptagnings-hastighet $V_{max}$ och halvmättnadskonstant $K_c$. Dessa parametrar används för att beskriva hastigheten för näringsämnesupptag V av det tillväxtbegränsande näringsämnet med koncentrationen C enligt så kallad Michaelis-Menten kinetik där

$$V = V_{max} \frac{C}{K_c + C} \qquad (1)$$

En sammanställning av näringsupptaget av ammonium och nitrat för 76 olika alger visar att $V_{max}$ för mikroalger i genomsnitt är flera gånger större än $V_{max}$ för makroalger medan $K_c$ för mikroalger i genomsnitt är åtminstone tio gånger större än $K_c$ för makroalger [Hein et al., 1995]. Detta betyder att näringsämneskoncentrationerna i vatten där planktoniska mikroalger kan blomma ordentligt blir så små att tillväxten av makroalger blir kraftigt hämmad. D.v.s. för att vi ska få en kraftig tillväxt av makroalger krävs en miljö där planktoniska mikroalger inte kan växa.! Vi vet inte idag om det är möjligt för bentiska mikroalger att utnyttja näringsämnen direkt från vattenkolumnen i sådan mån att koncentrationerna i vattnet blir så låga att tillväxten av makroalger hämmas. Däremot vet vi att bentiska mikroalger kan fungera som filter och eventuellt hämma flödet av regenererade näringsämnen från bottensedimentet till vattnet [Sundbäck et al., 1991].

### 8.4.2. Definition av grund vik

Hur är det då möjligt att makroalgerna som tar sin näring från vattnet kan växa på de grunda områdena. För att avgöra detta undersöker vi växtplanktonsamhällets tillväxtdynamik. Denna kan enklast beskrivas genom

$$\frac{dPON}{dt} = Growth + Resp - \frac{W_p}{H} PON \qquad (2)$$

där PON är koncentrationen av växtplankton i det välblandade ytskiktet med tjockleken H och $W_p$ fallhastigheten för plankton i vattnet [för en fördjupad beskrivning se t.ex. Stigebrandt & Djurfeldt, 1996]. D.v.s. den sista termen beskriver mängden plankton som faller ur ytskiktet till djupare delar av vattnet eller sedimenterar på botten om djupet H bestäms av bottendjupet som i fallet med grunda vikar. Tillväxten av växtplankton beskrivs genom

$$Growth = Nutlim \bullet Ltlim \bullet G_{max} \bullet PON \qquad (3)$$

där Nutlim och Ltlim beskriver näringsämnes- respektive ljusbegränsning av planktontillväxten. $G_{max}$ beskriver den maximala tillväxthastigheten av planktonsamhället (typsikt värde c:a 0.7 per dygn). Tillväxten hämmas av energiförluster (respiration) för ämnesomsättning och eventuella förflyttningar, denna beskrivs genom

$$Resp = -r \bullet G_{max} \bullet PON \qquad (4)$$

där r~0.1. För vår klassificering av en grund vik ansätter vi Nutlim=Ltlim=1, d.v.s. ingen näringsämnes eller ljusbegränsning på tillväxten, vilket medför att tillväxten av planktonsamhället kommer att begränsas av fallhastigheten $W_p$ och djupet H i ekvation (2).

Vi definierar en grund vik genom villkoret att

$$\frac{dPON}{dt} = 0 \qquad (5)$$

Detta villkor uppfylls för områden med bottendjup (d) mindre än

$$d < \frac{W_p}{(1-r)\cdot G_{max}} \qquad (6)$$

D.v.s. med ovan angivna värden på r och $G_{max}$ samt med ett ofta antaget värde på planktons fallhastighet $W_p$=1m per dygn finner vi att ett växtplanktonsamhälle inte kan tillväxa på grunda områden med ett djup understigande c:a 1.5m eftersom sedimentationen då överstiger tillväxten av växtplankton. Vi kan notera att detta djup sammanfaller väl med den observerade övre utbredningsgränsen för Zostera ängar på c:a 1m djup [t.ex. Rosenberg, 1982]. Zostera är en blomväxt med rotsystem som kan ta upp näring både från vattnet och från sedimenten. Denna djuplinje har tidigare använts t.ex. för definition av grunda vikar observerade från flygfotografier tagna efter Bohuskusten [L.Pihl, pers. komm.].

### 8.4.3. Ett djupt ytterområde

Genom ovanstående definition av ett grundområdet vet vi att näringsämneskoncentrationerna i djupområdet utanför den grunda viken är huvudsakligen bestämda av blommande mikroplankton under sommarhalvåret. Detta kan observeras till exempel från vattenvårdsförbundets kustvattenkontroller som generellt visar på låga och konstanta ytfosfatvärden (~0.05µM) från och med mars-april varje år under perioden 1992-1997. D.v.s. vi kan lätt ansätta ett yttre randvillkor för näringsämneskoncentrationen för att driva flöden av lösta näringsämnen i modellen. Undantag från denna regel kan dock uppstå då tillförseln av näringsämnen till produktionsskiktet i djupområdet är så stor att tillväxten av planktonsamhället inte kan absorbera den tillförda näringen helt. Det kan t.ex. bero på att något annat näringsämne begränsar produktionen, eller på att djupet på produktions skiktet är så litet att det begränsar produktionen. Produktionsskiktets djup kan begränsas av densitets skiktning eller av havsbotten. Vattnets grumlighet kan också begränsa produktionen genom ljusbegränsning. I dessa fall kan koncentrationerna vara förhöjda relativt ovanstående randvillkor. Det yttre randvillkoret till modellen måste i dessa fall antingen bestämmas genom direkta mätningar eller genom uppskattningar med andra modeller som beskriver tillståndet i ytterområdet.

Vi kan grovt uppskatta om planktonsamhället kan absorbera tillförda näringsämnen till ytterområdet genom att jämföra storleken på tillförsel och möjlig tillväxt från

$$Q\cdot\Delta N = V\cdot\frac{dPON}{dt} \qquad (7)$$

där Q•ΔN är nettotillförseln av näring genom vattenutbytet Q i området med ytan A. ΔN är skillnaden i näringsämneskoncentration i till och från flödet. V=H•A är volymen av området där vattenytbytet sker.

### 8.4.4. Produktion av makroalger i en grund vik

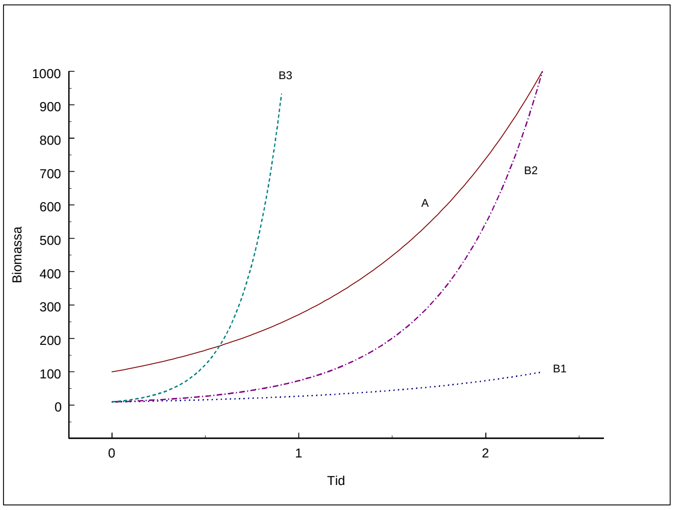
Tillväxten av makroalgbiomassa kan approximativt beskrivs av

$$\frac{dBiomassa}{dt} = startbiomassa\cdot e^{k\cdot t} \qquad (8)$$

där k är en tillväxtkonstant för biomassan av den givna algtypen. Tillväxt konstanten är en variabel som beror på ett flertal andra parametrar varav en kan vara koncentrationen av näringsämnen i vattnet. Till exempel Magnusson [1997] visar att upptagningshastigheten av näringsämnen (nitrat) från vattnet per torrviktsenhet av tången Chondrus crispus (exempel på önskvärd algtyp A) är relativt liten och konstant för låga som höga nitratkoncentrationer, medan upptagningshastigheten för den fintrådiga algen Enteromorfa (exempel på icke önskvärd algtyp B) ökar med ökande koncentrationer i vattnet.

För att undersöka effekten på makroalgernas sammansättning vid olika koncentrationer studerar vi här tre olika fall (Figur 1). Vid låga koncentrationer antar vi att tillväxt koefficienten k är lika för algtyp A ($k_A$) och B ($k_B$), d.v.s. $k_B$=$k_A$=1 (fall B1). Sedan antar vi att koncentrationerna i vattnet ökar så att tillväxtkoefficienten för algtyp B ökar till $k_B$ =2 (fall B2) respektive $k_B$=5 (fall B3). För att simulera tillståndet i början av våren antar vi att en del av den relativt långlivade algtypen A har klarat att övervintra medan den kortlivade algtypen B måste börja om från början med en mycket liten startbiomassa. D.v.s. vi antar här att startbiomassan av algtyp A är 100 gånger större än biomassan av algtyp B.

Resultaten visar att tillväxten av biomassa A kommer att dominera vid ett lika värde på k på grund av den större startbiomassan medan tillväxten av biomassa B kommer att dominera vid en tidpunkt given av storleksskillnaden mellan $k_A$ respektive $k_B$ då $k_B$>$k_A$. Eftersom tillväxt koefficienten för algtyp B beror på koncentrationerna av näringsämnen i vattnet kommer utvecklingen av algsammansättningen i viken huvudsakligen att bero av de fysiska förhållandena i den givna viken. Detta förutsätter förstås också att det finns tillräckligt mycket näringsämnen tillgängliga för att den kritiska biomassan av algtyp B skall uppnås. Fysisk stress kan ytterligare påverka möjligheten för algtyp B att uppnå en kritisk massa t.ex. genom naturlig algskörd orsakad av vågor och vind.

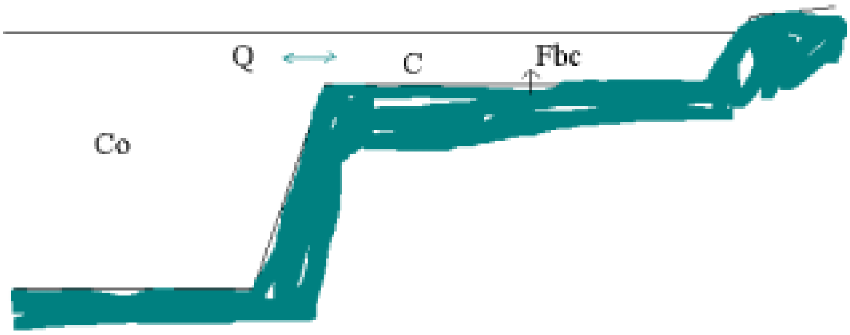



**Figur 1**. *Förväntad tillväxt av algtyp A och algtyp B. Antagit att biomassan av algtyp A och B är 100 respektive 1 vid start. Tillväxt koefficienten (k) för A och för fall B1 är 1. Tillväxtkoefficienten i fall B2 och B3 är 2 respektive 5.*

Möjligheten att uppnå höga näringsämneskoncentrationer (C) i vattnet i viken bestäms huvudsakligen av vattenutbytet mellan grundområdet och det djupare området utanför viken, samt av flödet av regenererade näringsämnen från bottnarna ($F_{BC}$) till vattnet. Vid ett stationärt tillstånd utan färskvattentillförsel till viken kan vi beskriva C genom

$$C = C_o + \frac{A}{Q} \cdot F_{BC} \qquad (9)$$

där Co är koncentrationen i vattnet utanför viken.




**Figur 2.** *Genomskärning av grund vik med ett djupare område utanför. C och Co betecknar näringsämneskoncentrationen inne respektive utanför viken. Q är vattenutbytet och $F_{BC}$ flödet av regenererade näringsämnen från bottnarna i den grunda viken.*

D.v.s. skillnaden mellan $k_B$och $k_A$ ($\Delta$k) kan för en given vik beskrivas med en funktion f så att

$$\Delta k = f(Q, C_0, F_{BC}) \qquad (10)$$

Om vi tar hänsyn till effekten av färskvattentillförsel $Q_f$ till viken fås att

$$C = C_O + \frac{A}{Q_2} \cdot F_{BC} + \frac{1}{P}[C_f - C^o] \quad (11)$$

där

$$C^o = \frac{A}{Q_2} \cdot F_{BC} + C_O \qquad (12)$$

$P=Q_1/Q_f$. $Q_1$ är utflöde från viken, $Q_2$ inflöde och $Q_f$ färskvatten tillflöde till viken. $C_f$ är koncentrationen av näringsämnen i färskvattnet. $C^o$ beskriver koncentrationen i viken om färskvattenflödet är försumbart. D.v.s. eventuell färskvattentillförsel till viken bör principiellt kunna behandlas som en korrektionsfaktor till i funktionen i ekvation (10). Man kan notera att färskvattentillförsel ökar koncentrationerna i viken endast om koncentrationen i färskvattnet överstiger den förväntade koncentrationen utan färskvatten tillförsel till viken.

## 8.6 PC Program manual

### Manual for expert PC program: Shallow bay

**Basic user information**

Name of program : Shallow bay
Version : 991115
Name of executable file : BAYMODEL.EXE
Required PC environment : The program may run within a PC DOS environment
Language of program code : Fortran
Form of input data : ASCI files
Required input data files :
FETCH.DAT : Fetch length of the bay in the main compass directions (N,NNE,NE,ENE,E...)
This file is created by the program Fetch model described below
INDATA.LST : Information about the modelled time period and the specific bay
COASTDAT.LST : Temperature, and nutrient and oxygen concentrations in coastal waters
WLEV_QF.LST : Coastal water level, freshwater supply and corresponding concentrations
HARVEST.LST : Specification about days of the year with man made harvest

Form of output data : ASCI files
Output data files :
ALGAE.DAT : Biomass of algae, detritus and the sum of algae and detritus in the bay
CONCENTR.DAT : Temperature, and nutrient and oxygen concentrations in the bay
SEDIMENT.DAT : Nitrogen and phosphorus concentrations in the bay sediments

Complementary program : Fetch model
Name of executable file : FETCHMOD.EXE
Required PC environment : The program may run within a PC DOS environment
Language of program code : Fortran
Form of input data : ASCI files
Required input data files :
BAYDATA.LST : Raw data of the fetch length of the bay divided into steps of 6°

Form of output data : ASCI .DAT files
Output data files :
FETCH.DAT : Fetch length of the bay in the main compass directions (N, NNE,NE,ENE,E...)

### Specified information about the input and output data

**Brief examples from the input and output files of the programs are presented and commented below.**

### BAYDATA.LST-The file is used as input to the program Fetch model

The basic information about the fetch length of a specific bay in different compass directions (0°-360°) is here divided into steps of 6°. The fetch length is measured in mm from sea charts and the value is saved in the file as shown in the example below. It is important to write down the scale of the sea chart in this file. The text of the file is written in Swedish. The place of the decimal point of the figures given in the file is important. Do not change it's place!

```
Filen innehåller en mall för testvikar till programmet Shallow bay
Filen används som indata till programmet Fetch model
--------------------------------------------------
  25000.0 Sjökortets skala
       0.0    Strykländgd (mm) i riktning norrut  ( 0 grader)    0
       0.0                            ( 6 grader)    6
       0.0                            (12 grader)   12
       0.0                              18
       0.0                              24
       0.0                              30
       0.0                              36
      10.0                             42
      10.0                             48
      10.0                             54
      10.0                             60
      10.0                             66
      10.0                             72
      10.0                             78
      10.0                             84
      10.0                  Österut   90
      10.0                             96
      10.0                            102
      10.0                            108
      10.0                            114
      10.0                            120
      10.0                            126
      10.0                            132
      10.0                            138
      10.0                            144
      0.0                            150
      0.0                            156
      0.0                            162
      0.0                            168
      0.0                            174
      0.0                  Söderut 180
       0.0                                186
        .
        .
        .
       o.s.v.
```

## INDATA.LST-The file is used as input to the program Shallow bay

- The basic informations about the model run are given by the user in this file.
- The place of the decimal point of the figures given in the files is important. Do not change it's place!
- The maximum number of days may not exceed 2000 in the present version of the model.
- If the depth of the modelled bay becomes less than 30 cm, the program will automatically be ended.
- If the oxygen concentrations decrease below 1ml/l, the program will automatically be ended.
- The extension of the atmospheric data base limits the use of the model to the period from January 1970 to October 1995.
- The input parameters are described below together with the parameter name used in the model.

| INDATA | PARAMETER | DESCRIPTION | (Dimension) |
|---|---|---|---|
| 00001000.000000000000 | =DAYS | , Number of days during the modled period | |
| 00040000.000000000000 | =A1 | , Bay area | (square meters) |
| 00000001.000000000000 | =D1 | , Factor to tune the average water depth. Average depth is given in file WLV_QF.LST. | |
| 00000001.000000000000 | =LS | , Length of the bay entrance | (meter) |
| 00000200.000000000000 | =WS | , Width of the bay entrance | (meter) |
| 00000000.100000000000 | =AT | , Tidal amplitude | (meter) |
| 00044712.000000000000 | =PT | , Tidal period | (seconds) |
| 00001992.000000000000 | =SYR | , Start year of modelled time period | |
| 00000001.000000000000 | =SMON | , Start month of modelled time period | |
| 00000001.000000000000 | =SDAY | , Start day of modelled time period | (day of month) |
| 00000012.000000000000 | =STE | , Start time of modelled time period | (hour) |
| 00001994.000000000000 | =EYR | , End year of modelled time period | |
| 00000012.000000000000 | =EMON | , End month of modelled time period | |
| 00000006.000000000000 | =EDAY , | End day of modelled time period | (day of month) |
| 00000012.000000000000 | =ETE , | End time of modelled time period | (hour) |
| 00000000.000000000000 | =QREX , | Define water exchange by large scale current | ($m^3s^{-1}$) |
| 00000100.000000000000 | =LABN , | Concentration of labile N i sediment | (mmol per square meter) |
| 00000400.000000000000 | =REFN , | Concentration of refractive N in sediment | (mmol per square meter) |
| 00000010.000000000000 | =LABP , | Concentration of labile P i sediment | (mmol per square meter) |
| 00000090.000000000000 | =REFP , | Concentration of refractive P in sediment | (mmol per square meter) |

## COASTDAT.LST-The file is used as input to the program Shallow bay

- The basic information about the concentrations in the adjacent water body are to be given by the user in this file. (see example below)
- One value of each of the concentrations are given for each day of the modelled time period.

### Explanation of parameters:

- Salt = Salinity is given in psu
- Temp = Temperature in degrees Celsius
- O2 = Oxygen in $mlO_2l^{-1}$
- POC = Particulate organic carbon in $mmolCm^{-3}$
- PO4P = Dissolved inorganic phosphate (DIP) in $mmolPm^{-3}$
- DIN = Dissolved inorganic nitrogen (DIN) in $mmolNm^{-3}$

### Example of the first rows in the file:

| Daynr | Salt | Temp | O2 | POC | PO4P | DIN |
|---|---|---|---|---|---|---|
| 1 | 32.90 | 5.50 | 7.80 | 48.90 | 0.70 | 8.70 |
| 2 | 32.90 | 5.50 | 7.80 | 48.90 | 0.70 | 8.70 |
| 3 | 32.90 | 5.50 | 7.80 | 48.90 | 0.70 | 8.70 |
| 4 | 32.90 | 5.50 | 7.80 | 48.90 | 0.70 | 8.70 |
| 5 | 32.90 | 5.50 | 7.80 | 48.90 | 0.70 | 8.70 |
| 6 | 32.90 | 5.50 | 7.80 | 48.90 | 0.70 | 8.70 |
| 7 | 32.90 | 5.50 | 7.80 | 48.90 | 0.70 | 8.70 |
| 8 | 32.67 | 5.40 | 7.81 | 47.59 | 0.70 | 8.69 |
| 9 | 32.44 | 5.30 | 7.83 | 46.27 | 0.69 | 8.68 |
| 10 | 32.20 | 5.20 | 7.84 | 44.96 | 0.69 | 8.67 |

## HARVEST.LST-The file is used as input to the program Shallow bay

- The number of each day (1 to 365) with man made harvest during a year in the model may be specified in this file.
- Maximum five days with harvest can be defined.
- Negative value is used when no man made harvest is done.

### Example from the file:

```
180   ; DEFINE HARVEST DAY NR1 OF YEAR
-1    ; DEFINE HARVEST DAY NR2 OF YEAR
-1    ; DEFINE HARVEST DAY NR3 OF YEAR
-1    ; DEFINE HARVEST DAY NR4 OF YEAR
-1    ; DEFINE HARVEST DAY NR5 OF YEAR
```

## WLEV_QF.LST -The file is used as input to the program Shallow bay

- The basic information about the average sea level and of the freshwater supply, and the concentrations of the freshwater are given in this file.
- One value are given for each day of the modelled time period.

### Explanation of parameters:

- H2 = Average sea level in meter
- QF = Freshwater supply to the bay in $m^3s^{-1}$
- CF(1) = Salinity is given in psu
- CF(2) = Temperature in degrees Celsius
- CF(3) = Oxygen in $mlO_2l^{-1}$
- CF(4) = Particulate organic carbon in $mmolCm^{-3}$
- CF(5) = Dissolved inorganic phosphate (DIP) in $mmolPm^{-3}$
- CF(6) = Dissolved inorganic nitrogen (DIN) in $mmolNm^{-3}$

### Example of the first rows in the file:

| H2 QF | CF(1) | CF(2) | CF(3) | CF(4) | CF(5) | CF(6) |
|---|---|---|---|---|---|---|
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |
| 1.00, 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, | 0.00, |

## ALGAE.DAT-The file is an output file of the program Shallow bay

- The basic information about the concentrations of algae and detritus are saved in this file.
- One value are saved for each hour of the modelled time period.

### Explanation of parameters:

- T = Time in days
- ALGAE = Concentration of algae in the bay in gram dry weight per square meter
- DETRITUS = Concentration of detritus in the bay in gram dry weight per square meter
- COVER = Concentration of the sum of algae and detritus in the bay in gram dry weight per square meter

### Example of the first rows in the file:

| T, | ALGAE, | DETRITUS, | COVER |
|---|---|---|---|
| 1.000 | 0.840 | 0.000 | 0.840 |
| 1.042 | 0.842 | 0.001 | 0.843 |
| 1.083 | 0.843 | 0.003 | 0.845 |
| 1.125 | 0.842 | 0.004 | 0.846 |
| 1.167 | 0.841 | 0.006 | 0.846 |
| 1.208 | 0.840 | 0.007 | 0.847 |
| 1.250 | 0.840 | 0.008 | 0.848 |
| 1.292 | 0.840 | 0.010 | 0.850 |
| 1.333 | 0.840 | 0.011 | 0.851 |
| 1.375 | 0.840 | 0.013 | 0.853 |
| 1.417 | 0.840 | 0.014 | 0.854 |
| 1.458 | 0.840 | 0.015 | 0.855 |
| 1.500 | 0.840 | 0.017 | 0.857 |
| 1.542 | 0.840 | 0.018 | 0.858 |
| 1.583 | 0.840 | 0.019 | 0.859 |
| 1.625 | 0.840 | 0.021 | 0.861 |
| 1.667 | 0.840 | 0.022 | 0.862 |
| 1.708 | 0.840 | 0.023 | 0.863 |
| 1.750 | 0.840 | 0.025 | 0.865 |
| 1.792 | 0.840 | 0.026 | 0.866 |
| 1.833 | 0.840 | 0.028 | 0.868 |
| 1.875 | 0.840 | 0.029 | 0.869 |
| 1.917 | 0.840 | 0.030 | 0.870 |
| 1.958 | 0.840 | 0.032 | 0.872 |
| 2.000 | 0.840 | 0.033 | 0.873 |
| 2.042 | 0.841 | 0.034 | 0.875 |
| 2.083 | 0.841 | 0.036 | 0.876 |

## CONCENTR.DAT-The file is an output file of the program Shallow bay

- The basic information about the concentrations of nutrients and oxygen of the bay and the depth of the bay are saved in this file.
- One value are saved for each hour of the modelled time period.

### Explanation of parameters:

- DEPTH = Momentary depth of the bay in meters
- SALINITY = Salinity is given in psu
- TEMP = Temperature in degrees Celsius
- OXYGEN = Oxygen in $mlO_2l^{-1}$
- PON = Particulate organic nitrogen in $mmolNm^{-3}$
- DIP = Dissolved inorganic phosphate (DIP) in $mmolPm^{-3}$
- DIN = Dissolved inorganic nitrogen (DIN) in $mmolNm^{-3}$
- QBELOW = Lower layer inflow to the bay in $m^{-3}s^{-1}$ (negative values denote outflow)
- QABOVE = Upper layer outflow to the bay in $m^{-3}s^{-1}$ (negative values denote inflow)

### Example of the first rows in the file:

| T, | DEPTH, | SALINITY, | TEMP, | OXYGEN, | PON, | DIP, | DIN, | QBELOW, | QABOVE |
|---|---|---|---|---|---|---|---|---|---|
| 1.000 | 1.000 | 32.900 | 5.500 | 7.800 | 7.381 | 0.700 | 8.700 | 0.000 | 0.000 |
| 1.042 | 0.959 | 32.901 | 5.497 | 7.788 | 7.043 | 0.705 | 8.728 | 0.422 | 0.881 |
| 1.083 | 1.008 | 32.902 | 5.483 | 7.778 | 6.768 | 0.709 | 8.751 | 1.025 | 0.477 |
| 1.125 | 1.055 | 32.903 | 5.443 | 7.769 | 6.549 | 0.712 | 8.773 | 1.214 | 0.689 |
| 1.167 | 1.089 | 32.903 | 5.393 | 7.762 | 6.380 | 0.715 | 8.791 | 1.395 | 1.023 |
| 1.208 | 1.100 | 32.903 | 5.350 | 7.756 | 6.247 | 0.717 | 8.806 | 1.499 | 1.374 |
| 1.250 | 1.086 | 32.904 | 5.314 | 7.750 | 6.134 | 0.719 | 8.820 | 1.493 | 1.646 |
| 1.292 | 1.051 | 32.905 | 5.238 | 7.745 | 6.018 | 0.721 | 8.833 | 1.321 | 1.715 |
| 1.333 | 1.002 | 32.907 | 5.170 | 7.741 | 5.915 | 0.723 | 8.845 | 1.319 | 1.853 |
| 1.375 | 0.954 | 32.908 | 5.109 | 7.737 | 5.824 | 0.725 | 8.855 | 1.303 | 1.844 |
| 1.417 | 0.917 | 32.909 | 5.056 | 7.734 | 5.748 | 0.726 | 8.863 | 1.322 | 1.734 |
| 1.458 | 0.900 | 32.910 | 5.015 | 7.733 | 5.699 | 0.727 | 8.867 | 1.401 | 1.582 |
| 1.500 | 0.909 | 32.911 | 4.988 | 7.733 | 5.682 | 0.728 | 8.868 | 1.540 | 1.443 |
| 1.542 | 0.940 | 32.911 | 4.976 | 7.734 | 5.698 | 0.727 | 8.866 | 1.718 | 1.368 |
| 1.583 | 0.987 | 32.911 | 4.976 | 7.735 | 5.738 | 0.727 | 8.862 | 1.903 | 1.387 |
| 1.625 | 1.037 | 32.911 | 4.982 | 7.737 | 5.790 | 0.726 | 8.858 | 2.059 | 1.507 |
| 1.667 | 1.077 | 32.911 | 4.991 | 7.739 | 5.840 | 0.725 | 8.854 | 2.151 | 1.700 |
| 1.708 | 1.098 | 32.911 | 4.999 | 7.740 | 5.879 | 0.725 | 8.851 | 2.158 | 1.922 |
| 1.750 | 1.095 | 32.911 | 5.001 | 7.741 | 5.899 | 0.724 | 8.850 | 2.079 | 2.116 |
| 1.792 | 1.068 | 32.909 | 5.055 | 7.740 | 5.904 | 0.724 | 8.850 | 1.981 | 2.282 |
| 1.833 | 1.024 | 32.908 | 5.090 | 7.738 | 5.873 | 0.725 | 8.853 | 1.720 | 2.210 |
| 1.875 | 0.974 | 32.906 | 5.112 | 7.736 | 5.817 | 0.726 | 8.858 | 1.500 | 2.057 |
| 1.917 | 0.930 | 32.906 | 5.127 | 7.733 | 5.749 | 0.727 | 8.865 | 1.359 | 1.841 |
| 1.958 | 0.904 | 32.905 | 5.154 | 7.730 | 5.685 | 0.728 | 8.870 | 1.316 | 1.603 |
| 2.000 | 0.902 | 32.904 | 5.198 | 7.729 | 5.637 | 0.729 | 8.872 | 1.346 | 1.367 |
| 2.042 | 0.925 | 32.904 | 5.258 | 7.729 | 5.624 | 0.729 | 8.871 | 1.488 | 1.237 |
| 2.083 | 0.966 | 32.903 | 5.299 | 7.729 | 5.626 | 0.729 | 8.870 | 1.569 | 1.109 |
| 2.125 | 1.016 | 32.903 | 5.316 | 7.729 | 5.640 | 0.729 | 8.869 | 1.650 | 1.096 |
| 2.167 | 1.062 | 32.902 | 5.316 | 7.728 | 5.660 | 0.729 | 8.869 | 1.719 | 1.210 |
| 2.208 | 1.092 | 32.902 | 5.316 | 7.728 | 5.679 | 0.729 | 8.869 | 1.743 | 1.406 |
| 2.250 | 1.099 | 32.902 | 5.316 | 7.728 | 5.686 | 0.729 | 8.871 | 1.689 | 1.609 |
| 2.292 | 1.082 | 32.901 | 5.292 | 7.725 | 5.641 | 0.730 | 8.877 | 1.323 | 1.520 |
| 2.333 | 1.044 | 32.901 | 5.269 | 7.722 | 5.585 | 0.731 | 8.885 | 1.215 | 1.639 |
| 2.375 | 0.994 | 32.901 | 5.245 | 7.719 | 5.518 | 0.732 | 8.893 | 1.108 | 1.653 |

## SEDIMENT.DAT-The file is an output file of the program Shallow bay

- The basic information about the concentrations of nutrients in the sediments of the bay are saved in this file.
- One value are saved for each hour of the modelled time period.

### Explanation of parameters:

- LABILE_N = Concentration of labile N in sediment (mmol per square meter)
- REFR_N = Concentration of refractory N in sediment (mmol per square meter)
- LABILE_P = Concentration of labile P in sediment (mmol per square meter)
- REFR_P = Concentration of Refractory P in sediment (mmol per square meter)

### Example of the first rows in the file:

```
T, LABILE_N, REFR_N, LABILE_P, REFR_P
  1.000  100.000  400.000   10.000   90.000
  1.042  100.166  400.115   10.010   90.006
  1.083  100.323  400.225   10.019   90.012
  1.125  100.473  400.330   10.027   90.017
  1.167  100.617  400.432   10.036   90.022
  1.208  100.758  400.531   10.044   90.027
  1.250  100.896  400.628   10.052   90.032
  1.292  101.030  400.722   10.059   90.037
  1.333  101.162  400.815   10.067   90.041
  1.375  101.292  400.907   10.074   90.046
  1.417  101.419  400.996   10.082   90.050
  1.458  101.545  401.085   10.089   90.055
  1.500  101.669  401.173   10.096   90.059
  1.542  101.794  401.261   10.103   90.063
  1.583  101.918  401.349   10.110   90.068
  1.625  102.044  401.437   10.117   90.072
  1.667  102.170  401.527   10.125   90.076
  1.708  102.298  401.617   10.132   90.081
  1.750  102.427  401.708   10.139   90.085
  1.792  102.557  401.799   10.147   90.090
  1.833  102.686  401.890   10.154   90.095
  1.875  102.815  401.981   10.162   90.099
  1.917  102.942  402.071   10.169   90.104
  1.958  103.067  402.159   10.176   90.108
  2.000  103.190  402.247   10.183   90.112
  2.042  103.313  402.333   10.190   90.116
  2.083  103.434  402.420   10.197   90.121
  2.125  103.556  402.506   10.204   90.125
  2.167  103.678  402.593   10.211   90.129
  2.208  103.800  402.680   10.218   90.133
  2.250  103.923  402.767   10.225   90.137
  2.292  104.046  402.854   10.232   90.142
  2.333  104.167  402.941   10.239   90.146
```

## 8.7 PC Program executable file on diskette

Two installation discettes. See read.me files.

# Projektrapporter och andra publikationer


## EU Life algae rapportserie

### 1997

Pettersson, K. 1997. *Report from the work-shop on "Algal mats on shallow soft bottoms".*

### 1998

Ascue, J. och Norberg, Å. 1998. Jordbrukstekniska institutet. *Kontinuerlig rötning av grönalger och källsorterat hushållsavfall, slutrapport 98-04-17.*

Berglund, J. 1998. *Kartering av makrofyter och drivande alger på grunda mjukbottnar i Ålands skärgård.*

Jöborn, A., Oscarsson, H. och Pihl, L. 1998. *A new approach to combat blooms of ephemeral opportunistic macro algae in Scandinavian coastal waters, ICES.*

Rönnberg, C. och Genberg, J. 1998. *Biologiska effekter av algskörd. Kontrollprogram på Åland 1997.*

### 1999

Stigebrandt, A. och Eilola, K. 1999. *Modelling filamentous algae mats in shallow bays.*

### 2000

Berglund, J. och Heikkilä, J. 2000. *Rapport över det biologiska kontrollprogrammet på Åland 1999, samt en jämförelse över 1997-1999.*

Jönsson, B. 2000. *Teknisk rapport för algskördare och skörd, under perioden 1997-2000.*

Lindahl, S. *Vägbankars inverkan på vattencirkulationen i grunda havsvikar.* SMHI.

Melin, Y. 2000. *Alternativ användning av marina fintrådiga makroalger.*

Olrog, L. 2000. *Fintrådiga alger som gödselmedel. Sammanställning av försök genomförda av Hushållnings-Sällskapet i Göteborg och Bohuslän 1997-99.*

Svensson, A. och Pihl, L. 2000. *Biologiskt kontrollprogram 1997-1999.*

Österling, M. och Pihl, L. 2000. *Effects of green algal mats on infaunal functional feeding.*

### 2001

Boman, U. *Försök med användning av alger och blåstång som gödselmedel i jordbruket. 1998-2000.*

Dåverhög, M. och Lindström, Å. 2001. *Remote sensing of filamentous algae in shallow waters along the Swedish West Coast.* Uppsala Universitet.

Harlén, A. och Zackrisson, A-C. 2001.
*Ekonomisk analys för algskörd och an-vändning av fintrådiga alger.*

Heikkilä, J. 2001. *Rapport över det biologiska kontrollprogrammet på Åland 2000.*

Jöborn, A., Sköld, M., Sterner, H. och Trefil Engström, M. 2001. *Final report.*

Jöborn, A., Oscarsson, H., Sköld, M. och Sterner, H. 2001. *Algae in excess - harvesting for Life.*

Melin, Y. 2001. *Can marine filamentous algae be used as fertiliser? An analysis of heavy metal and nutrient content.* Göteborgs Universitet.

Pihl, L. 2001. *Effekter av fintrådiga alger på rekrytering av rödspätta – en numerisk modell.*

Sterner, H. med flera. 2001. *Teknikbeskrivning.*

Sterner, H. med flera. 2001. *Rekommendationer för planering och förvaltning.*

Svensson, A. och Pihl, L. 2001. *Biologisk undersökning av grunda havsvikar – effekter av fintrådiga alger och skörd.*

Thulin Plate, L. med flera. 2001. *Rättsliga förutsättningar för att skörda alger och öka vattenflödet genom vägbankar.*

## Andra publikationer

Pihl, L., Svensson A., Moksnes P-O. och Wennhage, H. 1997. *Utbredning av fintrådiga grönalger i grunda mjukbottnensområden i Göteborgs och Bohus län under 1994-1996.* Länsstyrelsen i Göteborgs och Bohus län, 1997:22.

Pihl, L., Svensson A., Moksnes P-O., och Wennhage, H. 1999. *Distribution of algal mats throughout shallow soft bottoms of the Swedish Skagerrak archipelago in relation to nutrient sources and wave exposure.* Journal of Sea Research 41 (1999 281-294).

# Projektdeltagare

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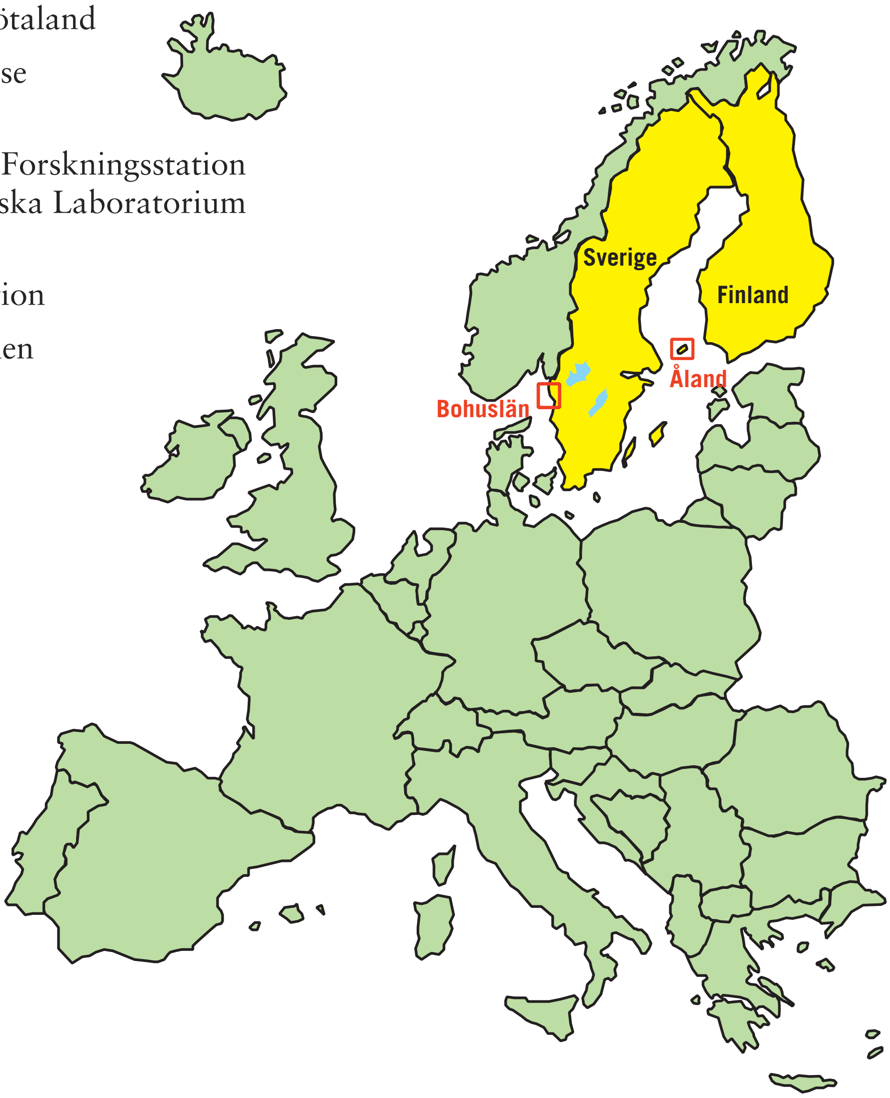
Strömstads Kommun

Fiskeriverket

Vägverket

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