Is there a green solution for a blue-green problem leading to clear blue water?

Results of the expert evaluation of model calculations on management scenarios to eradicate cyanobacteria from the Volkerak - Zoommeer area

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1. Introduction

1.1 Problem definition

The Krammer-Volkerak was originally an open transition area between river and sea. After the completion of the "Delta works" it was transformed into a freshwater lake with a more or less constant water level. Since 1994 the area is characterised by extensive blooms of toxic cyanobacteria in summer, which form a danger to human and environmental health. The cause of the excessive growth of these blue-green algae is the combination of high nutrient import through the rivers of Brabant and the Hollandsch Diep, combined with a high retention time in the basin.

The population of cyanobacteria in the Volkerak-Zoommeer is predominantly comprised of *Microcystis* species. They grow in colonies surrounded by a layer of mucus. Certain *Microcystis* species, such as the ones in the Volkerak-Zoommeer, produce toxins. The best-known ones are microcystines that particularly affect the liver. These toxins can cause mortality in fish and bird populations as well as severe health problems in humans.

When the concentration of blue-green algae is high, the concentrations of toxins are high. At such times swimming in the Volkerak-Zoommeer is dangerous and therefore prohibited. The contaminated water also cannot be used for agricultural purposes. The decay of large cyanobacterial blooms in late summer can cause severe stench problems. Record levels were reached in the summer of 2002 when cyanobacteria were the suspected cause of the death of about 5000 aquatic birds.

Apart from the problems with blue-green algae, the heavy load of nutrients from the rivers negatively affects the water quality in the area. The Volkerak-Zoommeer therefore does not comply with the European directives regarding water quality.

The Administrative Consultation Krammer-Volkerak (BOKV) has commissioned a study into which adaptations in the current infrastructure would be most effective in reducing the problem of the annual toxic blooms of blue-green algae in the Volkerak-Zoommeer. From the several available scenarios a limited number have been selected for extensive model calculations. More information about the area, the *Microcystis* problems and the possible solutions can be found at: http://www.volkerakzoommeer.nl.

On 12 and 13 October 2006 a workshop was held in Delft to assess the quality and applicability of these model calculations. The workshop was attended by the main parties involved in the previously mentioned studies and four external experts. This report details the outcome of this expert review. An introduction to the area and the problems with blue-green algae was given by René Boeters (RWS). The presentation is attached to this report in appendix A.

1.2 Area description

The Volkerak-Zoommeer straddles three provinces: Zuid-Holland, Noord-Brabant and Zeeland. It was created in 1987 by the construction of the "Philipsdam" and the "Oesterdam". This enclosure created a freshwater system used for shipping, recreation and freshwater supply for agriculture. With a surface area of 6450 hectares The Volkerak is the third largest freshwater body in the Netherlands, after the IJsselmeer and the Markermeer. A quarter of this area consists of former saltmarshes and mudflats that after the closure of the dams permanently fell dry. The average water depth is 5.2 m and the maximum depth is 24 m. The Zoommeer and the Scheldt-Rhine channel together comprise 1850 hectares. Around 7% of this area consists of emerged seabed. The Zoommeer has an average depth of 6m and a maximum depth of 20 m.

Figure 1.1
Outline map and detail map of the Volkerak- Zoommeer area

Several artificial structures regulate the water level and shipping.

- The Volkerak locks
- The Krammer locks
- The Bergsediep lock
- The Kreekrak locks

There are sluice gates in the outflows of the small rivers the Dintel and the Steenbergse Vliet. Since the closure of the Volkerak these are virtually permanently open. In the south of the area the sluices at Bath regulate the discharge on to the Westerschelde. They have a maximum capacity of 125 $m^3 s^{-1}$.

1.3 Committee members

The Directorate General for Public Works and Water Management (RWS) is responsible for the realisation of the construction works necessary to combat the blue –green algae problem. The National Institute for Coastal and Marine Management (RWS-RIKZ) and the Institute for Inland Water Management and Waste Water treatment (RWS-RIZA) are part of the project in an advisory role.

Over the past six years The University of Amsterdam (UvA) has carried out field and laboratory experiments on factors influencing the life cycle and population dynamics of *Microcystis.* These fundamental data served as input parameters for a model predicting the growth and development of this species under different circumstances. Dr. Jolanda Verspagen has recently published the results of this work in her PhD thesis (Verspagen 2006) under the supervision of Prof Jef Huisman.

Delft Hydraulics is responsible for the 2D and 3D hydrological modelling and the coupling between the hydrological models and the biological models.

Three international and two Dutch external experts have agreed to evaluate the models and the different scenario calculations. Below is a list of the participants of the workshop and a brief outline of qualifications and affiliations of the invited external experts.

Table 1
Participants of the workshop

First name	Institute	Country
Christian E.W. Steinberg	Humboldt University Berlin	Germany
Liisa Kyllikki Lepistö	Finnish Environmental Institute	Finland
Timo Huttula	Finnish Environmental Institute	Finland
Bas W. Ibelings	NIOO	Netherlands
Jutta Passarge*	Hoogheemraadschap Delfland	Netherlands
René E.A.M. Boeters	RWS Zeeland	Netherlands
Paul Boers	RWS-RIZA	Netherlands
Ies de Vries	RWS-RIKZ	Netherlands
Luca A. van Duren	RWS-RIKZ	Netherlands
Pascal Boderie	Delft Hydraulics	Netherlands
Harm Duel	Delft Hydraulics	Netherlands
Simon Groot	Delft Hydraulics	Netherlands
Hans Los	Delft Hydraulics	Netherlands
Jolanda M.H. Verspagen	UvA / IBED	Netherlands
Jef Huisman**	UvA / IBED	Netherlands
Tjeerd Blauw***	Province of Zeeland	Netherlands

* Jutta Passarge was absent due to illness.
**Jef Huisman was absent on day two.
***Tjeerd Blauw attended part of day one.

1.3.1. Christian E.W. Steinberg.

Prof Steinberg holds the chair of Freshwater Ecology at the Humboldt University in Berlin. From 1995-2005 he also was the Director of the Leibniz Institute of Freshwater Ecology and Inland Fisheries in Berlin.

His research interests comprise:

- Pure and Applied limnology, including eutrophication of lakes and rivers.
- Aquatic ecotoxicology.
- Ecosystem health and integrity including assessment of adverse effects on various levels of aggregation (e.g.: energy flow systematics), and ecosystem stability.
- Ecological role of humic substances: geochemical status of whole lakes, biochemical interactions on organism and sub-organism level.

He is an authority on the subject of eutrophication and is (co-)author of several publications on *Microcystis* population dynamics.

1.3.2. Liisa Lepistö

Prof Liisa Lepistö currently holds the chair of phytoplankton ecology at the Finnish Environmental Institute.

Her research interests comprise:

- Long-term changes in phytoplankton in lakes and reservoirs and related environmental factors (long-term monitoring)
- Blue-green algae
- The raw and treated water in water works connected with algal blooms

She is an authority on harmful algal blooms, specifically blue-green algae and is (co-)author on several publications on algal bloom dynamics.

1.3.3. Timo Huttula

Dr Timo Huttula works at the Finnish Environmental Institute and is the chief scientist of the unit of "Physical limnology, transport and fate of harmful substances and nutrients in limnetic environment". He also runs his own Environmental Consulting company and teaches courses in Hydrology at the Finnish Environmental Institute. He has also held lectureships in the Universities of Turku and Helsinki.

His research interests comprise:

- Ecohydrodynamics
- Lake Hydrology: including projects on e.g. lake Tanganyika and lake Ladoga as well as an EU project "Eurolakes" in which the most significant large lakes in Europe were studied.
- Dam safety
- Development of innovative measurement and research techniques within LUODE Consulting Ltd for spatial water quality monitoring.

He is an authority on the links between biological processes such as plankton bloom formation and hydrodynamics in lakes.

1.3.4. Bas Ibelings

Dr. Bas Ibelings is attached to the Netherlands Institute of Ecology (NIOO) and was previously employed at RIZA.

His research Interests comprise:

- Freshwater ecology

- Foodweb studies
- Toxic Algal Blooms
- Lake Restoration

He is an authority on cyanobacterial blooms and population dynamics of freshwater algae and has written numerous publications on these subjects.

2. Three scenarios

The World Health Organisation predicts that skin irritation and intestinal problems in swimmers will be limited if Chlorophyll-*a* levels from *Microcystis* are kept below 10 µg l^{-1} (Verspagen et al. 2005a). Also the water framework directive sets chlorophyll standards for water quality. For Dutch transitional waters (type O2) the standards for "very good" quality water are < 8 µg l^{-1} while water with chlorophyll contents of between 8 and 12 may get the qualification "GET" or "good" (Backx et al. 2006). In the current situation the system is qualified as a lake (M20). In these systems the standard for obtaining the "GET" qualification is 14,5 µg l^{-1}. The various scenarios have therefore been chosen to prevent algal blooms with Chl-*a* levels exceeding 12 µg l^{-1}.

2.1 Reduction of the nutrient load

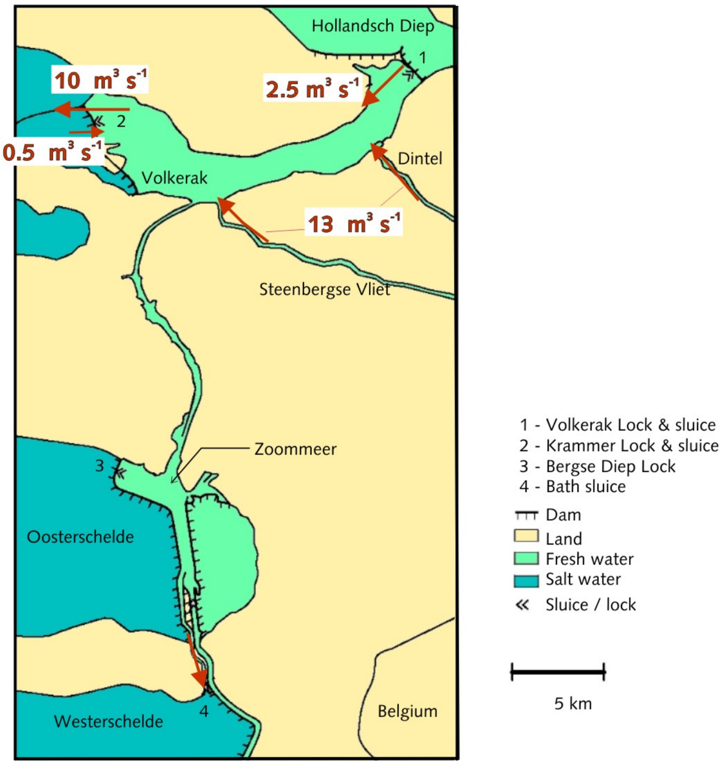
One of the management alternatives is to reduce the nutrient load in the area to levels where *Microcystis* cannot form such dense blooms, without drastically changing the water management. This alternative involves measures in the catchment area of the rivers of Brabant, preventing nutrients from entering the water or a relay of some of the small rivers. The inlet to the Hollandsch Diep is reduced, which also reduces nutrient transport into the Volkerak-Zoommeer.
Active management of fish stocks, specifically removing more bream and pikeperch from the area should promote clearer water. Increased use of helophyte filters should further reduce the nutrient concentrations, as well as the use of zebra mussels to remove phytoplankton.

As well as the inflow through the rivers of Brabant this reference scenario takes into account: an influx of 2.5 m^3 s^{-1} from the Hollandsch Diep through locking losses at the Volkerak locks. At the Krammer locks an outflow of 10 m^3 s^{-1} is taken into account through locking losses and an influx of 0.5 m^3 s^{-1} of saline water through leaking losses. Drainage of the excess of water takes place at the Bath sluices in the south of the area (Figure 2.1).

Three scenarios for nutrient reduction in the river of Brabant have been assessed:

- Stand-still scenario, in which nitrogen and phosphate remain constant with respect to the year 2000.
- Middle scenario: stand-still for phosphate and a 15% reduction of nitrogen levels with respect to the year 2000.
- Maximum scenario: maximum reduction based on maximum tolerable risk levels (MTR), unless concentrations are already below MTR levels. These levels are 0.15 mg l^{-1} for phosphate and 2.2 mg l^{-1} for nitrogen.

Figure 2.1
Current water balance in the Volkerak-Zoommeer



Similarly three scenarios for nutrient reduction in the Hollandsch Diep have been assessed:

- Stand-still scenario, in which nitrogen and phosphate levels are maintained with respect to the year 2000
- Middle scenario: A reduction of 36% for nitrogen and 18% for phosphate in the year 2015 with respect to the year 2000 according to the results of the Quick Scan Flux studies
- Maximum scenario: maximum reduction based on MTR levels, unless concentrations are already below MTR levels.

In the model calculations no nutrient reduction is enforced on waste water treatment plants and pumping plants that directly discharge onto the Volkerak-Zoommeer, since such a reduction would not contribute to the total load.

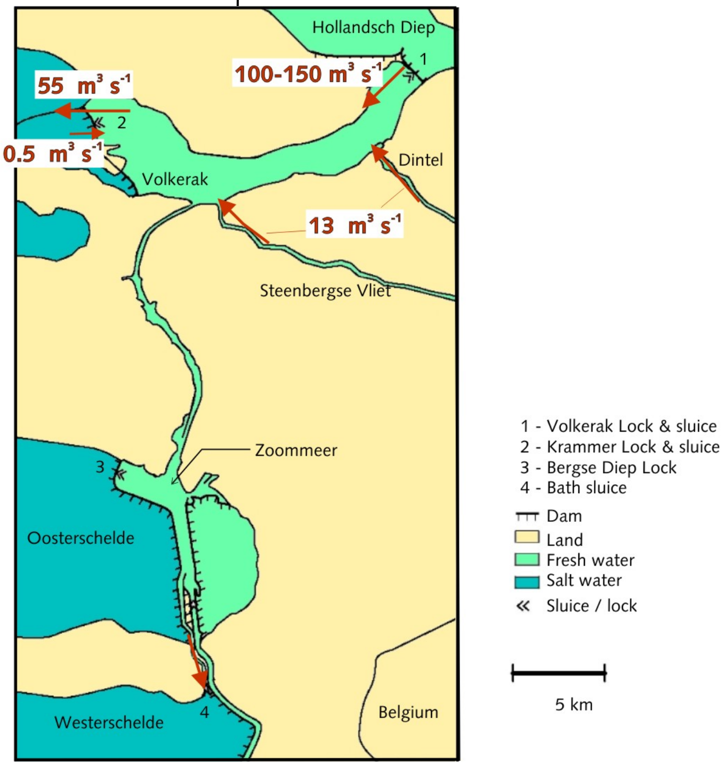
2.2 Flushing with fresh water

In this scenario, illustrated in figure 2.2 the retention time in the Volkerak-Zoommeer is drastically reduced by flushing the system with a large amount of fresh water from the Hollandsch Diep. In the summer period supply of fresh water is reduced in comparison to the winter period, because of limited availability. This option uses the possibility of an extra lock culvert in the Krammer locks. This allows an extra discharge of 55 m^3 s^{-1}, including a 9 m^3 s^{-1} daily average loss through regular locking losses.

The summer period is defined as the months June through to October. During this period only a limited amount of fresh water is available from the Hollandsch Diep that is assumed to equal 100 m^3 s^{-1}.There is also an influx of 0.5 m^3 s^{-1} of saline water by leaking losses through the

Krammer locks. In summer there is an additional supply of around 5 m^3 s^{-1} and at other times of the year 20 m^3 s^{-1} from the rivers of Brabant. The supply from the different rivers and the associated loads has been determined by a fixed ratio for the different contributors proportional to the average annual discharge. In the model input the maximum discharge capacity of the Bath sluices (125 m^3 s^{-1}) cannot be exceeded. As well as a simulation with 100 m^3 s^{-1} from the Hollandsch Diep, a calculation with 150 m^3 s^{-1} has been carried out, even though it has been established that such a large discharge is not available throughout the whole summer period.

Figure 2.2
Discharges in the scenario with freshwater flushing

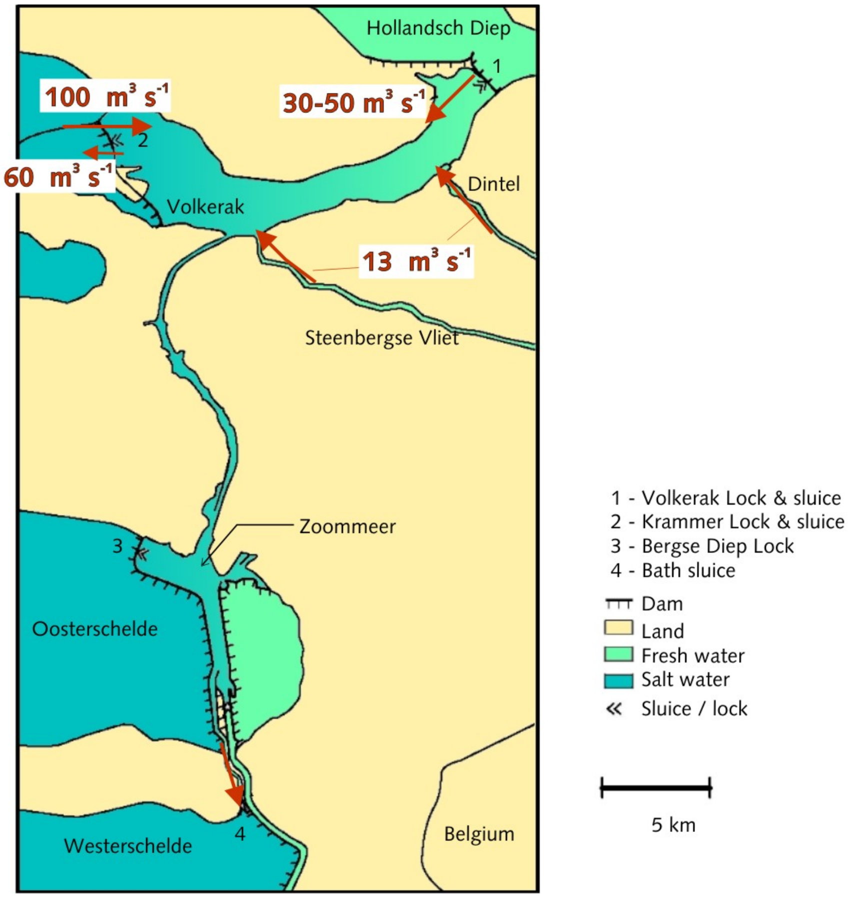


2.3 Flushing with saline water

Microcystis is reasonably tolerant of salt water, but cannot grow at higher chloride levels. Chloride levels of less than 5 g l^{-1} have little effect on the growth rate, but *Microcystis* dies off at chloride levels higher than 10 g l^{-1} (Peperzak 2003).

In the saline alternative (illustrated in figure 2.3) the Volkerak-Zoommeer is flushed with a large amount of salt water from the Oosterschelde. In this scenario a daily average intake of 100 m^3 s^{-1} saline water from the Oosterschelde is discharged through an inlet in the Philipsdam. The discharge from the Brabant rivers is variable. To counteract salt intrusion, the discharged water is temporarily stored and discharged daily at regular intervals. At the Volkerak locks a freshwater plug flow of 50 m^3 s^{-1} is created to counteract salt water intrusion in the Hollandsch Diep. Outflow through the inlet, including locking losses at the Krammer locks amounts to about 60 m^3 s^{-1}. Besides a small discharge via the Kreekrak locks (3 m^3 s^{-1}), the rest of the excess water is largely discharged via the sluices at Bath onto the Westerschelde. This also is limited by a maximum discharge capacity of a daily average of 125 m^3 s^{-1}. An additional simulation has been carried out for a situation where only 30 m^3 s^{-1} of water is let in through the Volkerak locks to counteract salt water intrusion in the Hollandsch Diep.

Figure 2.3
Discharges in the scenario with salt water flushing



3. Microcystis

Below follows a brief outline of the significant characteristics of *Microcystis* as well as the modelling studies carried out by the University of Amsterdam. More details can be found in appendix B.

3.1 Population dynamics

Microcystis is one of the most common species of freshwater cyanobacteria, particularly in eutrophic lakes. The cells are roughly spherical and they usually grow in colonies surrounded by a layer of mucus. Buoyancy of the colonies can be either positive or negative, depending on the recent light history. When mixing levels in the water are low and *Microcystis* concentrations are high, colonies can accumulate at the surface in so-called scums. *Microcystis* toxines can reach particularly high concentrations in these scums.

Growth starts in spring, generally when water temperatures exceed 15 °C and after the onset of thermal stratification. Pelagic *Microcystis* grow exponentially in early summer and reach a stationary phase in late summer. During this period this species can completely dominate the phytoplankton. Buoyancy gives them a better access to light and the increase of growth rate with temperature is stronger in *Microcystis* than in other species, giving them a competitive advantage.

From mid-July sedimentation of *Microcystis* colonies has been observed. Initially net sedimentation rates are low, but in autumn this increases, augmented by the breakdown of stratification. The sedimentation process may be influenced by two mechanisms:

- At lower temperatures growth is reduced. If photosynthesis is maintained a lot of excess carbohydrates can be produced, leading to a higher density.
- Colonies can attach to inorganic particles, increasing the average density of the colony. Inorganic particles are virtually absent from the water column during stratification, but can be resuspended during the autumn turnover.

Colonies that reach the bottom of the lake can stay there over the winter period. They can survive dark and even anoxic conditions. During winter the benthic population can be very large. This benthic store will serve the next spring to inoculate the lake. This large benthic inoculum may be an additional factor why *Microcystis* is such a dominant species.

Recruitment in spring can be either active or passive. Active recruitment occurs by changes of buoyancy through the reduction of stored carbohydrates. Passive recruitment occurs through resuspension by wind driven turbulence during the spring turnover.

3.2 Microcystis modelling

Two types of models have been developed by the department of Aquatic Microbiology from the University of Amsterdam that incorporate all the stages of the life cycle of *Microcystis*: a phenomenological model and a mechanistic model.

The phenomenological model is based on field monitoring data and aims to fit the description of the system to the observed dynamics. The mechanistic model aims to describe all the relevant processes and is based on field monitoring data and laboratory experiments. The latter can in theory be used to predict the impact of changes in conditions on the population dynamics. These models have been extensively described in the literature and an abbreviated version has been presented by Jolanda Verspagen at the workshop. The slides of this presentation have been attached to this report in appendix B.

3.2.1. Phenomenological model.

The details of the phenomenological model developed by Jolanda Verspagen et al is extensively described in chapter 4 of her PhD thesis (Verspagen 2006). The slides of this presentation are attached as an appendix to this report. Field observations suggest that after sedimentation there is significant horizontal transport from shallow parts of the lake to deeper parts. Model simulations suggest that the absence of benthic recruitment would reduce the bloom in summer by 50%. Absence of the small pelagic population in winter would reduce the summer bloom by 64%. Reduction of overwintering populations e.g. by flushing may work as a strategy to suppress or delay the dense summer blooms.

3.2.2. Mechanistic model

Details of this modelling tool have been described in chapter 5 of the PhD thesis of Jolanda Verspagen and other scientific papers (Verspagen et al. 2005b; Verspagen 2006). The basis for this model are 2 years of monitoring data from the benthic and the pelagic populations of *Microcystis* in the Volkerak-Zoommeer. Additionally field samples of *Microcystis* were incubated in the laboratory to assess growth and mortality rates as a function of light regime, temperature and salinity. Recruitment and sedimentation rates have been determined in the lake. The model predicts that flushing with freshwater will suppress *Microcystis* blooms, provided that the flushing rate is sufficiently high. Also introducing saline water into the system will reduce *Microcystis* blooms.

4.2D and 3D modelling

An extensive description (in Dutch) of the model studies performed by Delft hydraulics can be found in (Boderie et al. 2006). A comprehensive summary of the model environment has been presented at the workshop by Hans Los and of the model results by Simon Groot. The slides of this presentation have been attached to this report in appendix B.

Both the 2D and the 3D models of the Volkerak-Zoommeer have been developed with the software package Delft3D, an integrated modelling environment in which water flow, sediment transport, waves, water quality, geomorphological development and ecology can be simulated in separate modules.

Microcystis population dynamics have been incorporated into these models in two different ways:

- Using the mechanistic *Microcystis*-model developed by the UvA as a basis. This approach allows a dynamical forcing of different processes that regulate the growth and dispersal of *Microcystis*, such as transport, light intensity, salinity and temperature. Due to computational limitations this model can only be used in the 2D calculations, limiting the application to the reference situation and the scenario with freshwater flushing.
- Using the pre-existing DBS model DELWAQ-BLOOM-SWITCH. This module calculates primary production of four groups of algae, including *Microcystis*, based on annual changes in water movement and nutrient loads. This model provides insight into the responses of the (blue-green) algae to varying nutrient concentrations, light intensities, temperatures, salinities, as well as competition for resources with other algae and an enforced grazing pressure by zooplankton and benthic filter feeders. This model can run both in 2D and 3D and can therefore be used for all three types of scenarios.

4.1 Model results reference situation

At present the Volkerak-Zoommeer is a system with a relatively long water retention time that can amount to 100 days. Algal blooms have therefore ample time to produce very high biomass levels, leading to an exceeding of standards and complaints about stench. Currently the Volkerak-Zoommeer is a severely eutrophicated system where nutrients are not limiting for algal growth. Reduction of nutrient sources to MTR-levels have a positive effect, but this is not sufficient to prevent the occurrence of a bloom of blue-green algae.

Source sanitation, e.g. by disconnecting the Brabant rivers (a.k.a. hydrological isolation), has an important positive effect on the concentrations of nutrients, chlorophyll and (blue-green)algae. This will cause the chlorophyll levels within the Zoommeer to halve in the reference situation. However, to maintain the water level, it is necessary to take in water from the Hollandsch Diep, thereby increasing the nutrient load again. A side effect of the disconnection of the Brabant rivers is the increase of salinity to an order of magnitude of 1000 mg l^{-1}, by the limited influx of freshwater. This is caused primarily by the leaking losses at the Krammer locks. To maintain an agreed salinity of 450 mg l^{-1} Cl^{-}, even more water from the Hollands Diep will have to be taken in. Although no calculation has been made of the disconnection of the Brabant rivers combined with the sanitation of all other sources to MTR-level little effect is expected from such measures, as the most important nutrient source, the Hollandsch Diep, currently has phosphate levels close to MTR levels.

4.2 Model results on the freshwater option.

In all the model runs with freshwater flushing the retention time in the Volkerak-Zoommeer is reduced to about five weeks. This leaves the blue-green algae in the Zoommeer still with sufficient time to realise a substantial bloom. The water body remains eutrophicated, partially because of the very large influx of eutrophicated water from the Hollandsch Diep. Available nutrient levels will not be limiting, although a reduction in biomass is achieved through the reduction in retention time. Source sanitation, even a reduction down to MTR-levels, has no effect on the biomass because the influx from the Hollandsch Diep ensures that nutrient levels will not be limiting. The water supply will therefore ensure a larger flow–through of the water system, but cannot flush out the algae altogether. Due to the high nutrient load of the Hollandsch Diep, flushing the system is not equivalent to cleaning the system. For this freshwater flushing a large amount of water is needed from the Hollandsch Diep. Further analysis of availability of water indicated that such a supply hardly ever be achieved during the summer months, certainly not in the scenario where 150 m^3 s^{-1} is flushed through the system. The Delft hydraulics models indicate that the freshwater scenarios will not provide a practical solution for the blue-green algae blooms.

4.3 Model results of the saline option

As in the freshwater option, the retention time in the system is reduced to about five weeks. Because the water system is flushed with (more) saline water from the Oosterschelde, a fairly saline system is created where *Microcystis* cannot grow. However, this role will be taken over by non-toxic marine species with ample time and nutrients to grow. Consequently a reduction of algal biomass is expected. Nutrients will be imported predominantly through the Hollandsch Diep and the Brabant rivers. Due to the lower nutrient load of the salt water that is available for flushing, this scenario is more effective in reducing algal growth and biomass than the freshwater option. However, also in this scenario algal growth will still be substantial. Large-scale problems with excessive growth of “sea lettuce” *Ulva* are not expected, although local blooms of this species may occur in certain shallow parts of the system. Increases in seagrass meadows are also not expected to be substantial.

Although model calculations without grazing indicate that in a salt water system algal biomass can still accumulate to significant levels, in practice grazing by benthic filter feeders, such as mussels, will reduce the marine phytoplankton concentrations. Based on grazing rates found in the Veerse Meer, chlorophyll concentrations will reduce to levels around the water framework directive standard "GET" of between 8 and 12 µg l^{-1}. However, the duration of the transition period from the present freshwater system to a fully developed marine environment is difficult to establish.

A few other saline scenarios with a slightly larger (although still very limited) tidal amplitude have been calculated. The tidal dynamics cause a larger exchange between the Oosterschelde and the Volkerak-Zoommeer. The associated fluctuations in water level will often be only a few centimetres away from the upper and lower limits of water levels in the interim water level directive. Nutrient concentrations, chlorophyll concentrations and levels of algal biomass of marine phytoplankton in this weak tidal regime deviate only slightly from the previously described scenario.

The conclusion of the Delft-Hydraulics modelling is that any saline option will be effective in combating the blooms of blue-green algae in the Volkerak-Zoommeer. The associated non-toxic marine phytoplankton assemblage will probably eventually reach levels below the WHO standards, as soon as grazing by benthic suspension feeders such as shellfish is sufficiently developed. The duration of the transition period is unknown but will likely encompass several years. Disconnecting loads through the Brabant rivers has a positive effect on the nutrient concentrations, but contributes little to a reduction in biomass of non-toxic marine algal species.

5. Evaluation external experts

The workshop evaluating the model results took place over 2 days (12 and 13 October 2006). The first day included a visit to the area to acquaint all participants with the area. Part of the presentations were held at the Rijkswaterstaat building at the Krammer locks.

Figure 5.1
Visit to the Volkerak locks and sluices. By coincidence the committee could witness a test discharge at maximum capacity at the sluices.

During the first day a presentation was given to introduce the area and the *Microcystis* problem (Full presentation attached in Appendix A). Subsequently, the work of the University of Amsterdam was discussed on the biological parameters and modelling of *Microcystis* population dynamics (Appendix B). Finally, Delft Hydraulics showed how this knowledge was incorporated into the Delft 3D models and the model results of the freshwater scenario were shown and discussed (Appendix C). On the second day details of the Delft 3D modelling environment were explained as well as important issues specific to the Volkerak-Zoommeer parameterisation (Appendix D). Subsequently the model results, specifically those of the saline scenario were presented (Appendix E). The discussion subsequently focussed on the possible risks of the saline scenario and which components of the modelling could be improved.

The report below is loosely chronological, but mainly organised per topic.

5.1 Choice of scenario

5.1.1. Nutrient reduction

It was clear to the whole committee that any scenario entirely geared towards nutrient reduction and without significant changes in water management is not going to have a significant impact on the *Microcystis* population. Currently, the system is light limited and realistic reductions in nutrient availability will not change that. Any nutrient reduction is positive and in particular efforts to reduce the extremely high nutrient load in the run-off from agricultural areas draining into the rivers of Brabant may contribute to the effects of other scenarios. However, a reduction to levels where the growth of *Microcystis* becomes nutrient limited is not feasible. Even if the rivers of Brabant can be hydrologically isolated, the Hollandsch Diep, supplied with water from the rivers Rhine and Meuse, still carries a very significant nutrient load. This not only originates from the Netherlands but also from areas beyond Dutch control.

Any effective scenario to reduce algal growth clearly has to involve some mechanism of reducing the long water retention time in the system.

5.1.2. Freshwater flushing

The 0D model from the University of Amsterdam indicated that either continuous flushing with 75 m^3 s^{-1}, or a summer flushing rate of 65 m^3 s^{-1} and a winter flushing rate of 125 m^3 s^{-1} would just be sufficient to reduce *Microcystis* down to acceptable levels. According to René Boeters this amount of freshwater influx from the Hollandsch Diep cannot always be guaranteed. There is a risk of salt water intrusion through the Rhine outflow at Rotterdam which would compromise fresh water supply for several towns in the province of Zuid Holland. There is already a problem with salt intrusion. In dry summers (such as e.g. 1990) there may occasionally be as little as 30 m^3 s^{-1} available for flushing without compromising fresh water supplies. For a scenario where the system is flushed with 100 m^3 s^{-1} there is enough water available in summer around 50% of the time. For a scenario with 150 m^3 s^{-1} only 20% of the time during summer will there be sufficient water available.

The 0D model however, does not take the morphology of the system into account. It assumes a complete mixing and an equal flushing rate throughout the system. The 2D model from Delft Hydraulics using the 0D model from the University of Amsterdam to parameterise the wax and wane of *Microcystis* showed that the morphology of the Volkerak forces the bulk of the water to flow rapidly through the channel, directly into the Krammer, while a large part of the shallow areas in the western part of Volkerak is less effectively flushed. Even at a flushing rate of 150 m^3 s^{-1} this would still result in residence times that allow high concentrations of *Microcystis* to build up in large parts of the Volkerak-Zoommeer (Figures 5.2 and 5.3).

Figure 5.2
2D model results from Delft-3D. Water residence times (days) in the system with a fresh water flushing rate of 150 $m^3 s^{-1}$.

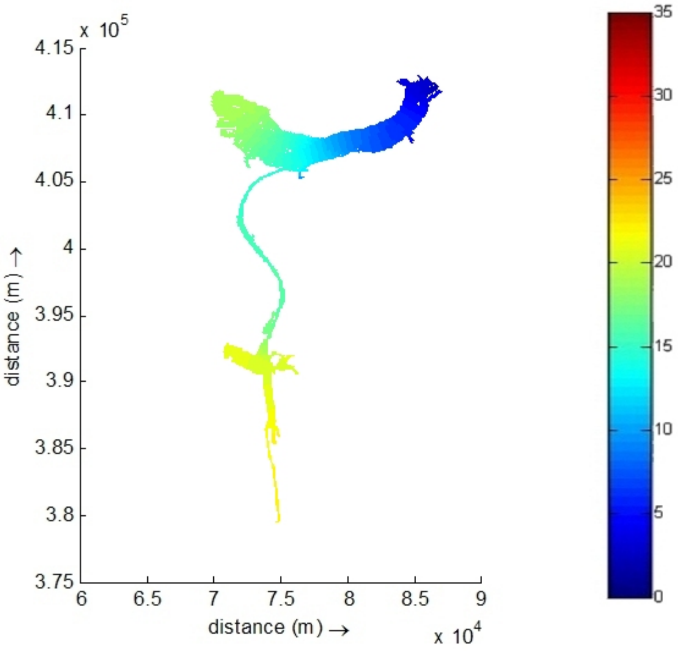
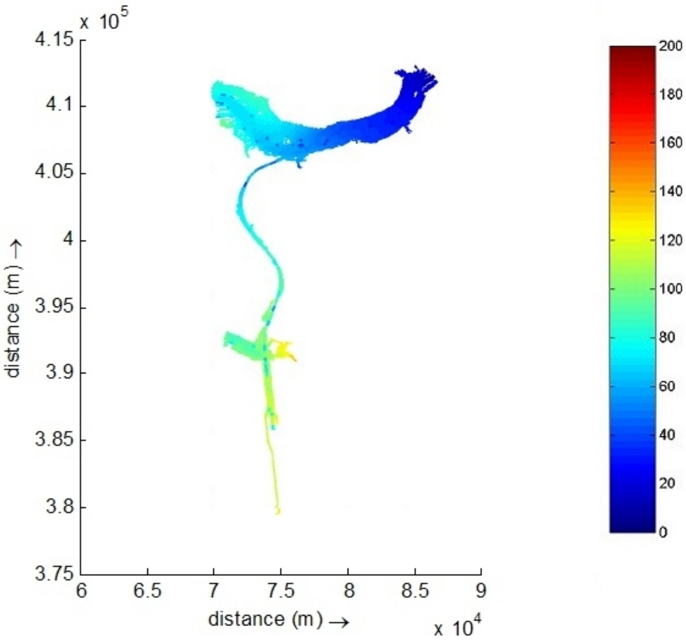


Figure 5.3
2D model results from Delft-3D showing the algal concentration (µg Chl*a* l^{-1}) in the Volkerak-Zoommeer if the system is flushed with freshwater at a rate of 150 m^3s^{-1}. Note that the colour coding in this figure goes up to 200 µg Chl*a* l^{-1}, while *Microcystis*-levels of more than 10 µg Chl*a* l^{-1} can already cause health problems, Verspagen et al. 2005a.



Other freshwater flushing scenarios where part of the freshwater is discharged through the Krammer locks, would result in a slightly better flushing of the western part of the Volkerak, but a much higher retention time in the Krammer and the Zoommeer.

In certain (stratified) lakes measures to increase mixing can be effective to reduce blue-green algal growth. The Volkerak system is for the most part too shallow for this and in most places it is already fully mixed. Therefore this strategy is unlikely to work here.

Biomanipulation (removing fish species such as bream from the lake) was also suggested as an option. This has worked in a few systems, both in Finland and in the Netherlands but it requires constant maintenance, otherwise the system will quickly “flip back” to the algae dominated state. Due to the size of the system and the high nutrient import biomanipulation is not likely to be successful in Lake Volkerak.

5.1.3. Flushing with salt water

As the other two types of scenario are unlikely to be successful in eradicating the blue-green algae from the system, the committee agreed that flushing with salt water is the only type of scenario where the *Microcystis* problem would be effectively reduced to acceptable proportions.
The *Microcystis* assemblage in the system consists for the most part of *Microcystis aeruginosa*, although there are probably different strains present in the system. Although salt tolerance can vary among strains, all *Microcystis* should disappear completely at salinities higher than 17‰. The question was raised if this salinity can be achieved throughout the system without significant salt intrusion. According to the models this should be possible, certainly in summer when rain fall is low. At other times of the year the eastern part may be slightly less, down to 15‰. However, this should still be sufficient to reduce the *Microcystis* below nuisance levels.

A number of different saline flushing scenarios with different discharge rates have been assessed. In all feasible options the retention time in the system is still relatively high, particularly in the Zoommeer area. During the meeting a scenario was suggested with an extra saline exchange between the Oosterschelde and the Zoommeer. This would significantly reduce the retention time in that area. This scenario should be investigated with the Delft 3D model.

5.2 Risk of introduction of toxic Marine algae

Toxic algae not only occur in fresh water. Making the system saline may involve introducing problems into the area with marine species. The two groups that are most likely to cause problems are 1) other, more salt tolerant blue-green algae and 2) species from the group of the raphidophytes.

5.2.1. Other blue-green algae

There are a number of typical brackish water species that are likely to be able to survive in a saline Volkerak-Zoommeer system. The most likely species to be introduced here is *Anabaena*. *Aphanizomenon* is a species that is also a potential risk for the area, and is already present in the system. Both *Anabaena* and *Aphnizomenon* can produce toxins, although not all strains are hazardous (Heinis 1994). *Aphanizomenon* occurs in the Baltic up to salinities of 7 psu. Another risk is posed by the possible introduction of *Nodularia*. This species can be very toxic and regularly causes major bloom problems in the northern Baltic Sea. In principle this species should be able to grow under the salinities that can be expected. However, for unknown reasons it has until now been restricted to the Baltic area. In the Baltic *Nodularia* is a dominant species at salinities of 5-6 ppt. (Kauppila and Lepistö 2001). At lower salinities other species (such as *Anabaena*) become dominant. As the Volkerak-Zoommeer system will reach a salinity of more than 15 ppt, *Anabaena* is therefore not likely to become a problem.

It was also noted that if a combination of reducing retention times by salt water flushing and a reduction of nutrient input from the surrounding area results a nutrient limited status, *Anabaena, Aphanizomenon* and *Nodularia* could start to act as nitrogen fixers. This would be an extra source of nutrients into the system and deserves some attention from the modellers. However, due to the fact that the N:P ratio in the area is likely to become skewed towards phosphorus (>>16), nitrogen fixation is perhaps not very likely.

5.2.2. Raphidophytes

Raphidophytes form a small group of marine algae that have only recently been identified in Dutch waters. They were likely introduced in the late eighties via ballast water. In coastal waters two species appear to increase rapidly since the late nineties: *Heterosigma akashiwo* and *Fibrocapsa japonica*. In Japan these species regularly cause massive fish kills, but in Dutch waters they have thus far not caused any significant damage (van Duren 2006). However, due to their recent introduction it is difficult to predict if future damage is likely or not. Of the two, *Fibrocapsa* is capable of doing relatively well in turbid water with a high nutrient load. It does not grow well at salinities below 20, so in eastern parts of the system it is not likely to be a problem. However in the more saline western part it may find a suitable habitat. As not very much is known about their ecology and requirements these species should be well monitored.

5.3 Algal biomass in a saline system

Although flushing with salt water is a fairly certain way to eradicate *Microcystis* from the system, the nutrient concentrations in the area are likely to be high enough to support a high algal biomass. Benthic filter feeders can be very effective in removing a large proportion of this biomass. One square metre of a bed of blue mussels (*Mytilus edulis*) is capable of filtering several cubic metres per hour (Prins et al. 1996). However, in recent years settlement of mussel larvae in the Oosterschelde has been extremely low. The only significant settlement took place in 2001 and the beds that formed have since disappeared. One species that has good recruitment in the Oosterschelde is the Pacific Oyster (*Crassostrea gigas*). This is an aggressive invasive species that was introduced to the Oosterschelde after stocks of local oysters collapsed in 1963. Many people see this species as a nuisance and there are currently plans under development to eradicate the species from the Oosterschelde.

The Veerse Meer has been quoted as the most appropriate reference system for the Volkerak-Zoommeer. This area was a closed off brackish lake from the late eighties until 2004. The first years after closure of the system the benthic filter feeders were capable of keeping this system relatively clear. Over time stratification of the system increased. The top layer became much less saline and the bottom often became anoxic. From 2002 onwards the top layer was characterised by very high concentration of small (mainly unidentified) flagellates. Simultaneously, the population of benthic filter feeders collapsed. Whether or not there is a causal relationship between the occurrence of the microalgae and the collapse of the mussels, or whether both are related to the low salinity in the upper layers is not known. To prevent a similar situation arising in the Volkerak-Zoommeer, a model organism representing the microflagellates should be defined in the Delft 3D models to ascertain how these are likely to behave. Since 2004 the situation in the Veerse Meer has improved dramatically since exchange at the Zandkreek was restored.

The decline of the filter feeders was likely due to anoxia in the very strongly stratified water. Some extra attention should be paid to ascertain how enough dynamics in the system can prevent the occurrence of anoxia.
It may be possible to actively introduce mussels to the system to promote clear water. The EU project MaBenE (contract n° EVK3-CT-2002-00071) has developed various coupled hydrodynamical-biological models describing the interaction between filter feeders and the surrounding water. Long line cultures (mussels suspended from ropes) may be particularly effective at preventing the build-up of high biomass in the surface layers.

5.4 Simplifications in the model

5.4.1. Benthic-pelagic exchange of Microcystis

According to the research of Jolanda Verspagen, the sediment contains a significant part of the total the *Microcystis* biomass. Therefore the exchange of biomass between sediments and water may influence the dynamics in the water column. However, the model calculations presented by Pascal Boderie indicate that this process will not affect conclusions regarding the question whether sufficient fresh water is available to eradicate *Microcystis*-problems from the system in the studied scenarios. Hydrodynamic aspects appear to be more important.

5.4.2. Nutrient exchange at the sediment water interface

The phosphorus dynamics in the deeper layers were identified as potentially important. At present the nutrient dynamics at the bed are modelled using a mass-balance approach. This is quite a simplification from the actual processes that take place at the sediment water interface. The only way to model these PO_4-fluxes accurately is on the basis of the gradients at the bed.

This part of the model was identified as an area where there is some room for improvement. For scenarios that strongly reduce the residence time in the system (either by flushing with freshwater or with saline water) this will probably not strongly affect the results. However, for calculations on scenarios where nutrient reduction is important, accurate process modelling in biogeochemistry can improve the models.

5.4.3. Buoyancy effects

Very subtle effects, such as micro-stratification, have also not been taken into account. Also at present buoyancy of the cyanobacteria is taken as a fixed characteristic, while in reality this can be regulated by the cell. This may be a modifying factor regarding scum formation. There are facilities in the model environment to build in buoyancy regulation. This was in general not seen as an issue of high priority. For scenarios with artificial mixing these processes need to be accurately modelled. For the suggested scenarios in the Volkerak-Zoommeer it is less relevant.

5.4.4. Spatial heterogeneity

For the saline scenario, the model predicts significant gradients in salinity (horizontal as well as vertical). Particularly if this is associated with gradients in nutrients and different grazing pressures, it is likely that this will eventually result in a heterogeneous species composition. This is another area where the model can be refined. The algae will flush with the body of water in which they are suspended. There may be differences in horizontal flow velocity between different layers of water. If changes in buoyancy result in algae ending up in a different layer, this may eventually affect their distribution.

6. Conclusions and recommendations

6.1 Main conclusions and recommendations

6.1.1. Scenario choice

The model simulations conclude:

- Nutrient reduction alone (within feasible limits) is unlikely to reduce *Microcystis*
- Freshwater flushing is not really an option to get rid of *Microcystis* comprehensively, on top of that there is probably not enough water available
- Making the area saline is feasible and would get rid of *Microcystis*

The reviewers support the model approach. The combination of 2D/3D modelling of hydrodynamics in combination with algal growth modelling are state-of-the-art and adequate for this purpose. Although there are a few uncertainties the conclusions appear justified. The committee concludes that the saline option is the only scenario that is capable of eradicating Microcystis from the system.

6.1.2. Recommendations regarding the management scenario

The committee has identified that the current situation and the management option of introducing salt water into the Volkerak-Zoommeer comprises three problems that need to be addressed:

- Toxic *Microcystis* blooms are currently the status quo
- Making the system saline solves the *Microcystis* problem, but may provide a habitat for noxious saline species
- Prolonged periods of strong stratification and low salinity in the top layer may lead to high concentrations of micro-algae that cannot be grazed down by benthic filter feeders.

The committee recommends a combination of:

- **Making the system saline**
- **Flushing**
- **Making the system as dynamic as possible.**

This strategy should offer the best chance of eradicating all three problems.

6.1.3. Recommendation regarding monitoring

Regardless of the ultimate choice of management system, the committee strongly recommends the setup of an appropriate monitoring system.

The recommendation of a monitoring system has two purposes. Firstly, this allows an evaluation of the processes, so lessons can be learned for the future. Secondly, this will provide an early warning system for the occurrence of possible nuisance species. The monitoring should include sufficient stations to provide comprehensive information on the system and it also should take place at a sufficiently high frequency. The modellers should be involved in setting up an efficient monitoring programme as they can provide information on which sites are likely to give the most important and useful information and what minimum sampling frequencies are required.

6.2 Assessment of uncertainties

6.2.1. Is it likely that a large and effective grazer population will develop in Volkerak-Zoommeer?

Due to limited recruitment it is debatable that mussels (*Mytilus edulis*) will settle naturally in the area. Pacific Oysters (*Crassostrea gigas*) will possibly settle, but they are a nuisance species and it is undesirable to promote these. *Mya arenaria* may settle, but it is uncertain how quickly a population will establish that is sufficiently large to have an impact on the algal biomass in the system. In Lake Veere this species is not capable of grazing down the algal biomass efficiently enough.

Further attention needs to be paid to this and possible measures to actively introduce mussels to the area ought to be investigated.

6.2.2. How likely is it that we get toxic marine or brackish water species such as Fibrocapsa and Nodularia?

The risk of introducing species such as *Anabaena*, *Aphanizomenon* and *Nodularia* needs further investigation with models.

The risk of introducing species such as Raphidophytes is significant. *Fibrocapsa* and *Heterosigma* are present in Dutch coastal waters and the circumstances that are likely to occur in a saline Volkerak-Zoommeer seem suitable for these species. However, strong blooms and damage have until now not occurred in Dutch waters.

A good monitoring programme with sample stations at various locations should be in place to provide an early warning system for these algae.

6.2.3. Is the PO_4-flux to/from sediment going to influence the outcome?

The present model is unbalanced in the sense that phytoplankton is modelled in great detail, based on proper process description, while the sediment interaction with respect to phosphorus is highly simplified

It is unlikely that this will affect the results with respect to the suggested scenarios (flushing and salt water introduction). However, phosphate-reduction scenarios would be sensitive to this.

6.3 Additional recommendations and remarks

- *Aphanizomenon* and *Anabaena* should be specifically included in the model
- Microflagellates ought to be included. Although this is in reality a whole assembly of different (largely unidentified) species, in the model one species can be defined with characteristics similar to those that caused problems in Lake Veere a few years ago.
- Salt toleration of phytoplankton needs to be better defined in the models. This possibly needs further measurements, as this is only characterised in a few species.
- An extra inlet from the Oosterschelde to into the Zoommeer to reduce the retention time in this part of the system should be studied as a scenario.
- Very dynamic fluctuations in salt are likely to reduce the probability of introducing noxious species into the system. However, extremely high dynamics may also cause other water management problems for the area.

7. Literature

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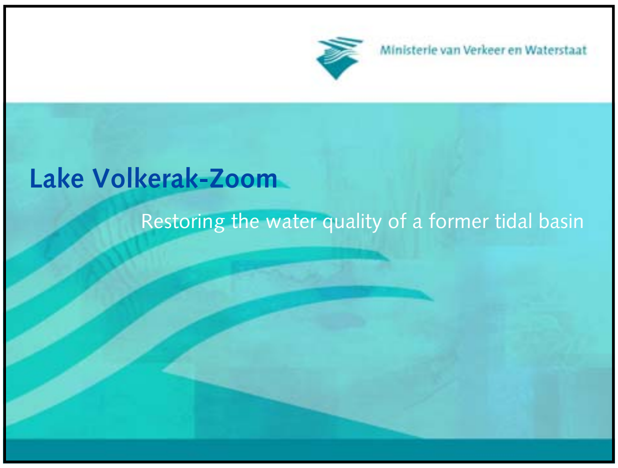
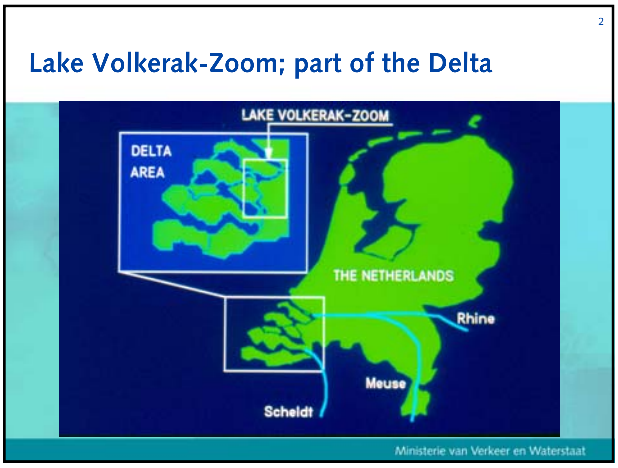
Appendix A: Presentation René Boeters (RWS)


Ministerie van Verkeer en Waterstaat

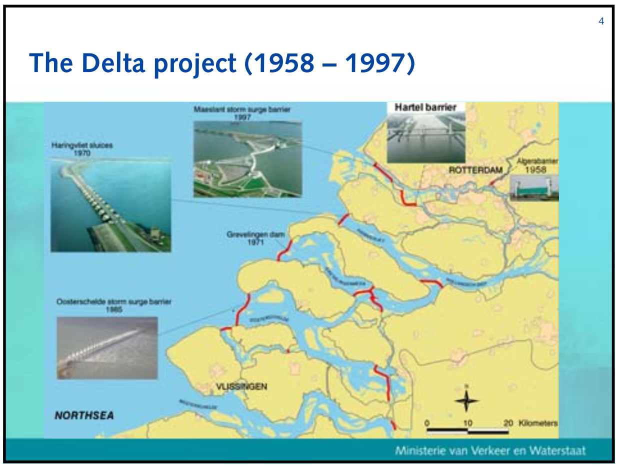
Lake Volkerak-Zoom

Restoring the water quality of a former tidal basin



Lake Volkerak-Zoom; part of the Delta

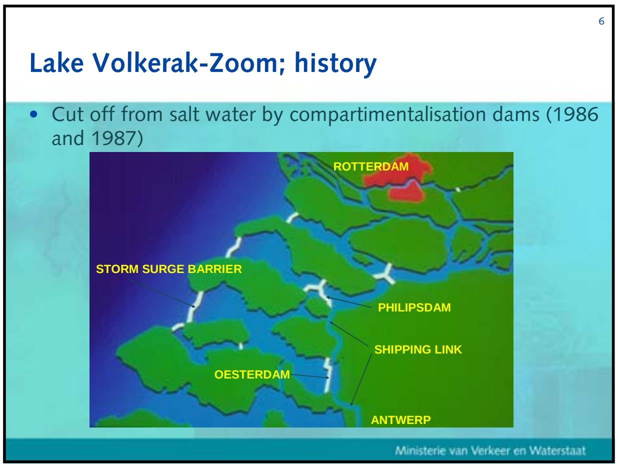
The 1953 flood disaster



The Delta project (1958 – 1997)

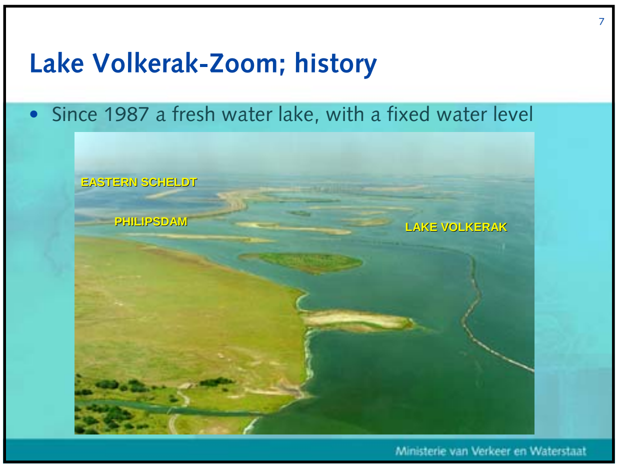
Lake Volkerak-Zoom; history

- Result of the Delta project (1958 – 1997)



Lake Volkerak-Zoom; history

- Cut off from salt water by compartimentalisation dams (1986 and 1987)



Lake Volkerak-Zoom; history

- Since 1987 a fresh water lake, with a fixed water level

Lake Volkerak-Zoom; water quality

- Short term target (2010): clear fresh water basin, with submerged vegetation and shallow vegetated foreshores

Lake Volkerak-Zoom; water quality

- Long term target (2030): self regulating, sustainable water system

Lake Volkerak-Zoom; water quality

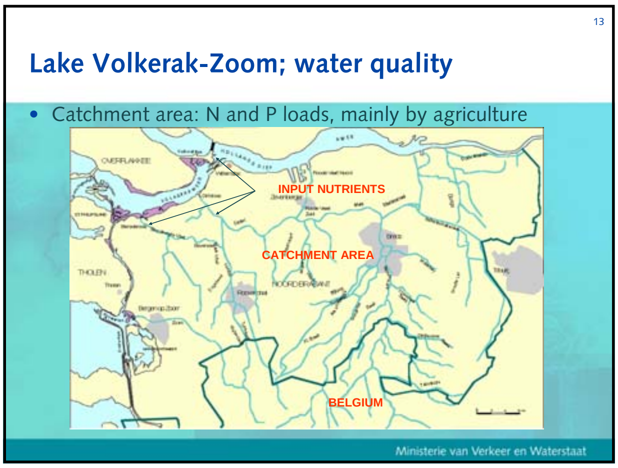
- Since 1994: increasing bloom of blue-green algae

Lake Volkerak-Zoom; water quality

- Since 1994: increasing bloom of blue-green algae

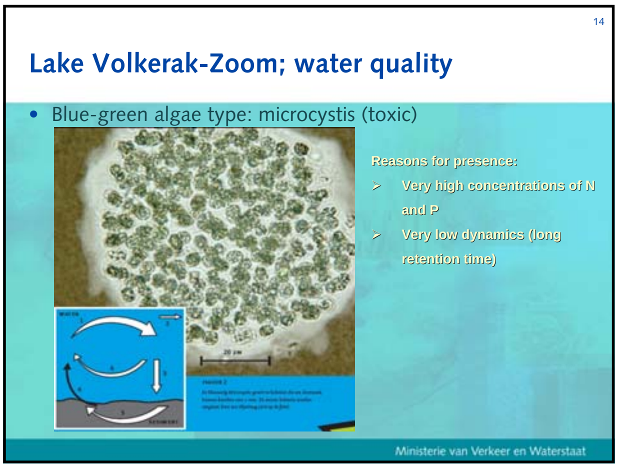
Lake Volkerak-Zoom; water quality

- 2002: large number of dead birds



Lake Volkerak-Zoom; water quality

- Catchment area: N and P loads, mainly by agriculture

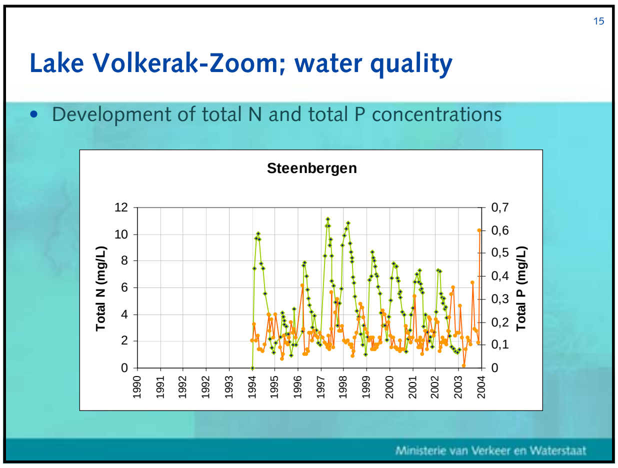


Lake Volkerak-Zoom; water quality

- Blue-green algae type: microcystis (toxic)

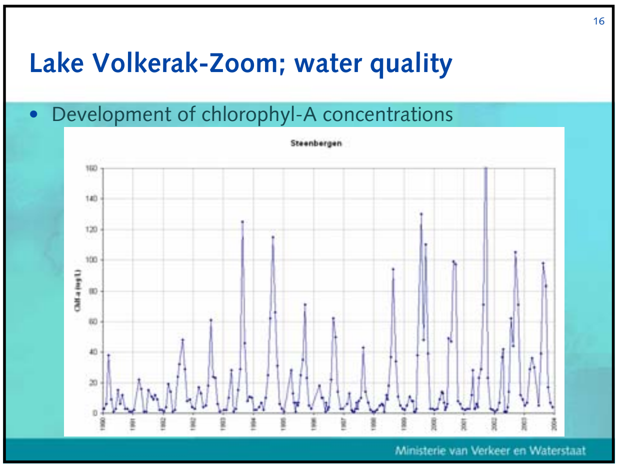
Reasons for presence:

- Very high concentrations of N and P
- Very low dynamics (long retention time)



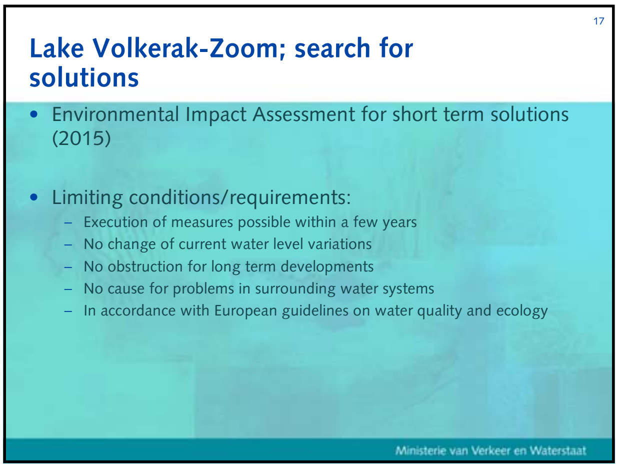
Lake Volkerak-Zoom; water quality

- Development of total N and total P concentrations



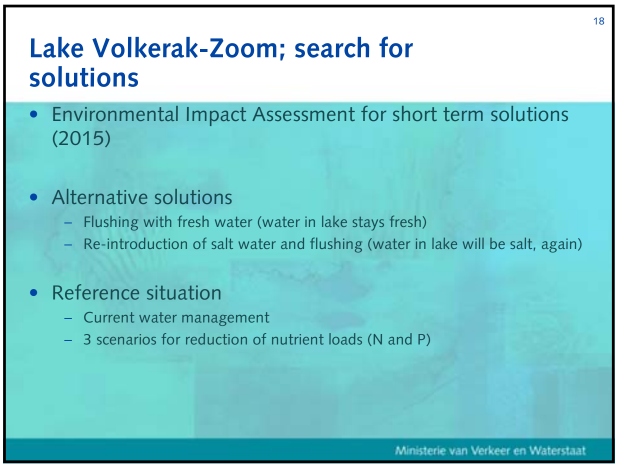
Lake Volkerak-Zoom; water quality

- Development of chlorophyl-A concentrations



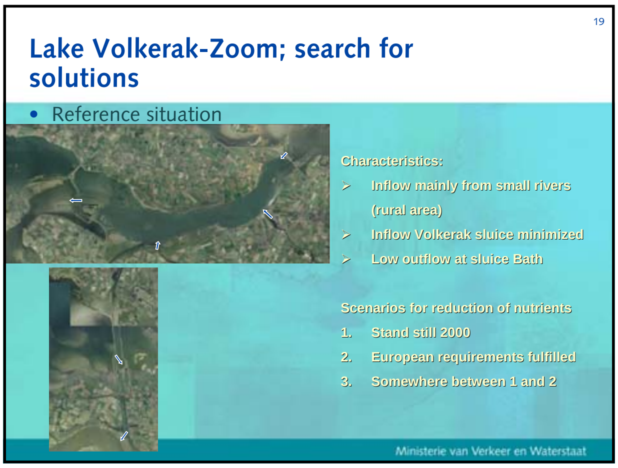
Lake Volkerak-Zoom; search for solutions

- Environmental Impact Assessment for short term solutions (2015)
- Limiting conditions/requirements:
  - Execution of measures possible within a few years
  - No change of current water level variations
  - No obstruction for long term developments
  - No cause for problems in surrounding water systems
  - In accordance with European guidelines on water quality and ecology



Lake Volkerak-Zoom; search for solutions

- Environmental Impact Assessment for short term solutions (2015)
- Alternative solutions
  - Flushing with fresh water (water in lake stays fresh)
  - Re-introduction of salt water and flushing (water in lake will be salt, again)
- Reference situation
  - Current water management
  - 3 scenarios for reduction of nutrient loads (N and P)



Lake Volkerak-Zoom; search for solutions

- Reference situation

Characteristics:

- Inflow mainly from small rivers (rural area)
- Inflow Volkerak sluice minimized
- Low outflow at sluice Bath

Scenarios for reduction of nutrients

1. Stand still 2000
2. European requirements fulfilled
3. Somewhere between 1 and 2

Lake Volkerak-Zoom

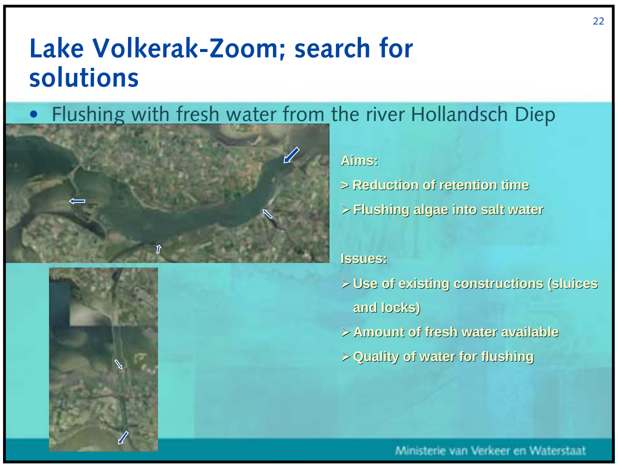
- Upper part

Lake Volkerak-Zoom

- Sluices

Volkerak sluice and navigation locks (in)

Sluice Bath (out)



Lake Volkerak-Zoom; search for solutions

- Flushing with fresh water from the river Hollandsch Diep

Aims:

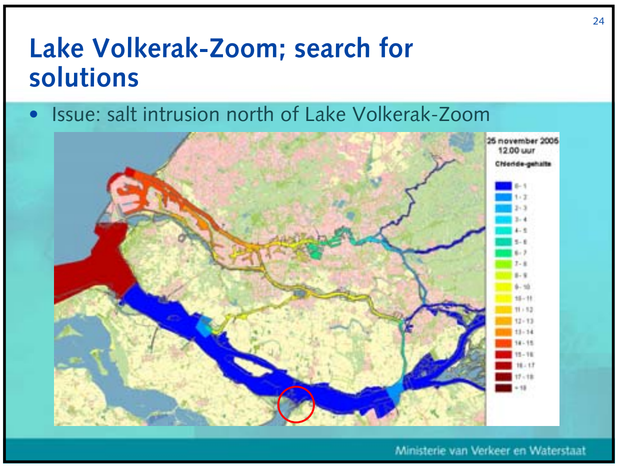
- Reduction of retention time
- Flushing algae into salt water

Issues:

- Use of existing constructions (sluices and locks)
- Amount of fresh water available
- Quality of water for flushing

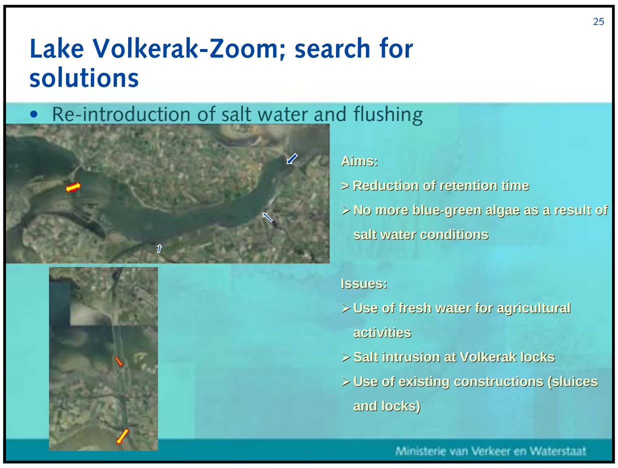
Lake Volkerak-Zoom; search for solutions

- Krammer locks: possible outflow channel



Lake Volkerak-Zoom; search for solutions

- Issue: salt intrusion north of Lake Volkerak-Zoom

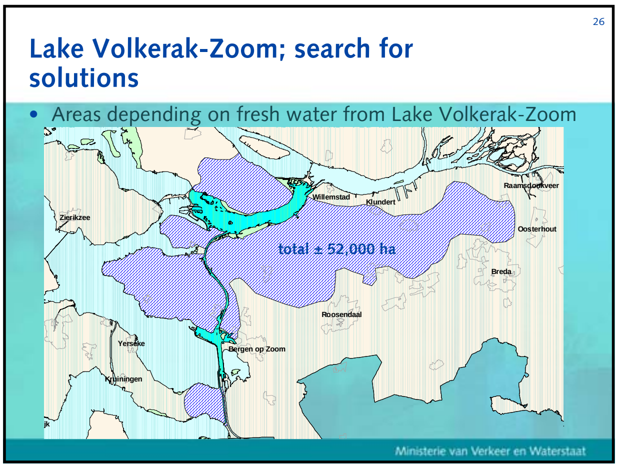


Lake Volkerak-Zoom; search for solutions

- Re-introduction of salt water and flushing

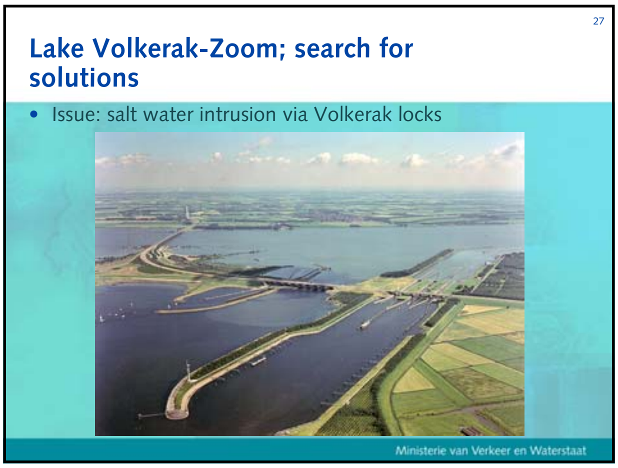
Aims:
- Reduction of retention time
- No more blue-green algae as a result of salt water conditions

Issues:
- Use of fresh water for agricultural activities
- Salt intrusion at Volkerak locks
- Use of existing constructions (sluices and locks)



Lake Volkerak-Zoom; search for solutions

- Areas depending on fresh water from Lake Volkerak-Zoom



Lake Volkerak-Zoom; search for solutions

- Issue: salt water intrusion via Volkerak locks

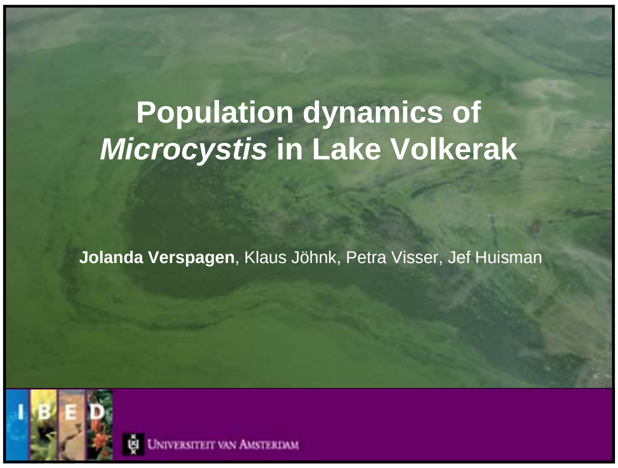
Lake Volkerak-Zoom; search for solutions

- Issue: use of existing constructions

Lake Volkerak-Zoom; search for solutions

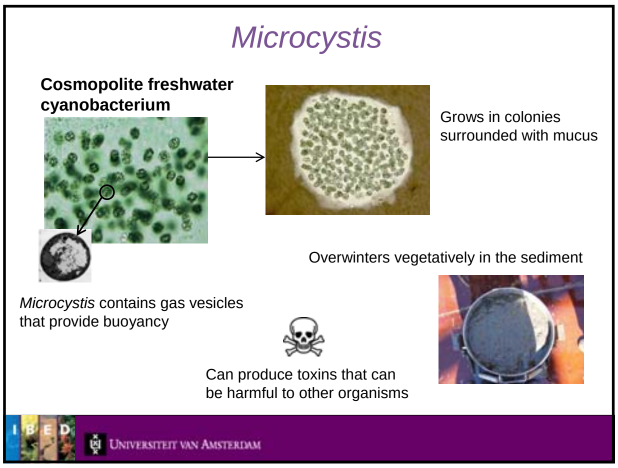
- Reasons for a second opinion
  - Model results point out that a solution in which Lake Volkerak-Zoom stays fresh, will not solve our blue-green algae problem; only with the alternative in which Lake Volkerak-Zoom becomes salt again we seem to get rid of the problem
  - Opposition against the solution in which Lake Volkerak-Zoom becomes salt again is strong (regional waterboards, farmers)
  - Many interests are at stake; the authorities who commissioned the study want to be sure of having obtained the right results on which they can base their decisions

Appendix B: Presentation Jolanda Verspagen (UvA)



Population dynamics of *Microcystis* in Lake Volkerak

Jolanda Verspagen, Klaus Jöhnk, Petra Visser, Jef Huisman



Microcystis

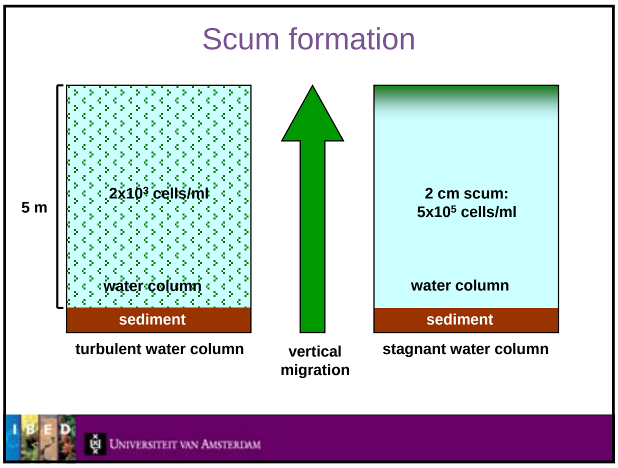
Cosmopolite freshwater cyanobacterium

Grows in colonies surrounded with mucus

Microcystis contains gas vesicles that provide buoyancy

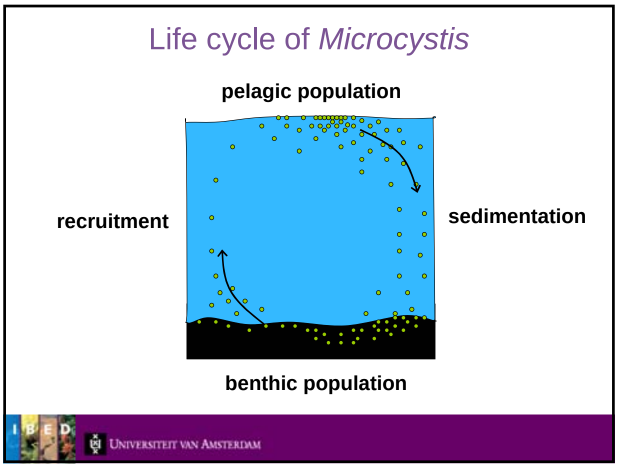
Overwinters vegetatively in the sediment

Can produce toxins that can be harmful to other organisms

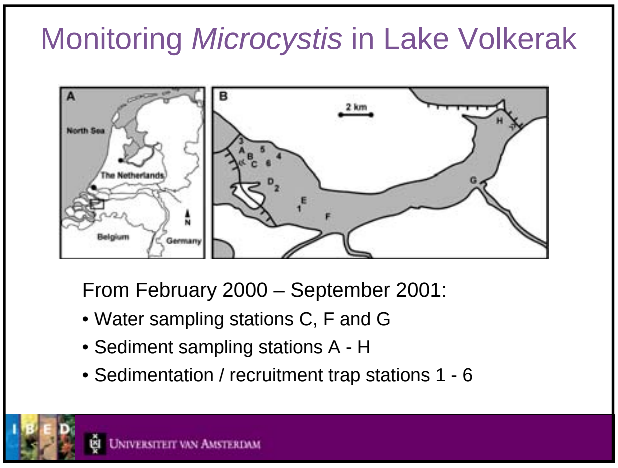


Scum formation

Scums



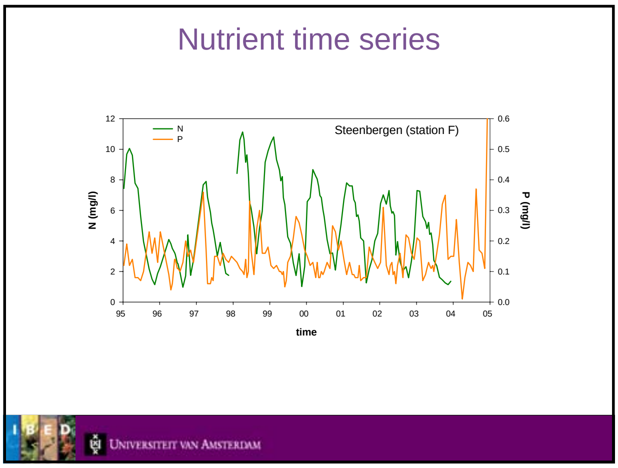
Life cycle of *Microcystis*



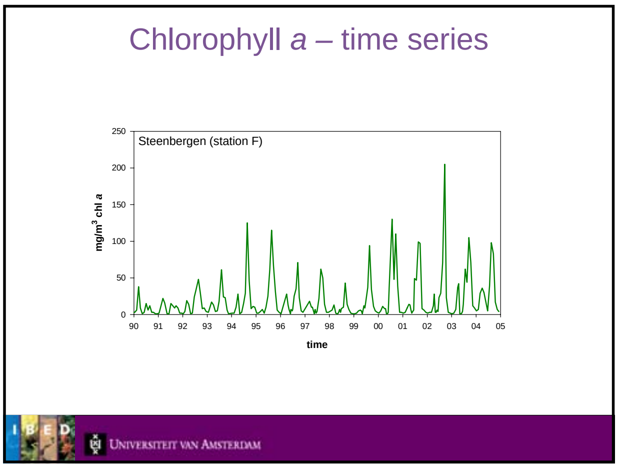
Monitoring *Microcystis* in Lake Volkerak

From February 2000 – September 2001:

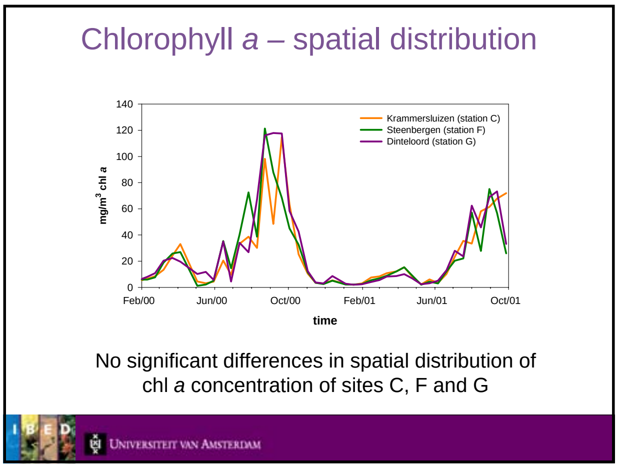
- Water sampling stations C, F and G
- Sediment sampling stations A - H
- Sedimentation / recruitment trap stations 1 - 6



Nutrient time series

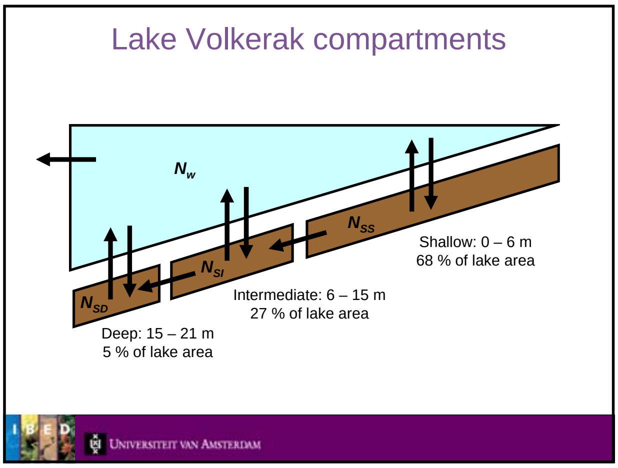


Chlorophyll *a* – time series



Chlorophyll *a* – spatial distribution

No significant differences in spatial distribution of chl *a* concentration of sites C, F and G

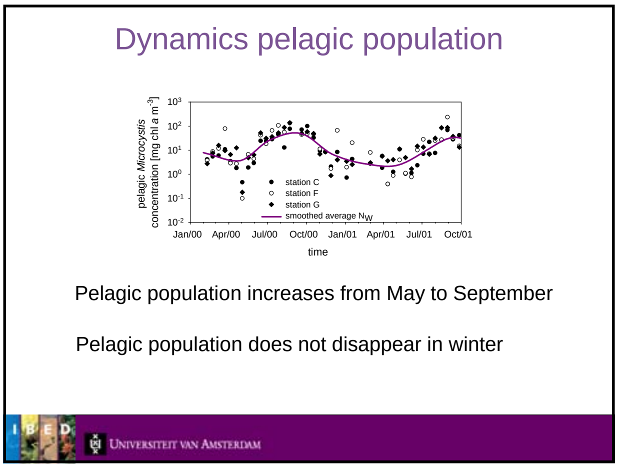


Lake Volkerak compartments

Shallow: 0 – 6 m
68 % of lake area

Intermediate: 6 – 15 m
27 % of lake area

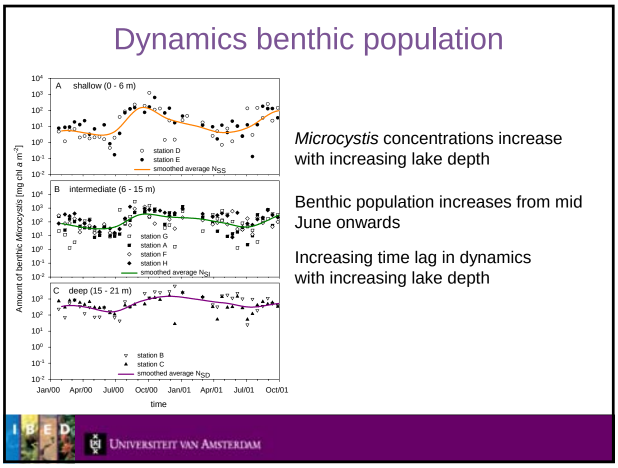
Deep: 15 – 21 m
5 % of lake area



Dynamics pelagic population

Pelagic population increases from May to September

Pelagic population does not disappear in winter

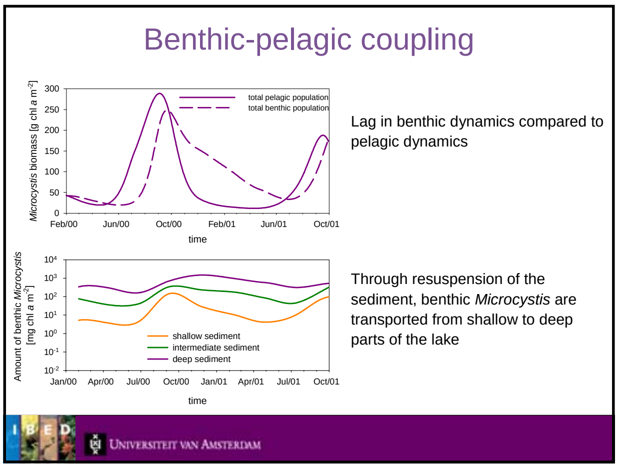


Dynamics benthic population

Microcystis concentrations increase with increasing lake depth

Benthic population increases from mid June onwards

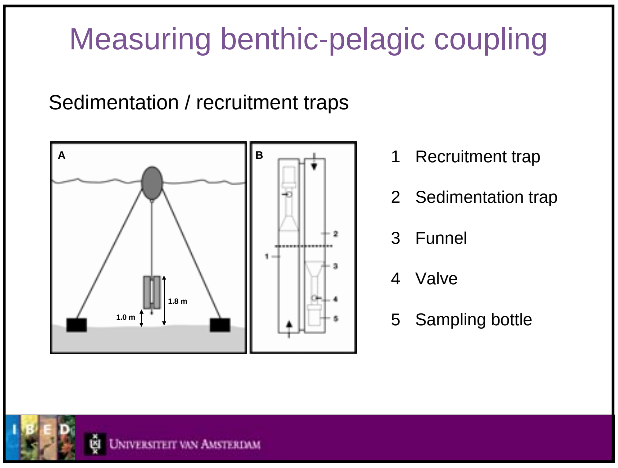
Increasing time lag in dynamics with increasing lake depth



Benthic-pelagic coupling

Lag in benthic dynamics compared to pelagic dynamics

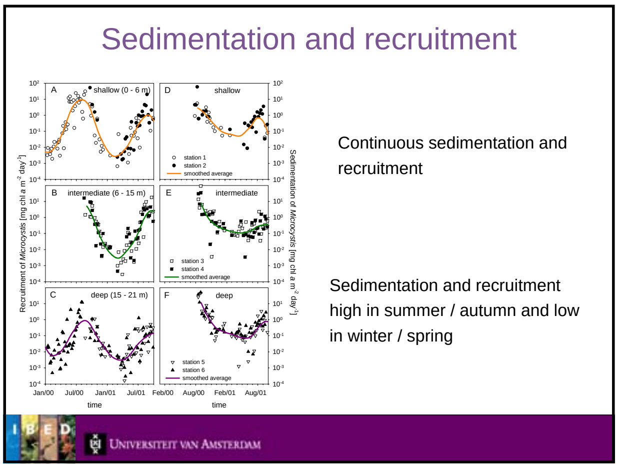
Through resuspension of the sediment, benthic *Microcystis* are transported from shallow to deep parts of the lake



Measuring benthic-pelagic coupling

Sedimentation / recruitment traps

1 Recruitment trap
2 Sedimentation trap
3 Funnel
4 Valve
5 Sampling bottle



Sedimentation and recruitment

Continuous sedimentation and recruitment

Sedimentation and recruitment high in summer / autumn and low in winter / spring

Benthic-pelagic model formulations

Pelagic population

$$\frac{dN_W}{dt} = \mu N_W - mN_W - S + R - qN_W$$

Benthic population

Shallow sediment

$$\frac{dN_{SS}}{dt} = S_S - R_S - mN_{SS} - T_{SI}$$

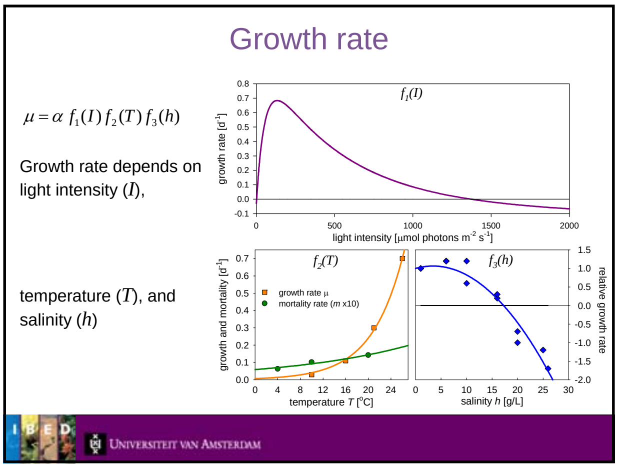
Intermediate sediment

$$\frac{dN_{SI}}{dt} = S_I - R_I - mN_{SI} + \frac{A_S}{A_I}T_{SI} - T_{ID}$$

Deep sediment

$$\frac{dN_{SD}}{dt} = S_D - R_D - mN_{SD} + \frac{A_I}{A_D}T_{ID}$$

μ	growth rate
m	mortality rate
S	sedimentation
R	recruitment
q	flushing rate
T	benthic transport
A	area

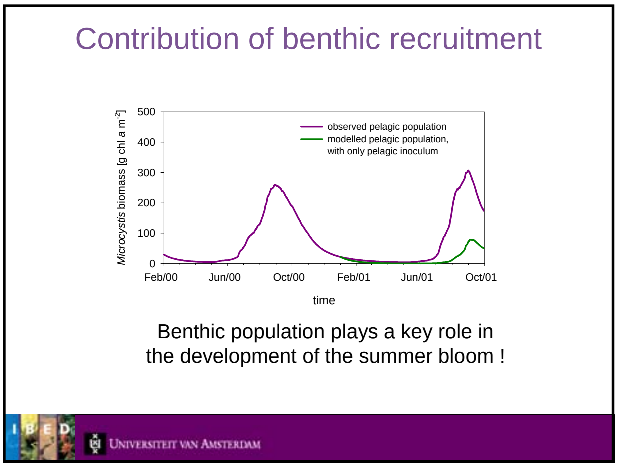


Growth rate

$$\mu = \alpha\, f_1(I)\, f_2(T)\, f_3(h)$$

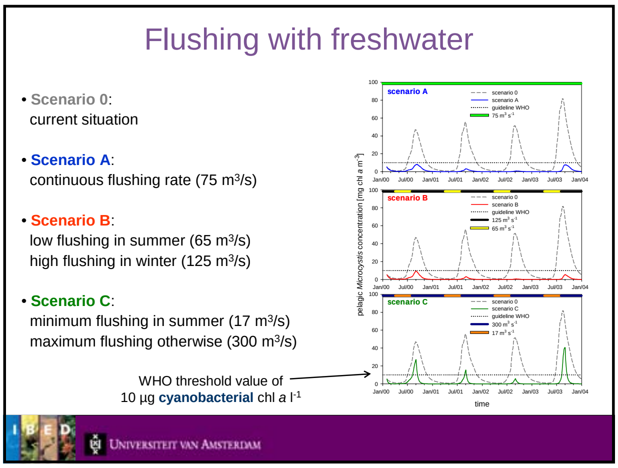
Growth rate depends on light intensity (I),

temperature (T), and salinity (h)



Contribution of benthic recruitment

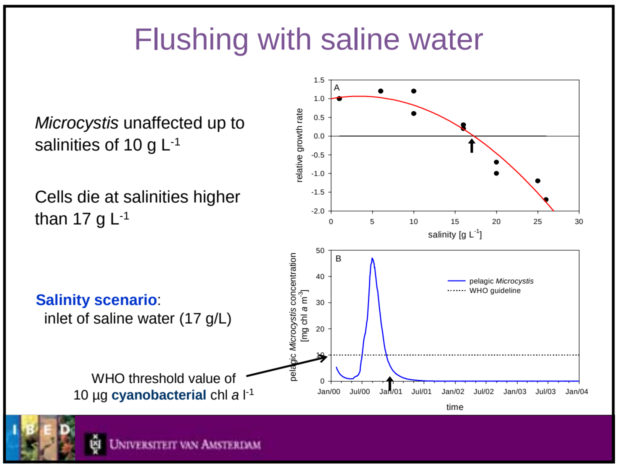
Benthic population plays a key role in the development of the summer bloom !



Flushing with freshwater

- **Scenario 0**:
  current situation
- **Scenario A**:
  continuous flushing rate (75 m^3/s)
- **Scenario B**:
  low flushing in summer (65 m^3/s)
  high flushing in winter (125 m^3/s)
- **Scenario C**:
  minimum flushing in summer (17 m^3/s)
  maximum flushing otherwise (300 m^3/s)

WHO threshold value of
10 µg **cyanobacterial** chl *a* l^{-1}



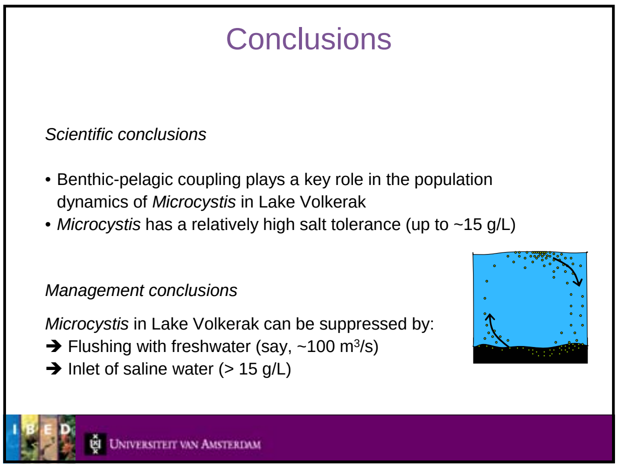
Flushing with saline water

Microcystis unaffected up to salinities of 10 g L^{-1}

Cells die at salinities higher than 17 g L^{-1}

Salinity scenario:
inlet of saline water (17 g/L)

WHO threshold value of
10 µg **cyanobacterial** chl *a* l^{-1}



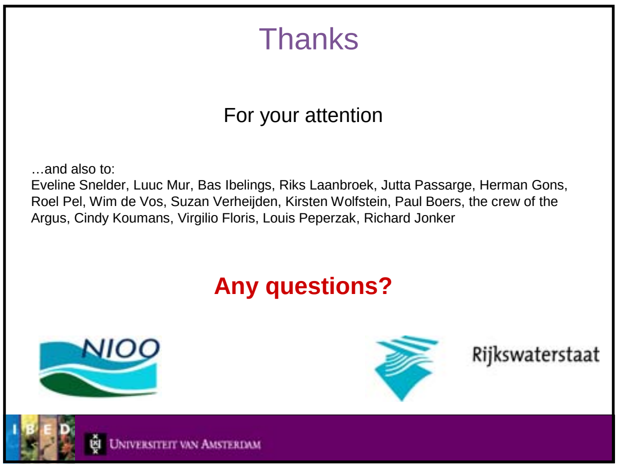
Conclusions

Scientific conclusions

- Benthic-pelagic coupling plays a key role in the population dynamics of *Microcystis* in Lake Volkerak
- *Microcystis* has a relatively high salt tolerance (up to ~15 g/L)

Management conclusions

Microcystis in Lake Volkerak can be suppressed by:
➔ Flushing with freshwater (say, ~100 m^3/s)
➔ Inlet of saline water (> 15 g/L)



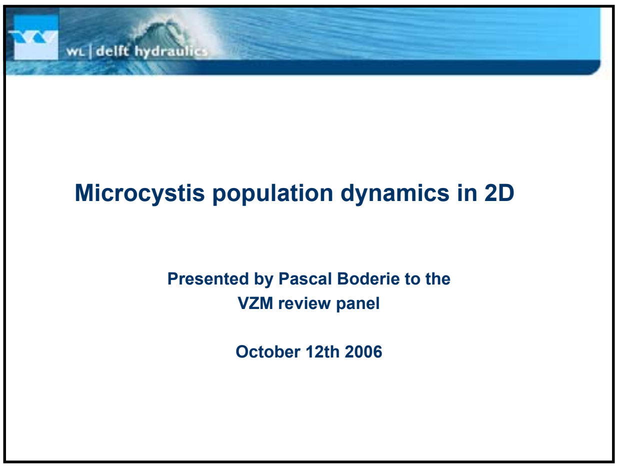
Thanks

For your attention

…and also to:
Eveline Snelder, Luuc Mur, Bas Ibelings, Riks Laanbroek, Jutta Passarge, Herman Gons, Roel Pel, Wim de Vos, Suzan Verheijden, Kirsten Wolfstein, Paul Boers, the crew of the Argus, Cindy Koumans, Virgilio Floris, Louis Peperzak, Richard Jonker

Any questions?

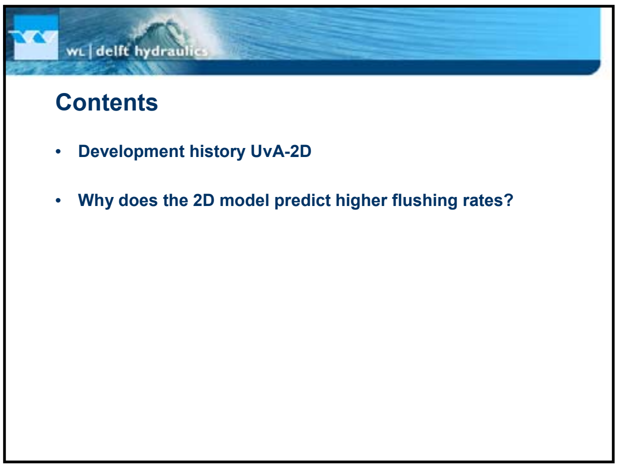
Appendix C: Presentation Pascal Boderie (Delft Hydraulics)



Microcystis population dynamics in 2D

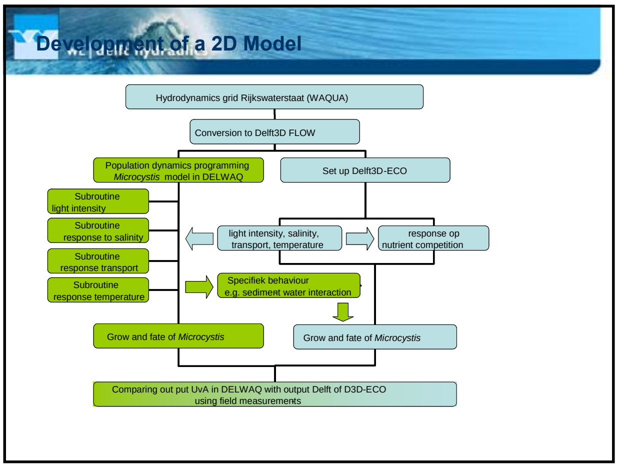
Presented by Pascal Boderie to the
VZM review panel

October 12th 2006



Contents

- Development history UvA-2D
- Why does the 2D model predict higher flushing rates?



Development of a 2D Model

Hydrodynamics grid Rijkswaterstaat (WAQUA)

Conversion to Delft3D FLOW

Population dynamics programming *Microcystis* model in DELWAQ

Set up Delft3D-ECO

Subroutine light intensity

Subroutine response to salinity

Subroutine response transport

Subroutine response temperature

light intensity, salinity, transport, temperature

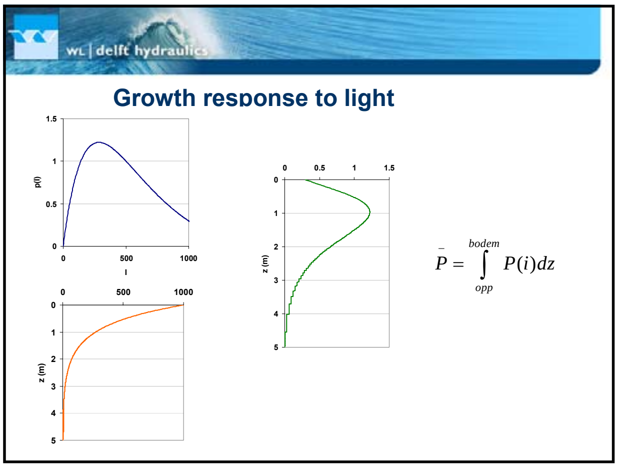
response op nutrient competition

Specifiek behaviour e.g. sediment water interaction

Grow and fate of *Microcystis*

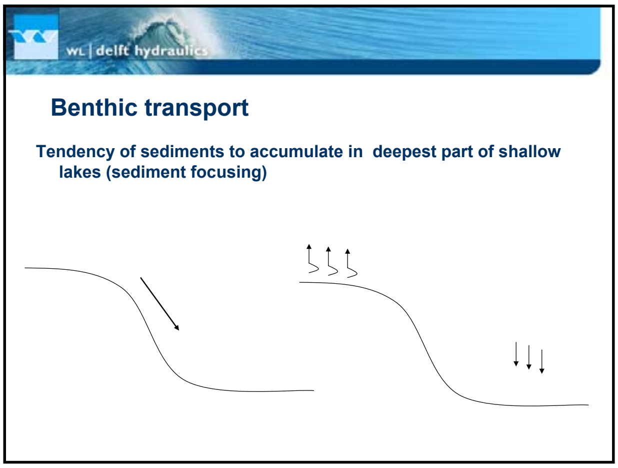
Grow and fate of *Microcystis*

Comparing out put UvA in DELWAQ with output Delft of D3D-ECO using field measurements



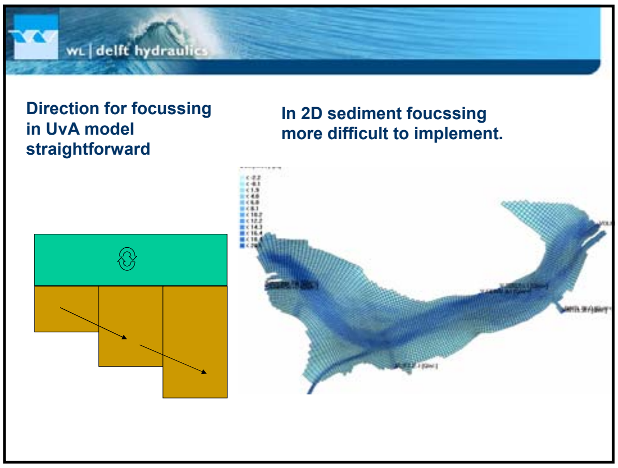
Growth response to light

$$\bar{P} = \int_{opp}^{bodem} P(i)dz$$



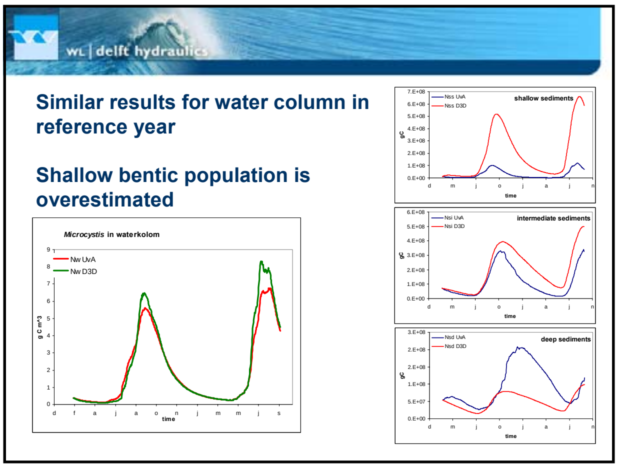
Benthic transport

Tendency of sediments to accumulate in deepest part of shallow lakes (sediment focusing)

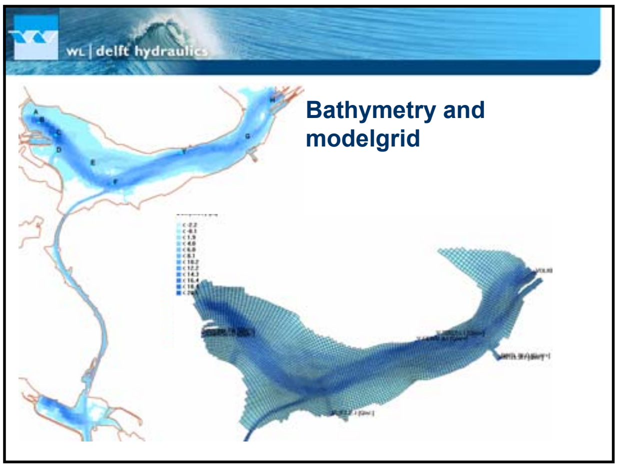


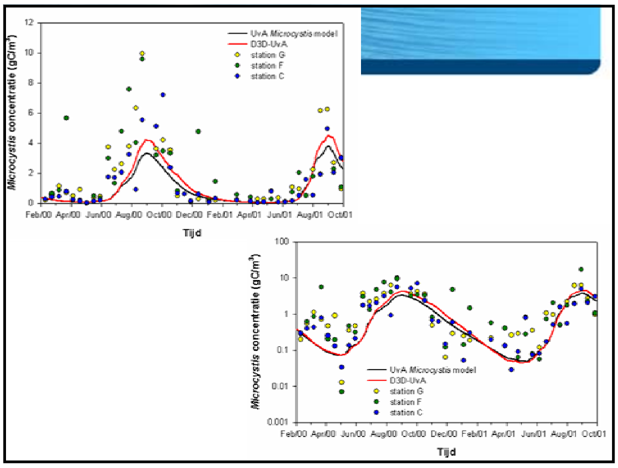
Direction for focussing in UvA model straightforward

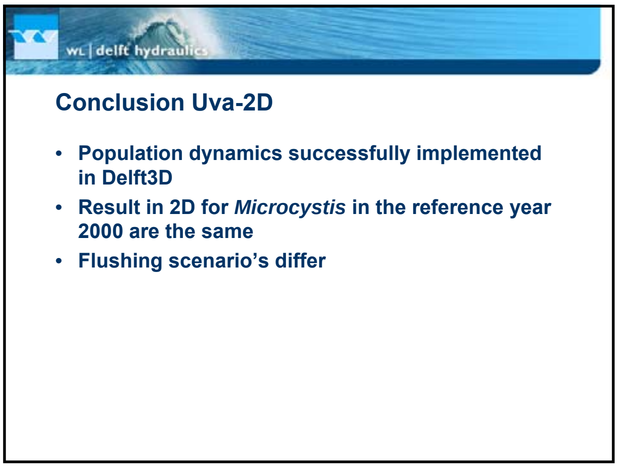
In 2D sediment foucssing more difficult to implement.


Similar results for water column in reference year

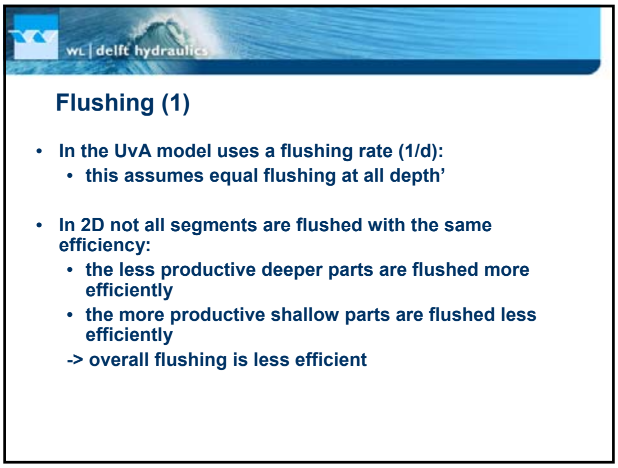
Shallow bentic population is overestimated


Bathymetry and modelgrid



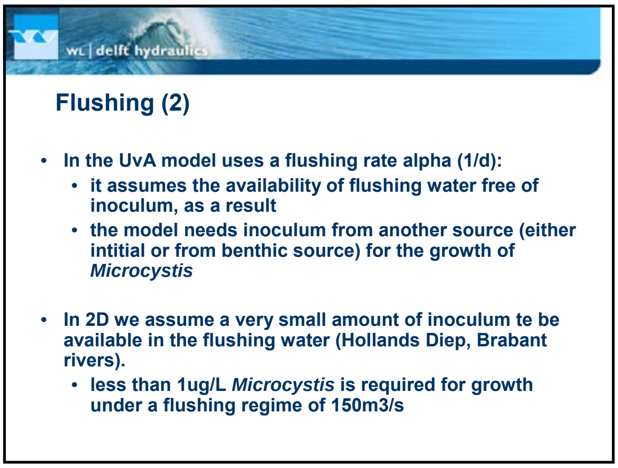

Conclusion Uva-2D

- Population dynamics successfully implemented in Delft3D
- Result in 2D for *Microcystis* in the reference year 2000 are the same
- Flushing scenario's differ

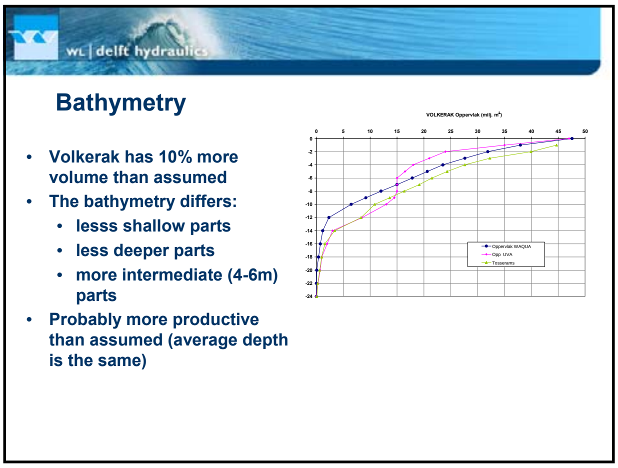

Flushing (1)

- In the UvA model uses a flushing rate (1/d):
  - this assumes equal flushing at all depth'
- In 2D not all segments are flushed with the same efficiency:
  - the less productive deeper parts are flushed more efficiently
  - the more productive shallow parts are flushed less efficiently

  -> overall flushing is less efficient

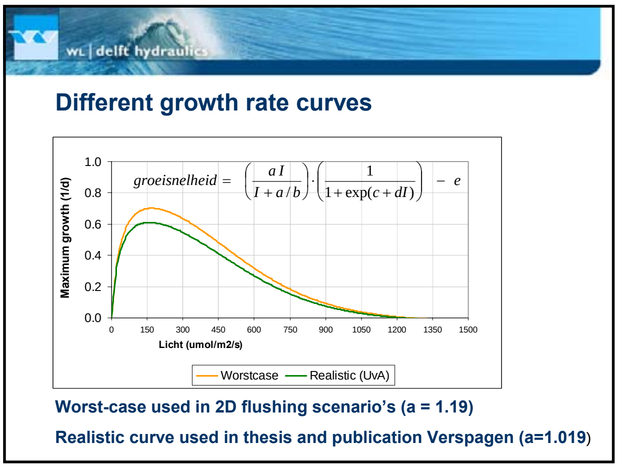

Flushing (2)

- In the UvA model uses a flushing rate alpha (1/d):
  - it assumes the availability of flushing water free of inoculum, as a result
  - the model needs inoculum from another source (either intitial or from benthic source) for the growth of *Microcystis*
- In 2D we assume a very small amount of inoculum te be available in the flushing water (Hollands Diep, Brabant rivers).
  - less than 1ug/L *Microcystis* is required for growth under a flushing regime of 150m3/s



Bathymetry

- Volkerak has 10% more volume than assumed
- The bathymetry differs:
  - lesss shallow parts
  - less deeper parts
  - more intermediate (4-6m) parts
- Probably more productive than assumed (average depth is the same)

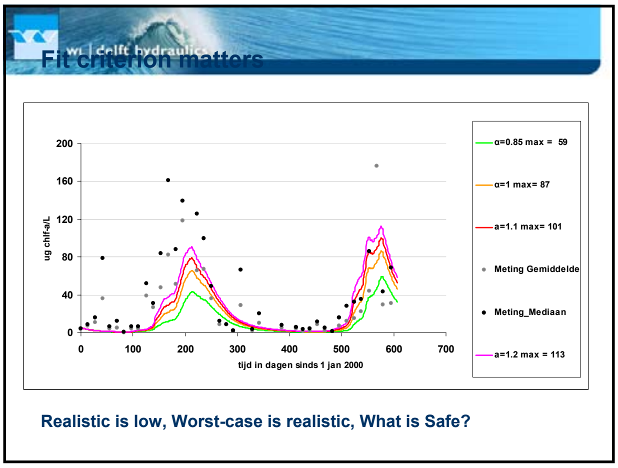


Different growth rate curves

$$groeisnelheid = \left(\frac{a\,I}{I + a/b}\right) \cdot \left(\frac{1}{1 + \exp(c + dI)}\right) - e$$

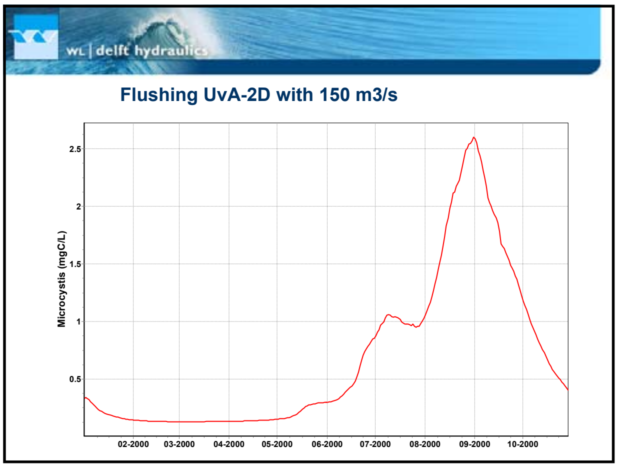
Worst-case used in 2D flushing scenario's (a = 1.19)

Realistic curve used in thesis and publication Verspagen (a=1.019)

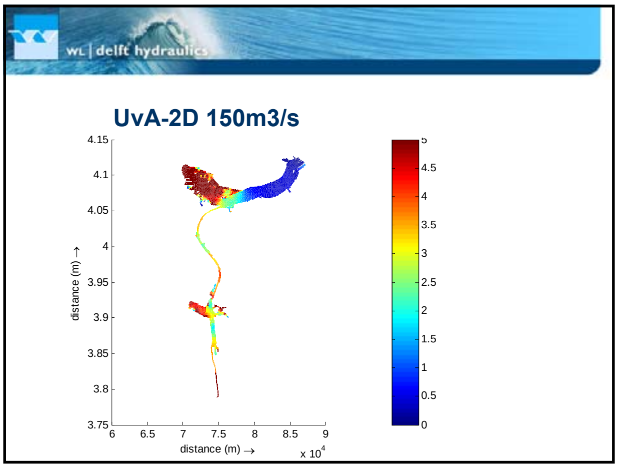


Fit criterion matters

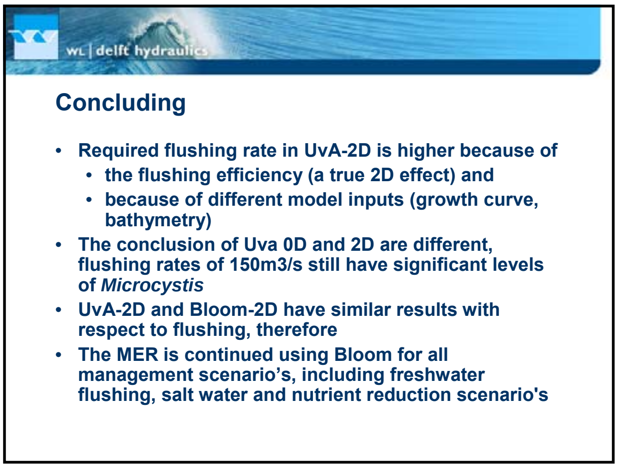
Realistic is low, Worst-case is realistic, What is Safe?



Flushing UvA-2D with 150 m3/s

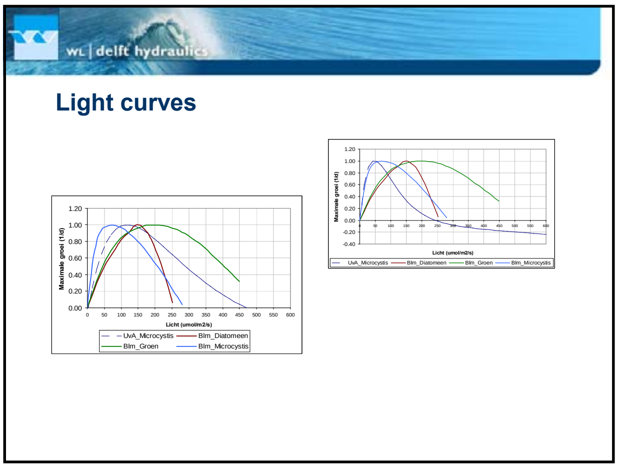


UvA-2D 150m3/s

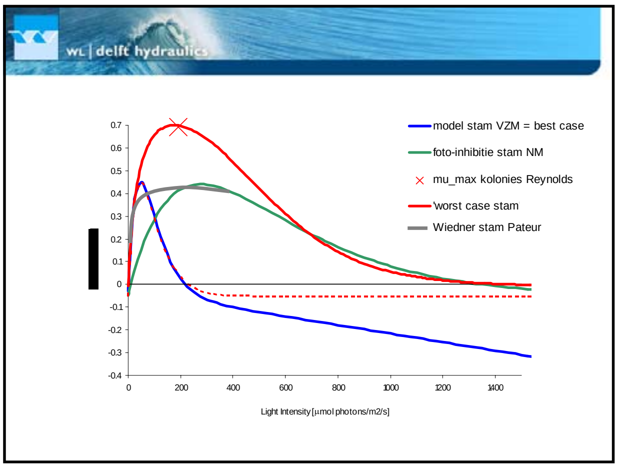


Concluding

- Required flushing rate in UvA-2D is higher because of
  - the flushing efficiency (a true 2D effect) and
  - because of different model inputs (growth curve, bathymetry)
- The conclusion of Uva 0D and 2D are different, flushing rates of 150m3/s still have significant levels of *Microcystis*
- UvA-2D and Bloom-2D have similar results with respect to flushing, therefore
- The MER is continued using Bloom for all management scenario's, including freshwater flushing, salt water and nutrient reduction scenario's



Light curves



Appendix D: Presentation Hans Los (Delft Hydraulics)

Modelling system used for Lake Volkerak Zoom study

Hans Los
Presented to review pannel
October 2006

Conclusion adequacy model

- Fresh water model (Delft3D-DBS) is well validated
- Fresh water model results Lake Volkerak Zoom adequate ('fit for purpose')
  - but 2000 agrees better with observations than 2002
- Can be used for scenario prediction

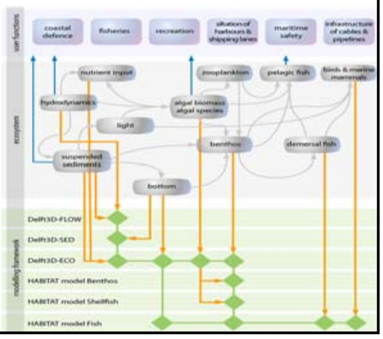
- Marine model (Delft3D-GEM) is well validated
  - but a marine Lake Volkerak Zoom does not exist yet
- Empirical results other systems in region valuable but expected conditions in Lake Volkerak Zoom not exactly the same
- Relatively high loadings, typical morphometry, short residence time

Contents

1. Overview of Delft3D modelling system
2. Validation results phytoplankton model
3. Set-up of Lake Volkerak Zoom models

Delft3D: tool for effect chain annalyses

Physical parameters
Transports (SPM, ..)
Water quality
Ecology
Fish, Birds
other user functions,
etc.

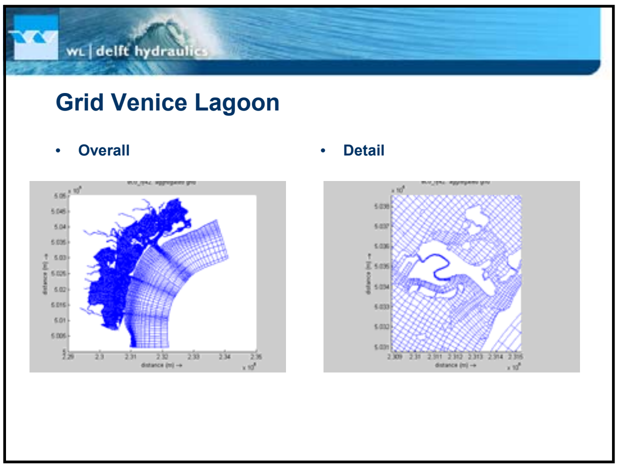


Modelling approach (general)

- Delft3D-FLOW
  - hydrodynamics
- Delft3D-SED
  - suspended particulate matter (SPM)
- Delft3D-WAQ
  - origin of water and residence times (tracer)
- Delft3D-ECO(DBS and GEM)
  - nutrients and primary production model

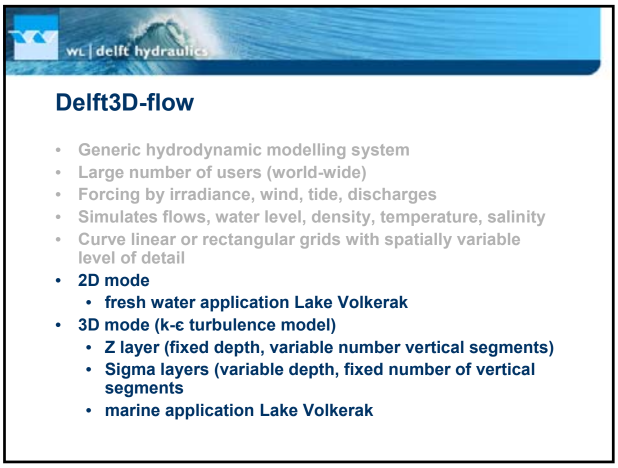
Delft3D-flow

- Generic hydrodynamic modelling system
- Large number of users (world-wide)
- Forcing by irradiance, wind, tide, discharges
- Simulates flows, water level, density, temperature, salinity
- Curve linear or rectangular grids with spatially variable level of detail



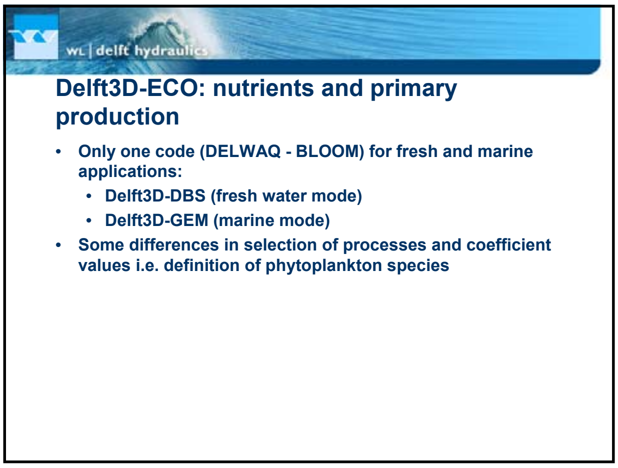
Grid Venice Lagoon

- Overall
- Detail



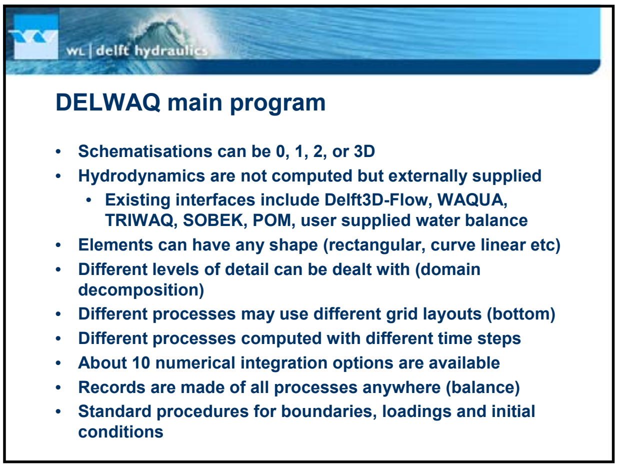
Delft3D-flow

- Generic hydrodynamic modelling system
- Large number of users (world-wide)
- Forcing by irradiance, wind, tide, discharges
- Simulates flows, water level, density, temperature, salinity
- Curve linear or rectangular grids with spatially variable level of detail
- 2D mode
  - fresh water application Lake Volkerak
- 3D mode (k-ε turbulence model)
  - Z layer (fixed depth, variable number vertical segments)
  - Sigma layers (variable depth, fixed number of vertical segments)
  - marine application Lake Volkerak



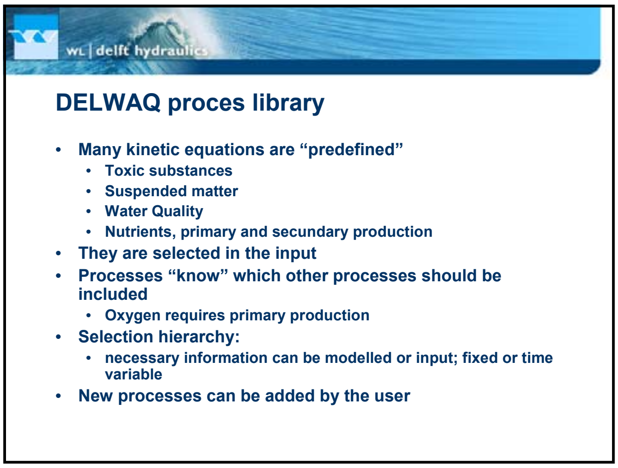
Delft3D-ECO: nutrients and primary production

- Only one code (DELWAQ - BLOOM) for fresh and marine applications:
  - Delft3D-DBS (fresh water mode)
  - Delft3D-GEM (marine mode)
- Some differences in selection of processes and coefficient values i.e. definition of phytoplankton species



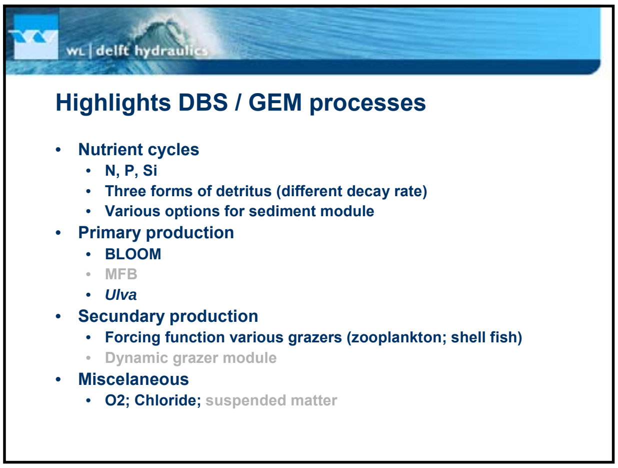
DELWAQ main program

- Schematisations can be 0, 1, 2, or 3D
- Hydrodynamics are not computed but externally supplied
  - Existing interfaces include Delft3D-Flow, WAQUA, TRIWAQ, SOBEK, POM, user supplied water balance
- Elements can have any shape (rectangular, curve linear etc)
- Different levels of detail can be dealt with (domain decomposition)
- Different processes may use different grid layouts (bottom)
- Different processes computed with different time steps
- About 10 numerical integration options are available
- Records are made of all processes anywhere (balance)
- Standard procedures for boundaries, loadings and initial conditions



DELWAQ proces library

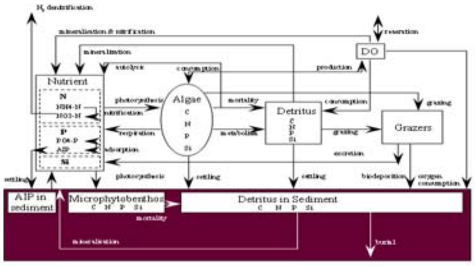
- Many kinetic equations are “predefined”
  - Toxic substances
  - Suspended matter
  - Water Quality
  - Nutrients, primary and secundary production
- They are selected in the input
- Processes “know” which other processes should be included
  - Oxygen requires primary production
- Selection hierarchy:
  - necessary information can be modelled or input; fixed or time variable
- New processes can be added by the user



Highlights DBS / GEM processes

- Nutrient cycles
  - N, P, Si
  - Three forms of detritus (different decay rate)
  - Various options for sediment module
- Primary production
  - BLOOM
  - MFB
  - *Ulva*
- Secundary production
  - Forcing function various grazers (zooplankton; shell fish)
  - Dynamic grazer module
- Miscelaneous
  - O2; Chloride; suspended matter

Highlights DBS / GEM processes (2)



Principle phytoplankton modelling
Empirical observations

- Lakes with high nutrient levels tend to be dominated by cyanobacteria
  - but green algae may also be dominant
- Light and perhaps grazing seem to be more important than nutrient requirements or affinity with respect to competition
- In the lab (hence under relatively stable conditions) nutrients can control phytoplankton competition
- Species switches during restoration correlate better with the light regime (Zeu/Zmix) than with the nutrient levels
  - but nutrients do limit the biomass and hence affect the light regime via the algal contribution to the extinction
- These empirical observations are the basis for competition in our phytoplankton model

Process formulations BLOOM (1): competition

- BLOOM is a multi-species phytoplankton model
- Competition between phytoplankton types is the guiding principle in BLOOM
- BLOOM selects the optimum composition based on the ratio of the net growth rate and the requirements for each environmental resource
- Trade-off principle between growth and requirement:

  Relatively high potential growth rates may compensate a relatively large requirement hence opportunistic species win when light is high, efficient species win when there is little light

Process formulations BLOOM (2): general

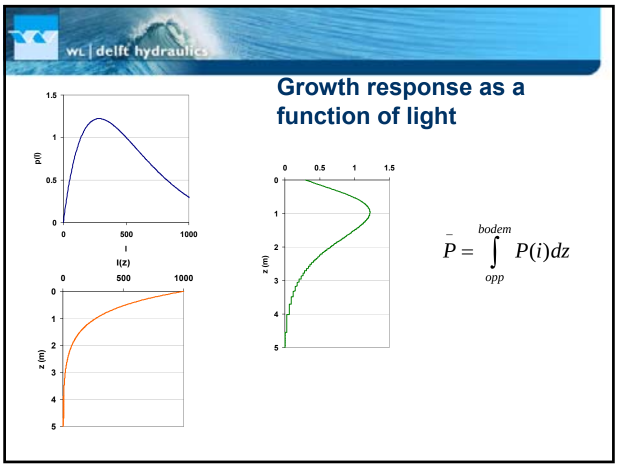
- BLOOM considers various kinds (3 to 15) of algae, as different kinds of species respond differently to their environment. Some kinds (like *Microcystis*) are considered nuisance algae.
- Every (kind of) species has its own:
  - growth response to light conditions
  - response to temperature
  - growth response to available nutrients
  - stochiometry (composition in C, N, P, Chlorophyll)
- (depending on environmental conditions)

Process formulations BLOOM (3): nutrients

- Variability of stochiometry is modelled as a distinction of the species in 3 types:
  - a nitrogen limited type
  - a phosphorus limited type
  - an energy limited type
- Every type has a constant stochiometry
- The model computes the optimal combination of types (or the most suitable stochiometry)
- Types can instantaneously convert into each other, (groups of) species can't convert into each other

Process formulations BLOOM (4): energy

- At sufficient (= not limiting) availability of nutrients light and temperature become the limiting factors
- Analogous to nutrients the available 'amount' of light is calculated
- A 'critical light intensity' is reached when growth averaged over depth equals all losses. This threshold varies:
  - per species
  - in time and space

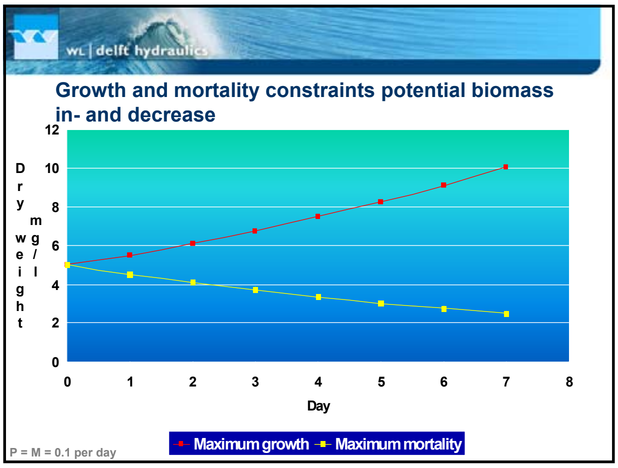


Growth response as a function of light

$$\bar{P} = \int_{opp}^{bodem} P(i)dz$$

Process formulations (5): time dependency

- The optimum concentration of a (group of) species cannot always be reached within one time step
- Constraints to the range of possible concentrations are determined by:
  - The concentration at the start of the time step,
  - Maximum growth rate,
  - Maximal mortality rate
- These constraints are considered during the species selection procedure.



Growth and mortality constraints potential biomass in- and decrease

P = M = 0.1 per day

Phytoplankton characteristics (1)

- Freshwater model version considers
  - Diatoms
  - Micro flagellates
  - Green algae
  - *Aphanozomenon*
  - *Microcystis*
  - *Oscillatoria*
- Data on characteristics of individual species have been obtained from lab cultures of UvA in the 1980s + other literature sources
- Some adjustments from numerous model applications

Phytoplankton characteristics (2)

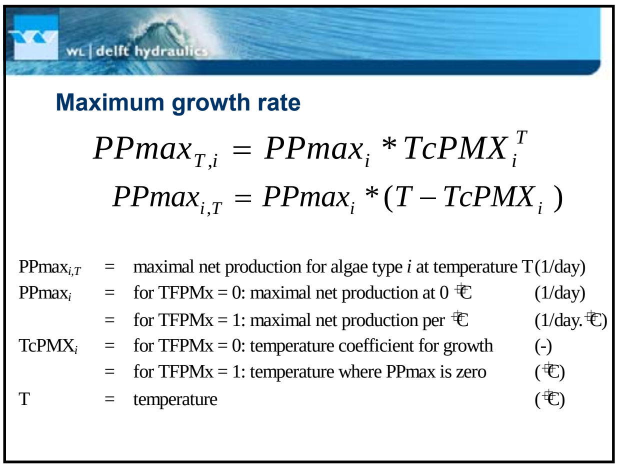
- Marine model version considers
  - Diatoms
  - Micro flagellates
  - Dinoflagellates
  - *Phaeocystis*
- Data on characteristics of individual species have been obtained from lab cultures
- For *Phaeocystis* and diatoms work by Roel Riegman was main source
- Some adjustments from model applications North Sea

Nutrient Constraints

$$\sum_{i=1}^{n} (St_{k,i} * Bm_i) + Nut_{k,diss} = Totnut_k$$

$$Bm_i \geq 0 \qquad Nut_{k,diss} \geq 0$$

i	=	algae type i	(-)
n	=	number of algae types in calculation	(-)
$St_{k,i}$	=	stochiometry of nutrient k (k = N, P or Si) in algae type i	(gk/gDM)
Bm_i	=	biomass of algae type i	(gDM/m^3)
$Nut_{k,diss}$	=	amount of dissolved nutrient k	(gk/m^3)
$Totnut_k$	=	total available amount of nutrient k	($gk.m^{-3}$)

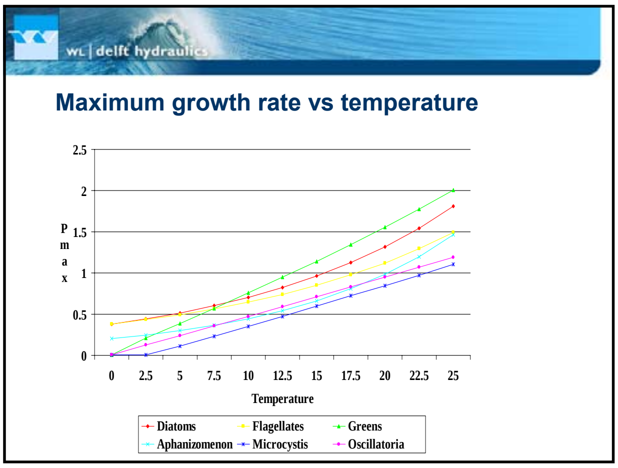


Maximum growth rate

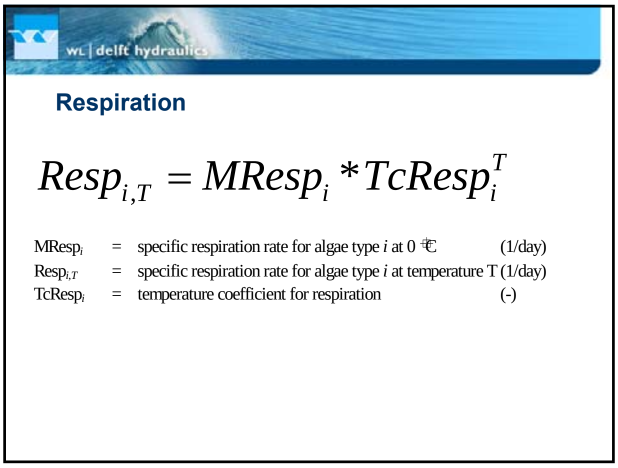
$$PPmax_{T,i} = PPmax_i * TcPMX_i^T$$

$$PPmax_{i,T} = PPmax_i * (T - TcPMX_i)$$

$PPmax_{i,T}$ = maximal net production for algae type *i* at temperature T (1/day)
$PPmax_i$ = for TFPMx = 0: maximal net production at 0 °C (1/day)
= for TFPMx = 1: maximal net production per °C (1/day.°C)
$TcPMX_i$ = for TFPMx = 0: temperature coefficient for growth (-)
= for TFPMx = 1: temperature where PPmax is zero (°C)
T = temperature (°C)



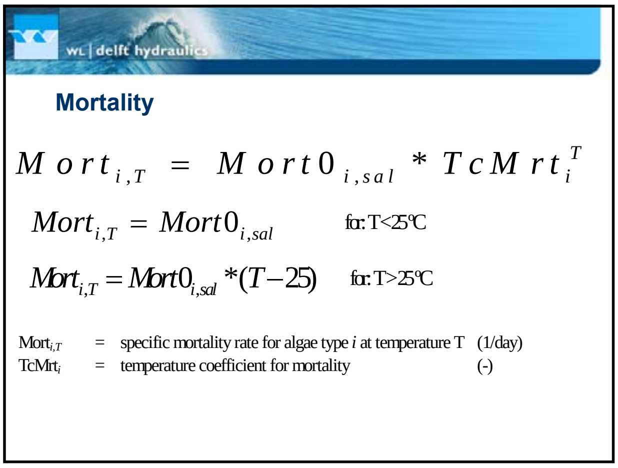
Maximum growth rate vs temperature



Respiration

$$Resp_{i,T} = MResp_i * TcResp_i^T$$

$MResp_i$ = specific respiration rate for algae type *i* at 0 °C (1/day)
$Resp_{i,T}$ = specific respiration rate for algae type *i* at temperature T (1/day)
$TcResp_i$ = temperature coefficient for respiration (-)



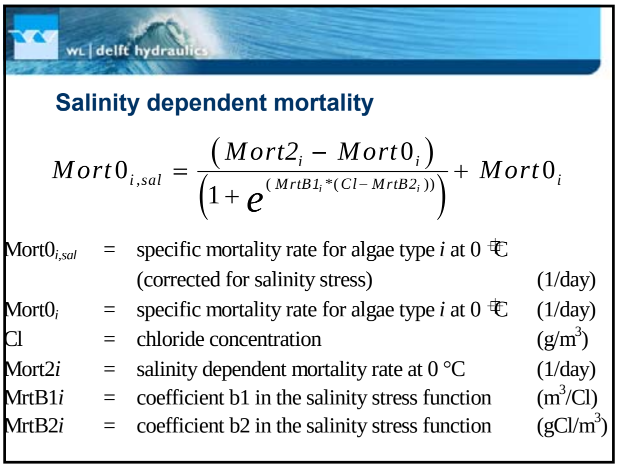
Mortality

$$Mort_{i,T} = Mort0_{i,sal} * TcMrt_i^T$$

$$Mort_{i,T} = Mort0_{i,sal} \qquad \text{for: } T<25\,°C$$

$$Mort_{i,T} = Mort0_{i,sal} * (T-25) \qquad \text{for: } T>25\,°C$$

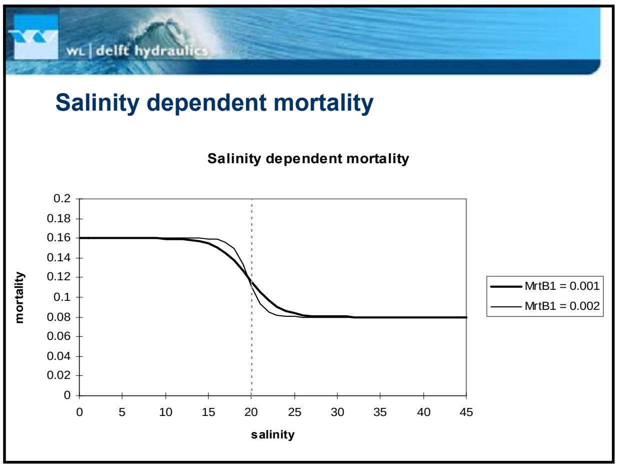
$Mort_{i,T}$ = specific mortality rate for algae type *i* at temperature T (1/day)
$TcMrt_i$ = temperature coefficient for mortality (-)



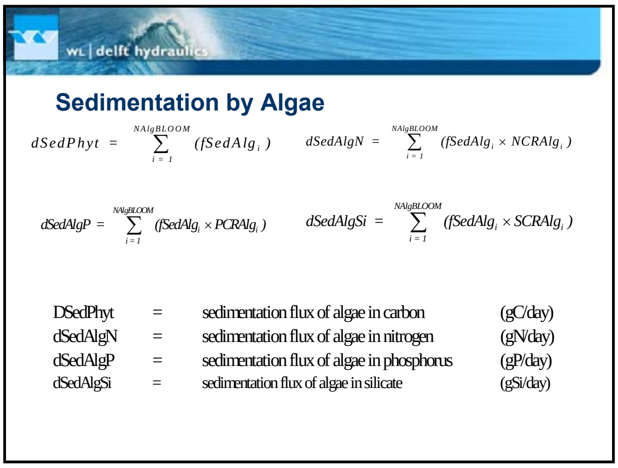
Salinity dependent mortality

$$Mort0_{i,sal} = \frac{(Mort2_i - Mort0_i)}{\left(1 + e^{(MrtB1_i * (Cl - MrtB2_i))}\right)} + Mort0_i$$

$Mort0_{i,sal}$ = specific mortality rate for algae type *i* at 0 °C (corrected for salinity stress) (1/day)
$Mort0_i$ = specific mortality rate for algae type *i* at 0 °C (1/day)
Cl = chloride concentration (g/m^3)
Mort2*i* = salinity dependent mortality rate at 0 °C (1/day)
MrtB1*i* = coefficient b1 in the salinity stress function (m^3/Cl)
MrtB2*i* = coefficient b2 in the salinity stress function (gCl/m^3)



Salinity dependent mortality

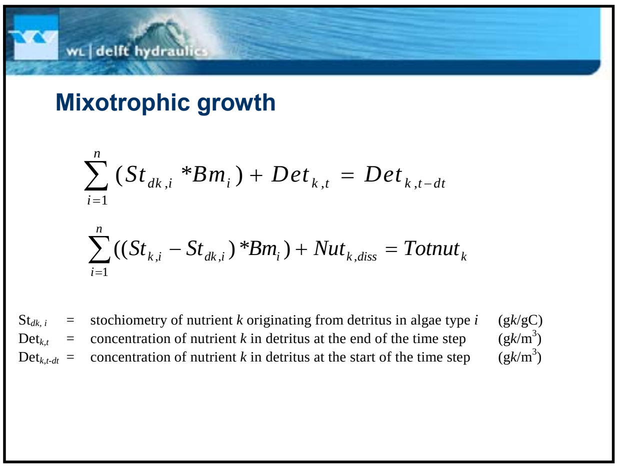


Sedimentation by Algae

$$dSedPhyt = \sum_{i=1}^{NAlgBLOOM} (fSedAlg_i) \qquad dSedAlgN = \sum_{i=1}^{NAlgBLOOM} (fSedAlg_i \times NCRAlg_i)$$

$$dSedAlgP = \sum_{i=1}^{NAlgBLOOM} (fSedAlg_i \times PCRAlg_i) \qquad dSedAlgSi = \sum_{i=1}^{NAlgBLOOM} (fSedAlg_i \times SCRAlg_i)$$

DSedPhyt = sedimentation flux of algae in carbon (gC/day)
dSedAlgN = sedimentation flux of algae in nitrogen (gN/day)
dSedAlgP = sedimentation flux of algae in phosphorus (gP/day)
dSedAlgSi = sedimentation flux of algae in silicate (gSi/day)

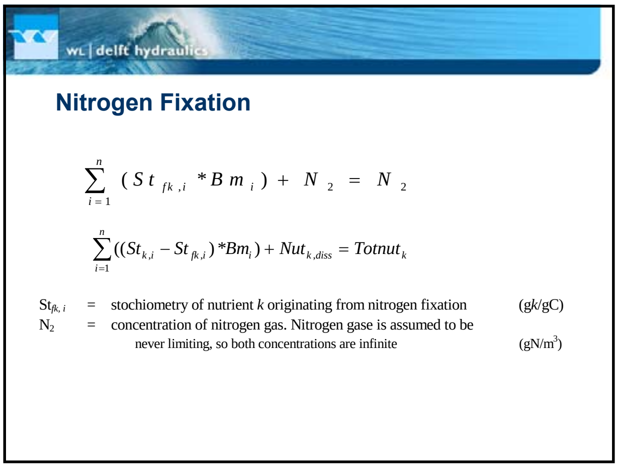


Mixotrophic growth

$$\sum_{i=1}^{n} (St_{dk,i} * Bm_i) + Det_{k,t} = Det_{k,t-dt}$$

$$\sum_{i=1}^{n} ((St_{k,i} - St_{dk,i}) * Bm_i) + Nut_{k,diss} = Totnut_k$$

$St_{dk,i}$ = stochiometry of nutrient *k* originating from detritus in algae type *i* (gk/gC)
$Det_{k,t}$ = concentration of nutrient *k* in detritus at the end of the time step (gk/m^3)
$Det_{k,t-dt}$ = concentration of nutrient *k* in detritus at the start of the time step (gk/m^3)

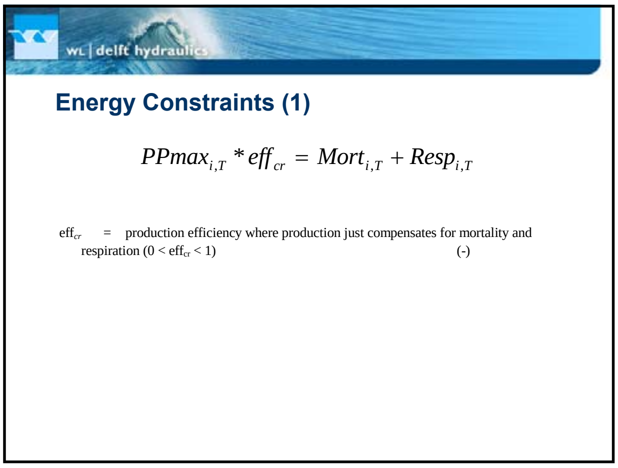


Nitrogen Fixation

$$\sum_{i=1}^{n} (St_{fk,i} * Bm_i) + N_2 = N_2$$

$$\sum_{i=1}^{n} ((St_{k,i} - St_{fk,i}) * Bm_i) + Nut_{k,diss} = Totnut_k$$

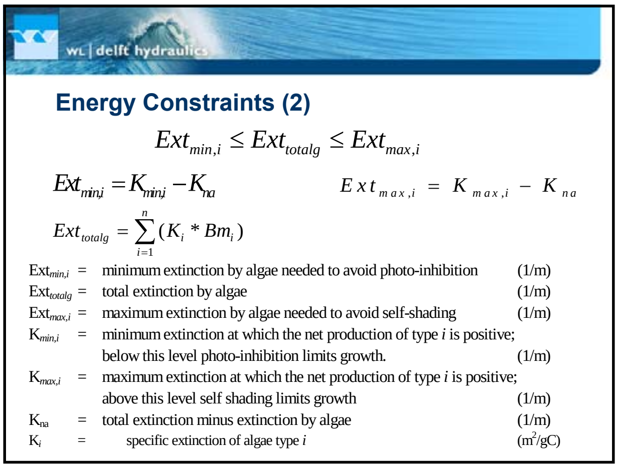
$St_{fk,i}$ = stochiometry of nutrient *k* originating from nitrogen fixation (gk/gC)
N_2 = concentration of nitrogen gas. Nitrogen gase is assumed to be never limiting, so both concentrations are infinite (gN/m^3)



Energy Constraints (1)

$$PPmax_{i,T} * eff_{cr} = Mort_{i,T} + Resp_{i,T}$$

eff_{cr} = production efficiency where production just compensates for mortality and respiration ($0 < eff_{cr} < 1$) (-)



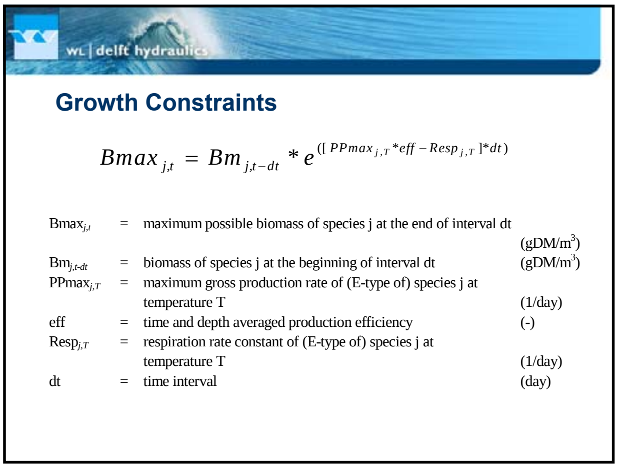
Energy Constraints (2)

$$Ext_{min,i} \leq Ext_{totalg} \leq Ext_{max,i}$$

$$Ext_{min,i} = K_{min,i} - K_{na} \qquad Ext_{max,i} = K_{max,i} - K_{na}$$

$$Ext_{totalg} = \sum_{i=1}^{n} (K_i * Bm_i)$$

$Ext_{min,i}$ = minimum extinction by algae needed to avoid photo-inhibition (1/m)
Ext_{totalg} = total extinction by algae (1/m)
$Ext_{max,i}$ = maximum extinction by algae needed to avoid self-shading (1/m)
$K_{min,i}$ = minimum extinction at which the net production of type *i* is positive; below this level photo-inhibition limits growth. (1/m)
$K_{max,i}$ = maximum extinction at which the net production of type *i* is positive; above this level self shading limits growth (1/m)
K_{na} = total extinction minus extinction by algae (1/m)
K_i = specific extinction of algae type *i* (m^2/gC)



Growth Constraints

$$Bmax_{j,t} = Bm_{j,t-dt} * e^{([PPmax_{j,T} * eff - Resp_{j,T}] * dt)}$$

$Bmax_{j,t}$ = maximum possible biomass of species j at the end of interval dt (gDM/m^3)
$Bm_{j,t-dt}$ = biomass of species j at the beginning of interval dt (gDM/m^3)
$PPmax_{j,T}$ = maximum gross production rate of (E-type of) species j at temperature T (1/day)
eff = time and depth averaged production efficiency (-)
$Resp_{j,T}$ = respiration rate constant of (E-type of) species j at temperature T (1/day)
dt = time interval (day)

Mortality Constraints

$$Bmin_{i,t} = Bm_{i,t-dt} * e^{(-Mort_{i,T} * dt)}$$

$Bmin_{i,t}$ = minimum possible biomass of algae type *i* at the end of interval dt (gDM.m^3).
$Bm_{i,t-dt}$ = biomass of algae type *i* at the beginning of interval dt (gDM.m^3).
$Mort_{i,T}$ = specific mortality rate constant of algae type *i* (1/day).

$$Bmin_{j,t} = \sum_{i=1}^{m} (Bmin_{i,t})$$

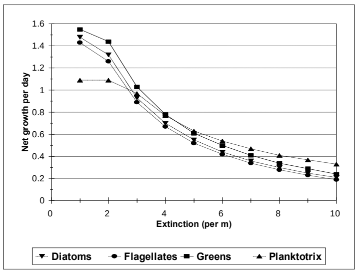
$Bmin_{j,t}$ = minimum possible biomass of species *j* at the end of interval dt (gDM.m^3)
m = number of types in species *j* (-)

Extinction by Algae

$$ExtVlPhyt = \sum_{i=1}^{NAlgBLOOM} (ExtVlAlg_i \; x \; [BLOOMAlg_i])$$

ExtVlPhyt	total extinction of visible light by all algae	(m^{-1})
NAlgBLOOM	actual number of algae types	(-)
ExtVlAlg$_i$	specific extinction coefficient of algae type i	(m^2.gC^{-1})
[BLOOMAlg$_i$]	concentration of algae type i	(gC.m^{-3})

Specific growth rate summer conditions

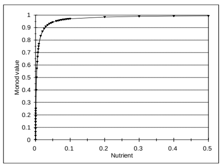


Monod type model

- **Monod term nutrient:**

Pn = Pn^{max} [C$_i$ / (Ks$_i$ + C$_i$)]

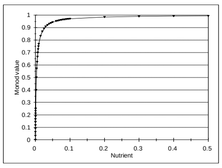
Monod type model



- **Monod term nutrient:**

Pn = Pn^{max} [C$_i$ / (Ks$_i$ + C$_i$)]

Monod type model

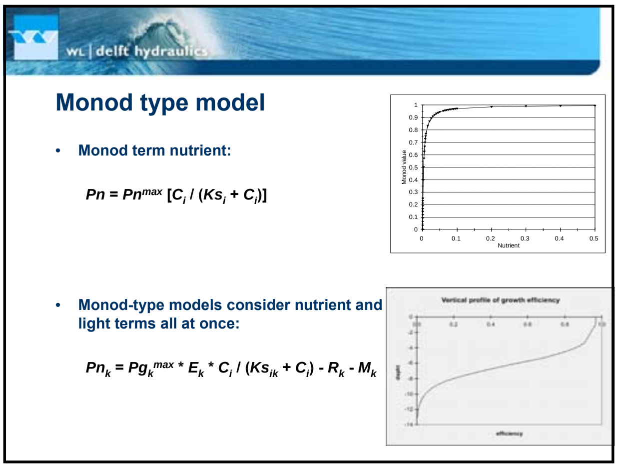


- **Monod term nutrient:**

Pn = Pn^{max} [C$_i$ / (Ks$_i$ + C$_i$)]

- **Monod-type models consider nutrient and light terms all at once:**

$Pn_k = Pg_k^{max} * E_k * C_i / (Ks_{ik} + C_i) - R_k - M_k$



Monod type model

- **Monod term nutrient:**

$$Pn = Pn^{max} [C_i / (Ks_i + C_i)]$$

- **Monod-type models consider nutrient and light terms all at once:**

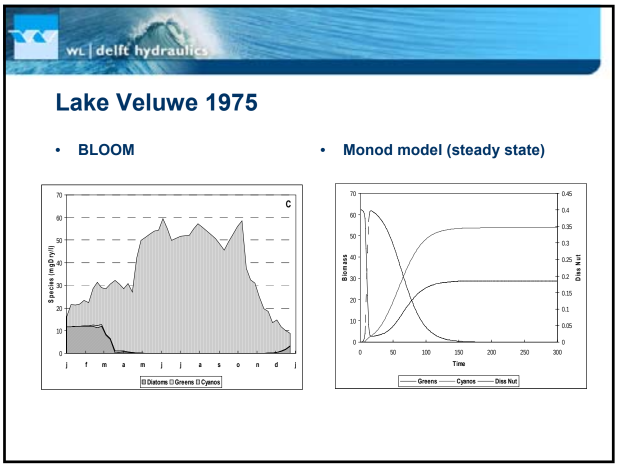
$$Pn_k = Pg_k^{max} * E_k * C_i / (Ks_{ik} + C_i) - R_k - M_k$$

Competition results

- **If nutrients high, Monod term ~ 1.0 → BLOOM and Monod model give same result if same light formulation**
- **If nutrients low:**
  - **competition in Monod model depends on half saturation constant Ks_{ik}**
  - **BLOOM result depends on nutrient stochiomety and potential growth rate**
- **Result could be the same but may be different**

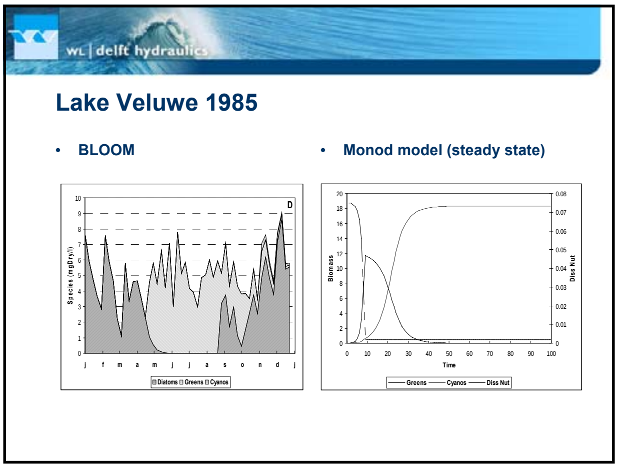
Competition results
Species characteristics

Greens	**Cyanos**
Pmax: 1.3	**Pmax: 0.85**
Resp: 0.2	**Resp: 0.05**
Specific extinction: 0.08 m^2/gdry weight	**Specific extinction: 0.16 m^2/gdry weight**
Iopt: 35 Watt	**Iopt: 20 Watt**
Ks_{ik} : 0.003	**Ks_{ik} : 0.001**
P requirement: 0.006 gP/g dry weight	**P requirement: 0.004 gP/g dry weight**



Lake Veluwe 1975

- **BLOOM**
- **Monod model (steady state)**



Lake Veluwe 1985

- **BLOOM**
- **Monod model (steady state)**

Comparison concluded

- **In Monod model cyanos always win regardless if there is a light or nutrient limitation**
- **In BLOOM cyanos win under light limitation and moderate nutrient limitation (still high enough to make water turbid) but Greens wins under moderate to strong nutrient limitation**
- **BLOOM better agreement empirical results**

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1. Overview of Delft3D modelling system
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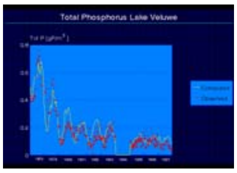
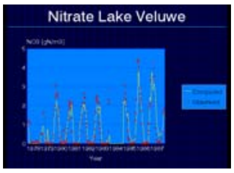
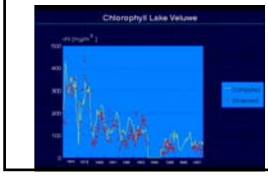
Validation: general

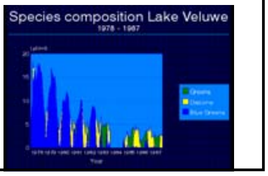
- First application fresh water model 30 years ago, marine version 15 years ago
- Both models started with coefficients from literature (lab and field)
- Some adjustments were made during previous applications (calibration)
- Both model versions have been applied very extensively (worldwide)
- At present over 90% of the coefficients are considered ‘fixed’, 5% might be adjusted locally (i.e. P sediment fixation), 5 % must be adjusted locally (i.e. background extinction)

Validation DBS Lake Veluwe

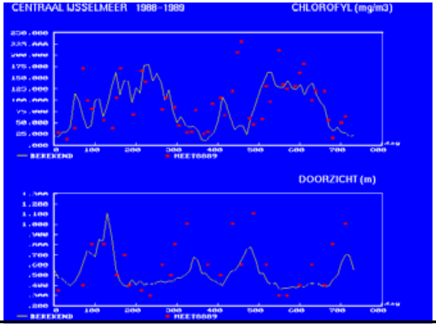




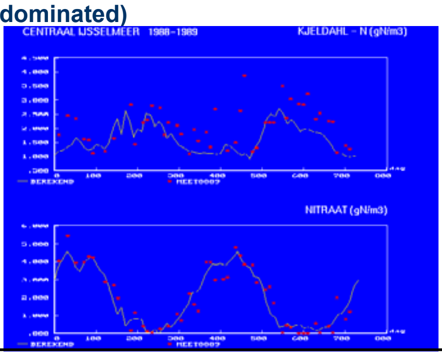




Validation DBS Lake IJssel (*Microcystis* dominated)

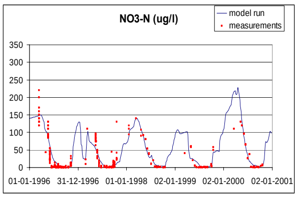


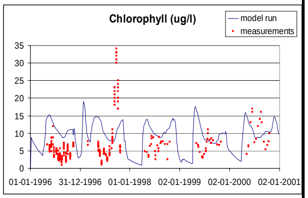
Validation DBS Lake IJssel (*Microcystis* dominated)

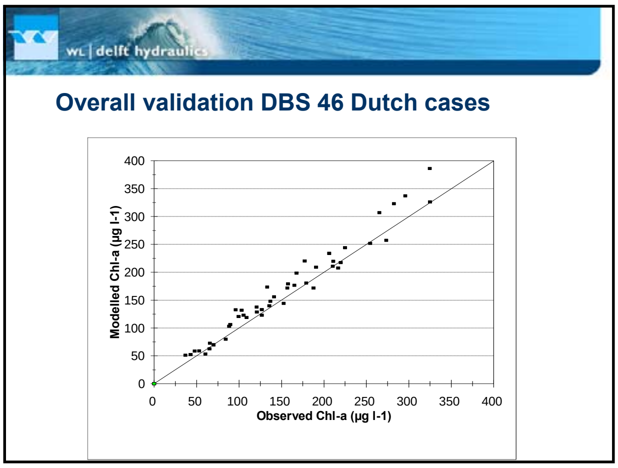


Delft3D-DBS validation Lake Pyhajarvi (Finland)

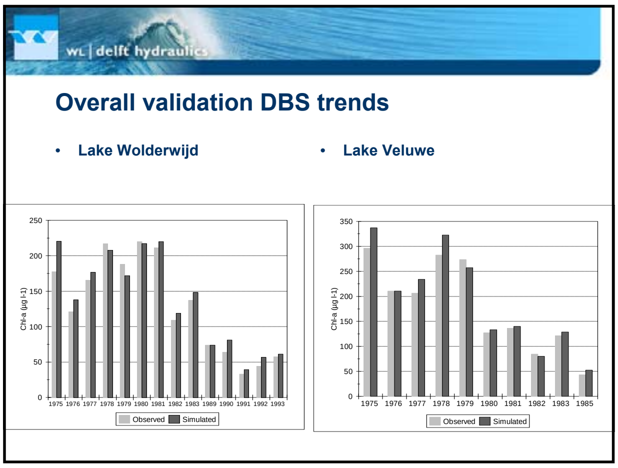
- Note: Default coefficient values were used





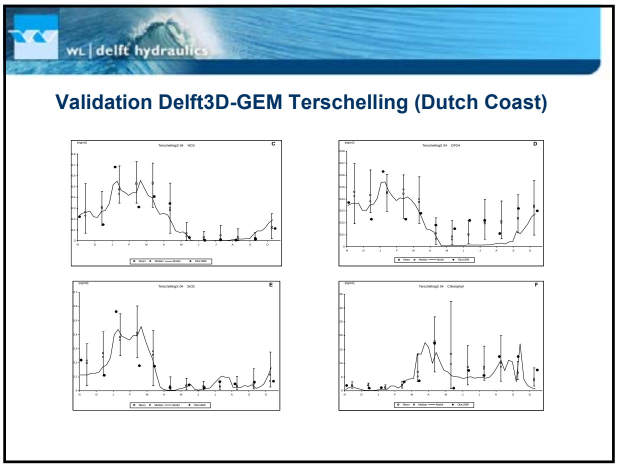


Overall validation DBS 46 Dutch cases

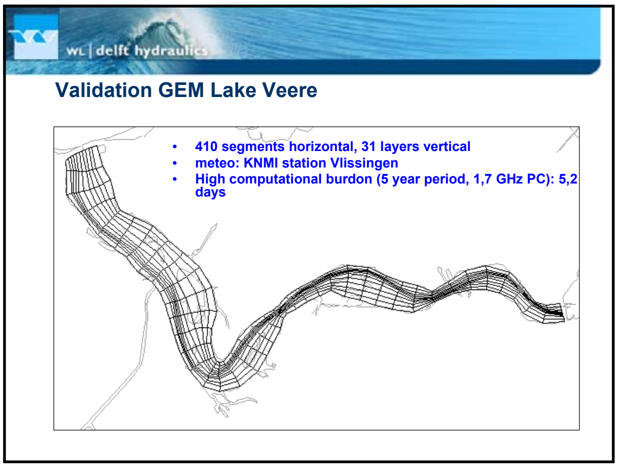


Overall validation DBS trends

- Lake Wolderwijd
- Lake Veluwe

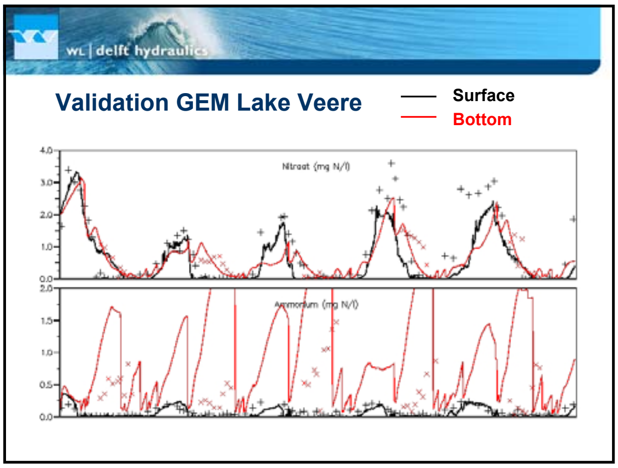


Validation Delft3D-GEM Terschelling (Dutch Coast)



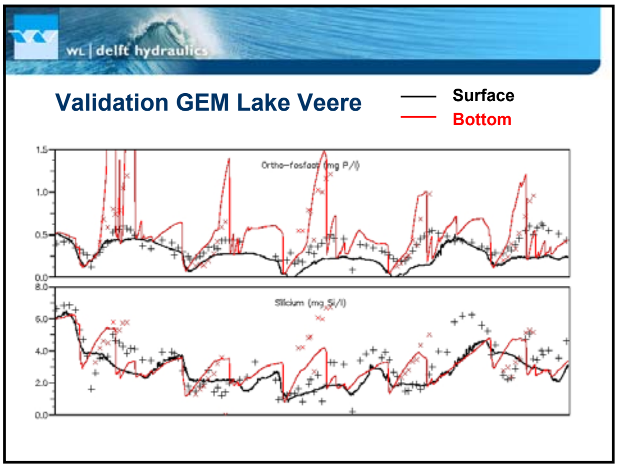
Validation GEM Lake Veere

- 410 segments horizontal, 31 layers vertical
- meteo: KNMI station Vlissingen
- High computational burdon (5 year period, 1,7 GHz PC): 5,2 days



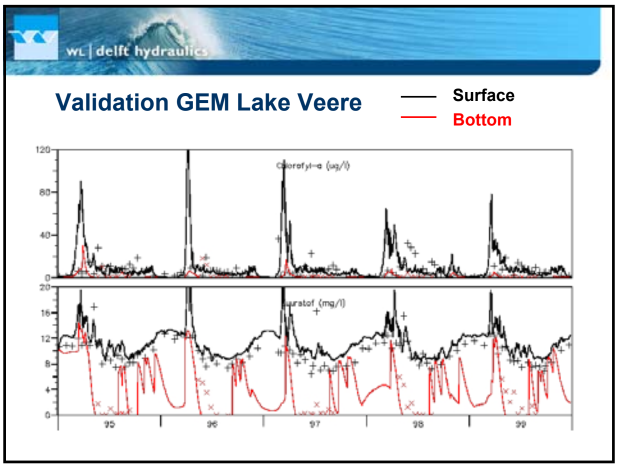
Validation GEM Lake Veere

Surface
Bottom



Validation GEM Lake Veere

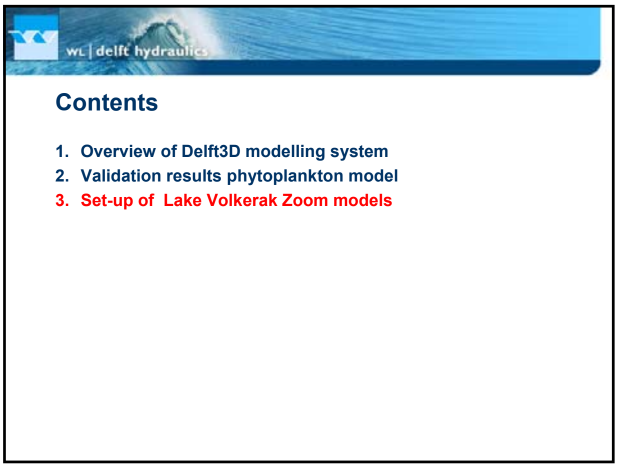
Surface
Bottom



Validation GEM Lake Veere

Surface

Bottom



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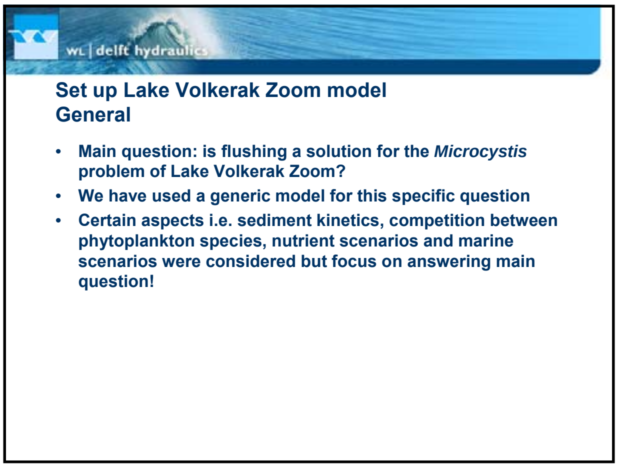
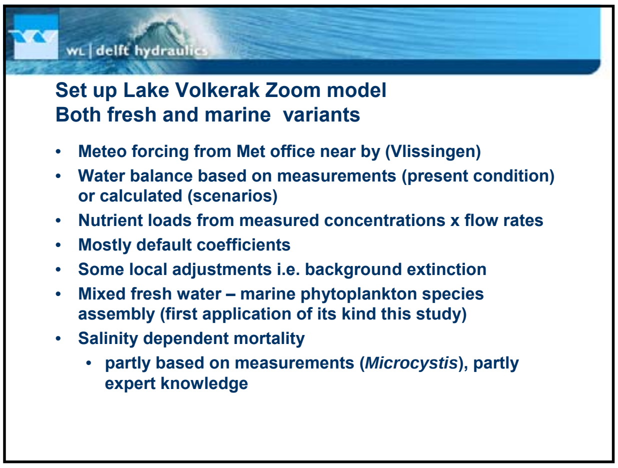
2. Validation results phytoplankton model
3. Set-up of Lake Volkerak Zoom models



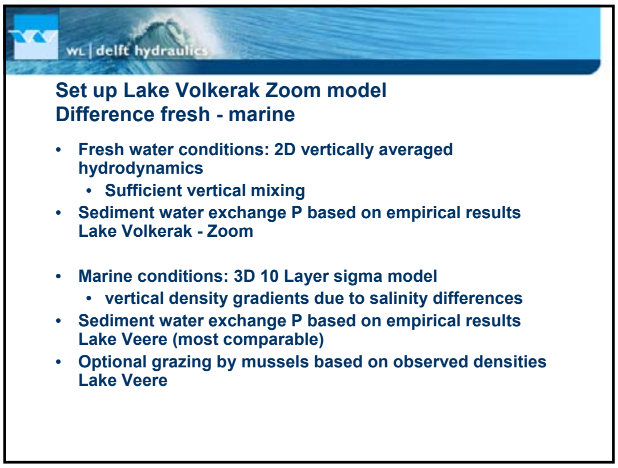
Set up Lake Volkerak Zoom model
General

- Main question: is flushing a solution for the *Microcystis* problem of Lake Volkerak Zoom?
- We have used a generic model for this specific question
- Certain aspects i.e. sediment kinetics, competition between phytoplankton species, nutrient scenarios and marine scenarios were considered but focus on answering main question!



Set up Lake Volkerak Zoom model
Both fresh and marine variants

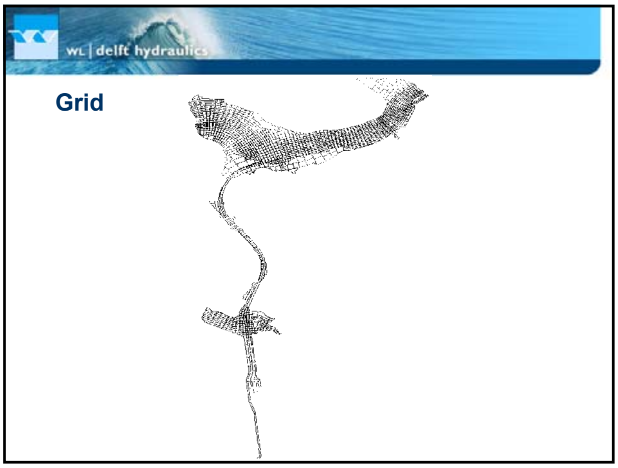
- Meteo forcing from Met office near by (Vlissingen)
- Water balance based on measurements (present condition) or calculated (scenarios)
- Nutrient loads from measured concentrations x flow rates
- Mostly default coefficients
- Some local adjustments i.e. background extinction
- Mixed fresh water – marine phytoplankton species assembly (first application of its kind this study)
- Salinity dependent mortality
  - partly based on measurements (*Microcystis*), partly expert knowledge



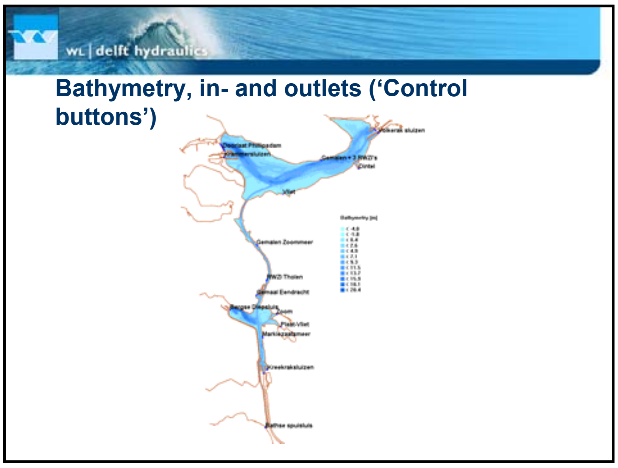
Set up Lake Volkerak Zoom model
Difference fresh - marine

- Fresh water conditions: 2D vertically averaged hydrodynamics
  - Sufficient vertical mixing
- Sediment water exchange P based on empirical results Lake Volkerak - Zoom

- Marine conditions: 3D 10 Layer sigma model
  - vertical density gradients due to salinity differences
- Sediment water exchange P based on empirical results Lake Veere (most comparable)
- Optional grazing by mussels based on observed densities Lake Veere



Grid



Bathymetry, in- and outlets ('Control buttons')

Nutrient loads

Huidige debieten

	Referentie (=2000)		Autonome ontwikkeling		MTR normen gehaald	
	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]
H. Diep	16	358	13	229	14	215
Dintel	94	4208	94	3577	62	926
Vliet	17	1854	17	1576	17	322
Kram	1	14	1	14	1	14
Rest	28	754	28	754	28	754
Totaal	156	7188	153	6151	122	2231

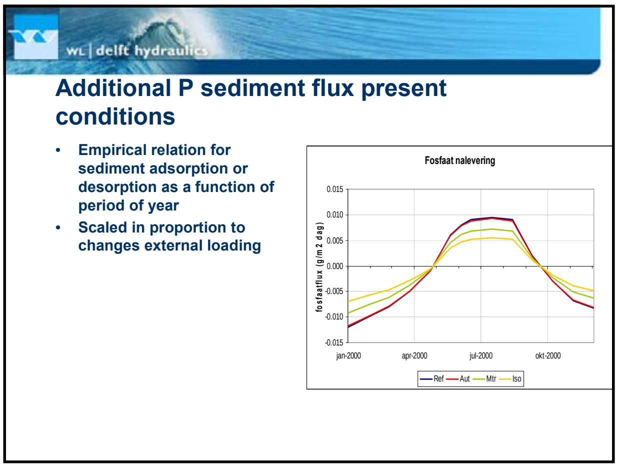
Zout

	Referentie (=2000)		Autonome ontwikkeling		MTR normen gehaald	
	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]
H. Diep	345	5571	209	3716	224	3478
Dintel	94	4208	94	3577	62	926
Vliet	17	1854	17	1576	17	322
Kram	92	1222	92	1222	92	1222
Rest	28	754	28	754	28	754
Totaal	576	13609	440	10845	423	6702

Zoet

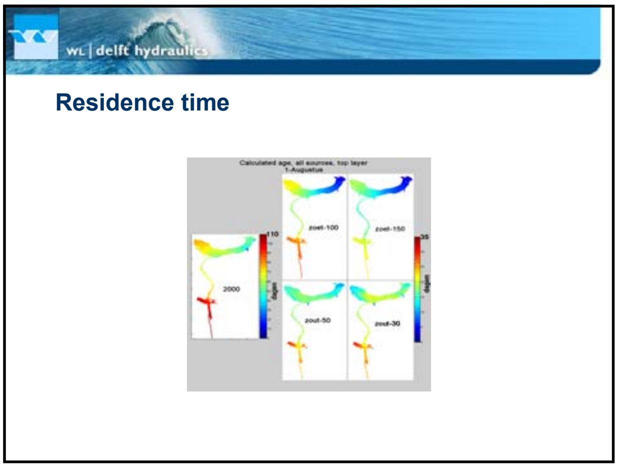
	Referentie (=2000)		Autonome ontwikkeling		MTR normen gehaald	
	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]
H. Diep	672	15934	551	10197	576	8932
Dintel	94	4208	94	3577	62	926
Vliet	17	1854	17	1576	17	322
Kram	1	14	1	14	1	14
Rest	28	754	28	754	28	754
Totaal	812	22764	692	16119	685	10948

- Under reference conditions dominated by Dintel
- Both freshwater and salt water flushing scenarios lead to enhanced loading by Hollands Diep
- Flushing combined with nutrient reduction still results in considerable increases in loading

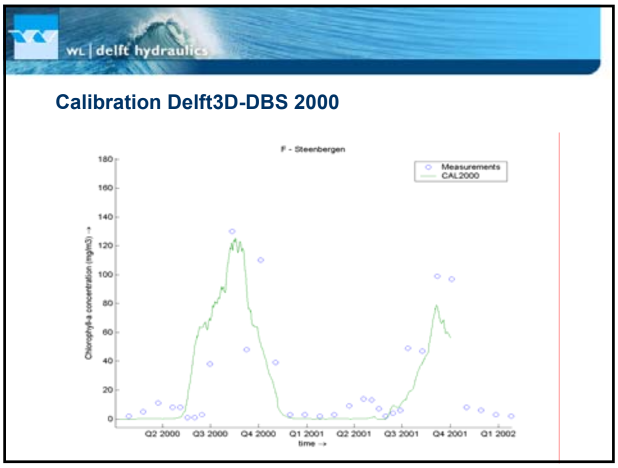


Additional P sediment flux present conditions

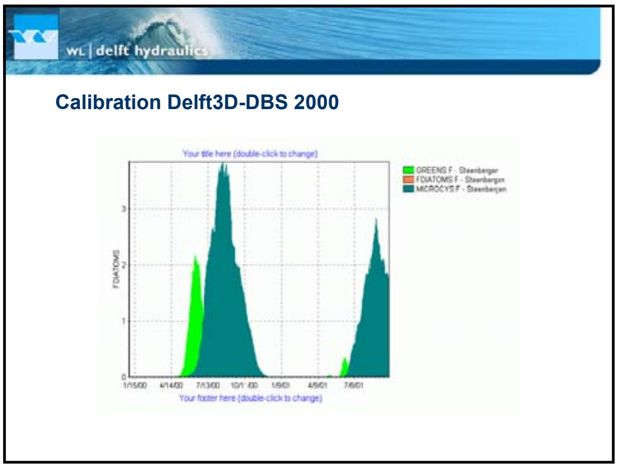
- Empirical relation for sediment adsorption or desorption as a function of period of year
- Scaled in proportion to changes external loading



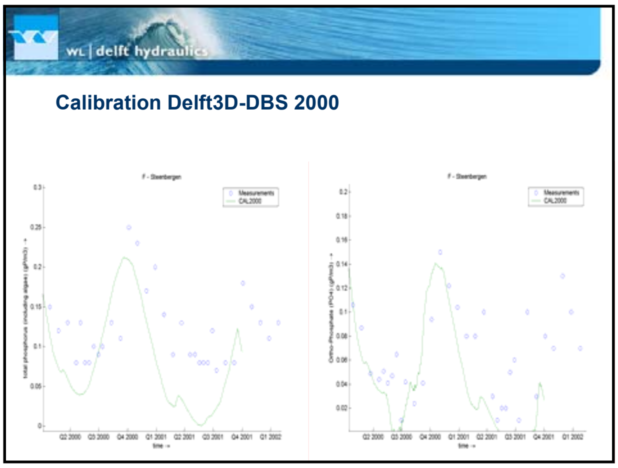
Residence time



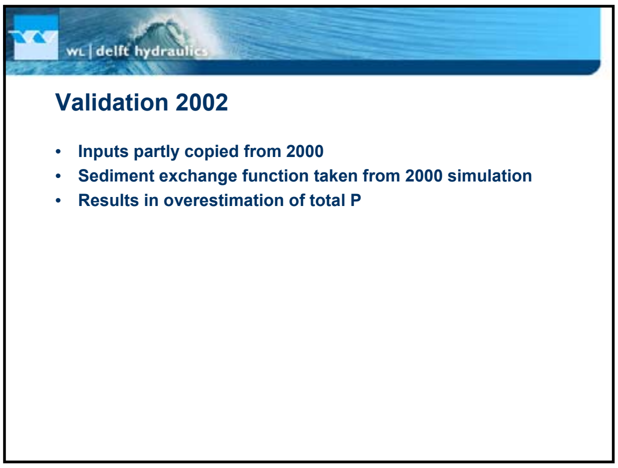
Calibration Delft3D-DBS 2000



Calibration Delft3D-DBS 2000

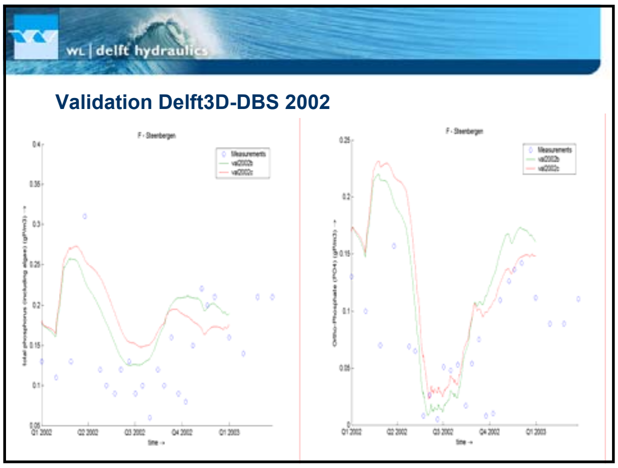


Calibration Delft3D-DBS 2000

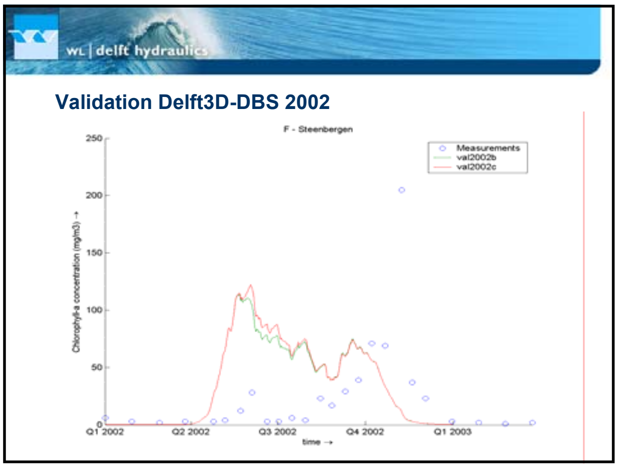


Validation 2002

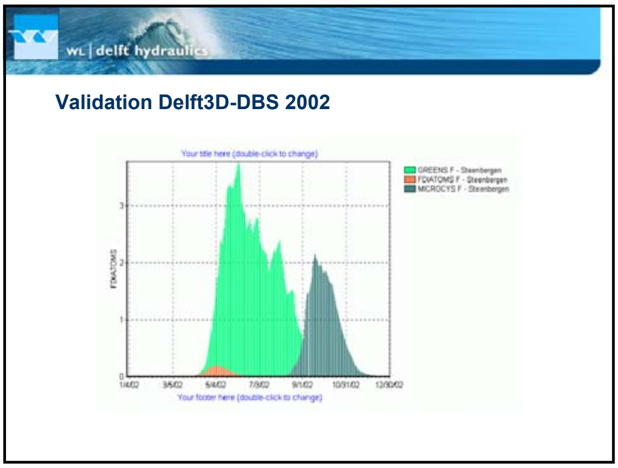
- Inputs partly copied from 2000
- Sediment exchange function taken from 2000 simulation
- Results in overestimation of total P



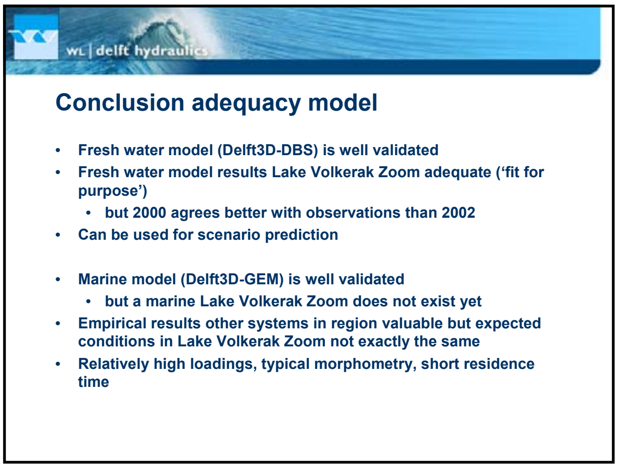
Validation Delft3D-DBS 2002



Validation Delft3D-DBS 2002



Validation Delft3D-DBS 2002

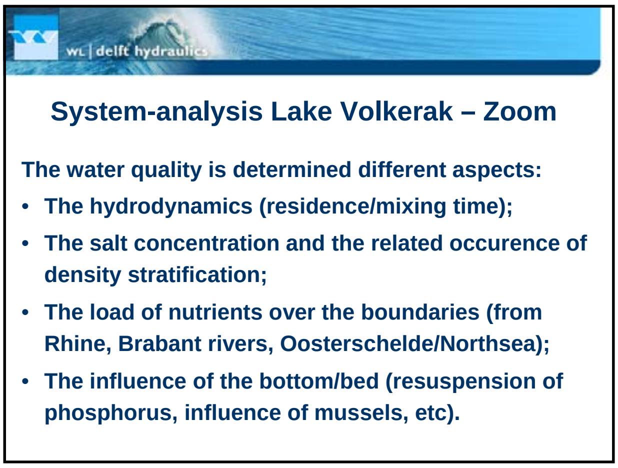


Conclusion adequacy model

- Fresh water model (Delft3D-DBS) is well validated
- Fresh water model results Lake Volkerak Zoom adequate (‘fit for purpose’)
  - but 2000 agrees better with observations than 2002
- Can be used for scenario prediction

- Marine model (Delft3D-GEM) is well validated
  - but a marine Lake Volkerak Zoom does not exist yet
- Empirical results other systems in region valuable but expected conditions in Lake Volkerak Zoom not exactly the same
- Relatively high loadings, typical morphometry, short residence time

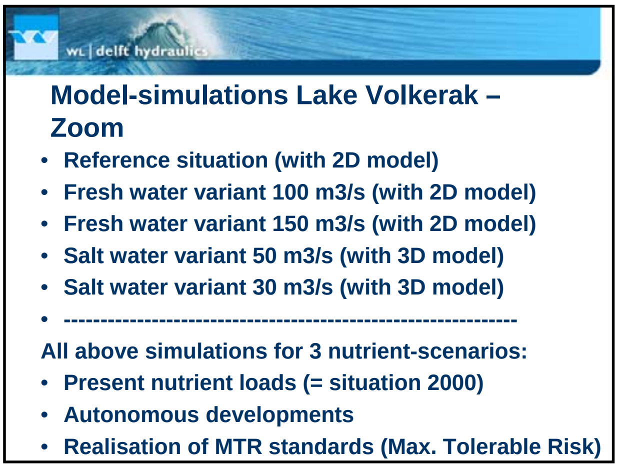
Appendix E: Presentation Simon Groot (Delft Hydraulics)



System-analysis Lake Volkerak – Zoom

The water quality is determined different aspects:

- The hydrodynamics (residence/mixing time);
- The salt concentration and the related occurence of density stratification;
- The load of nutrients over the boundaries (from Rhine, Brabant rivers, Oosterschelde/Northsea);
- The influence of the bottom/bed (resuspension of phosphorus, influence of mussels, etc).

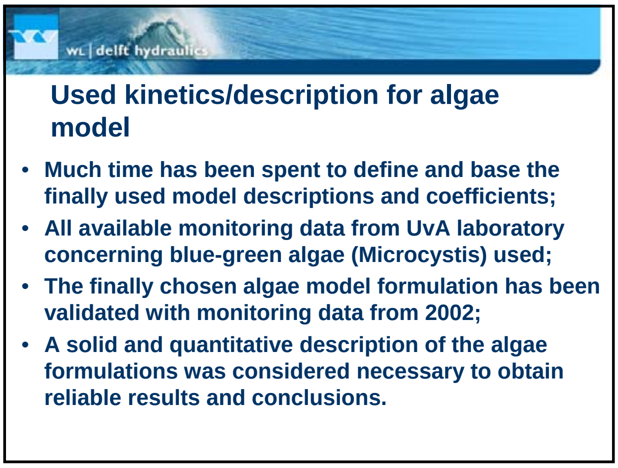


Model-simulations Lake Volkerak – Zoom

- Reference situation (with 2D model)
- Fresh water variant 100 m3/s (with 2D model)
- Fresh water variant 150 m3/s (with 2D model)
- Salt water variant 50 m3/s (with 3D model)
- Salt water variant 30 m3/s (with 3D model)
- ---

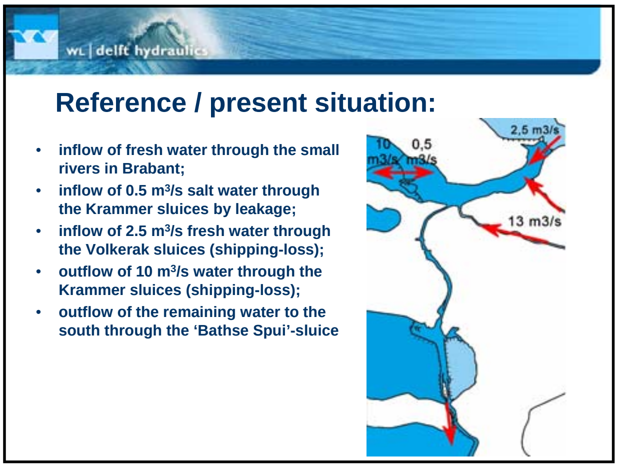
All above simulations for 3 nutrient-scenarios:

- Present nutrient loads (= situation 2000)
- Autonomous developments
- Realisation of MTR standards (Max. Tolerable Risk)



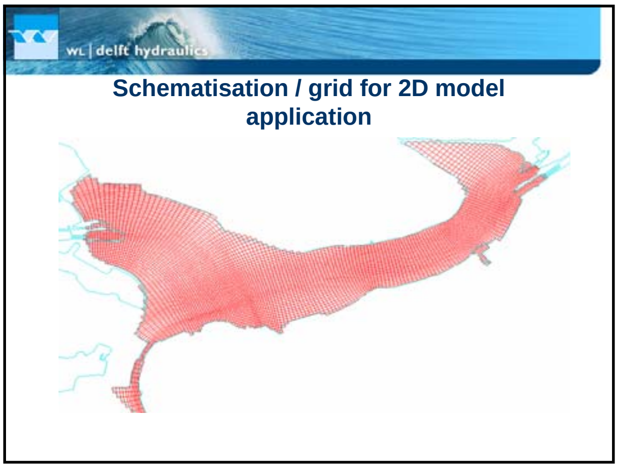
Used kinetics/description for algae model

- Much time has been spent to define and base the finally used model descriptions and coefficients;
- All available monitoring data from UvA laboratory concerning blue-green algae (Microcystis) used;
- The finally chosen algae model formulation has been validated with monitoring data from 2002;
- A solid and quantitative description of the algae formulations was considered necessary to obtain reliable results and conclusions.

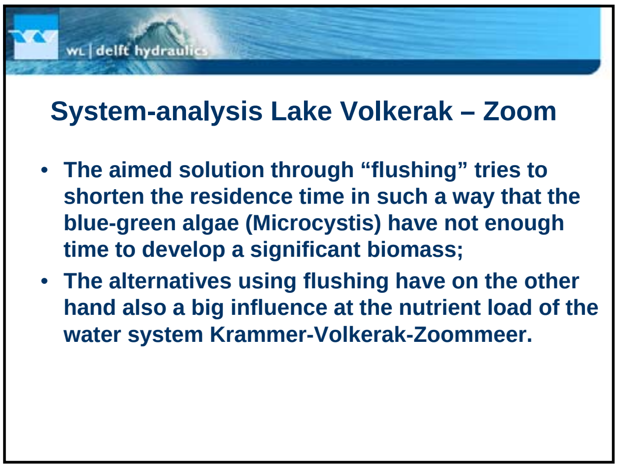


Reference / present situation:

- inflow of fresh water through the small rivers in Brabant;
- inflow of 0.5 m^3/s salt water through the Krammer sluices by leakage;
- inflow of 2.5 m^3/s fresh water through the Volkerak sluices (shipping-loss);
- outflow of 10 m^3/s water through the Krammer sluices (shipping-loss);
- outflow of the remaining water to the south through the ‘Bathse Spui’-sluice

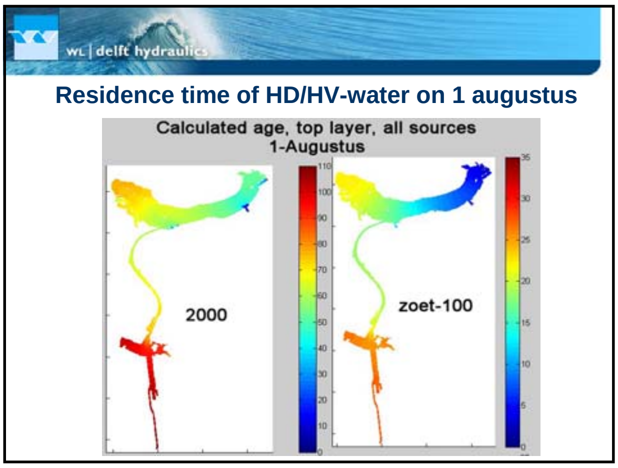


Schematisation / grid for 2D model application

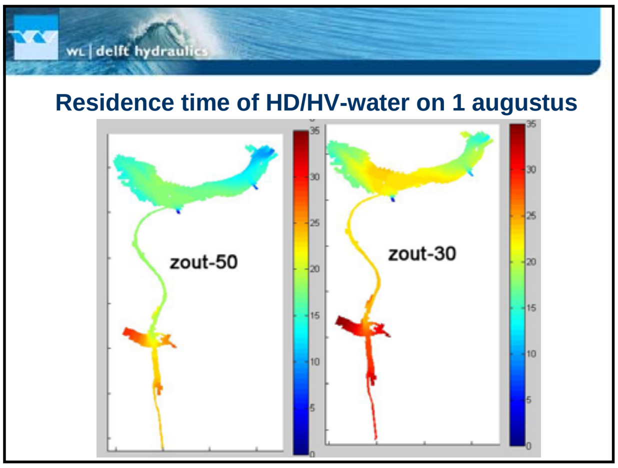


System-analysis Lake Volkerak – Zoom

- The aimed solution through “flushing” tries to shorten the residence time in such a way that the blue-green algae (Microcystis) have not enough time to develop a significant biomass;
- The alternatives using flushing have on the other hand also a big influence at the nutrient load of the water system Krammer-Volkerak-Zoommeer.



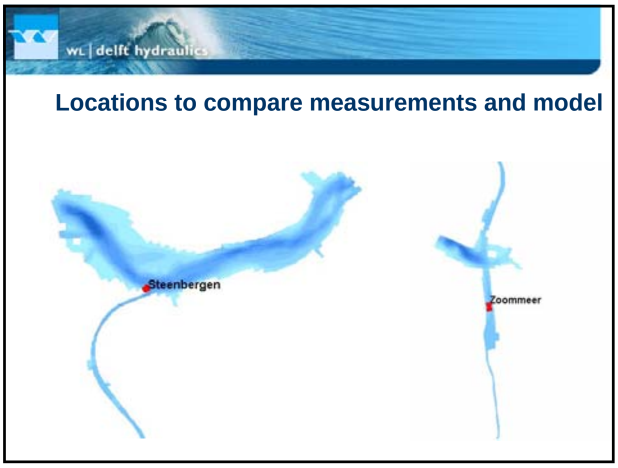
Residence time of HD/HV-water on 1 augustus



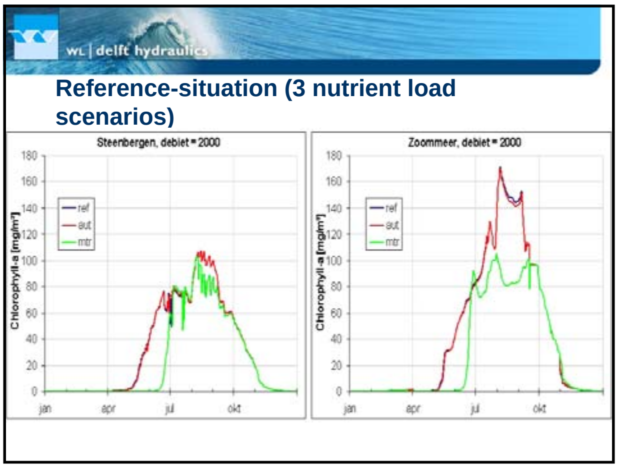
Residence time of HD/HV-water on 1 augustus

Used boundary concentrations:

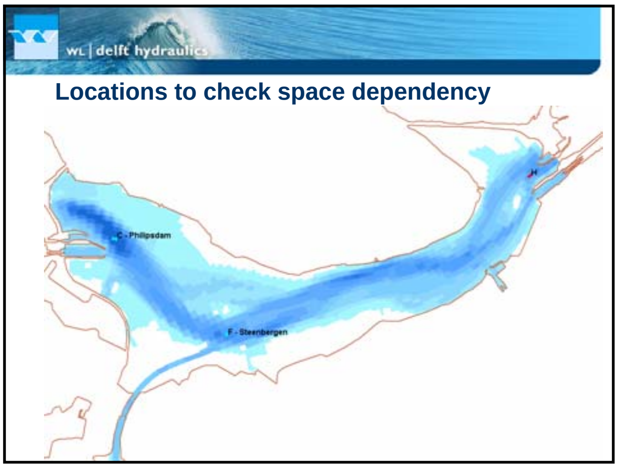
1. Present situation: all boundary concentrations as in the year 2000;
2. Autonomous development: as in the year 2000, with:
   - Brabant rivers: stand-still for P and 15% reduction for N;
   - Hollandsch Diep: 18% P-reduction and 36% for N;
3. MTR-standards have been realised: TotP < 0.15 mg/l and TotN < 2.2 mg/l.



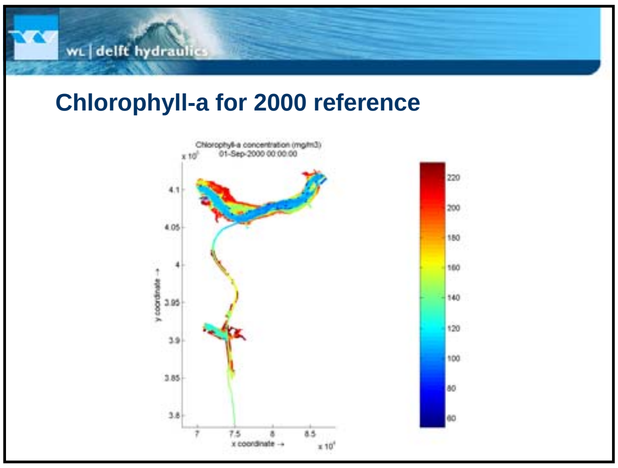
Locations to compare measurements and model



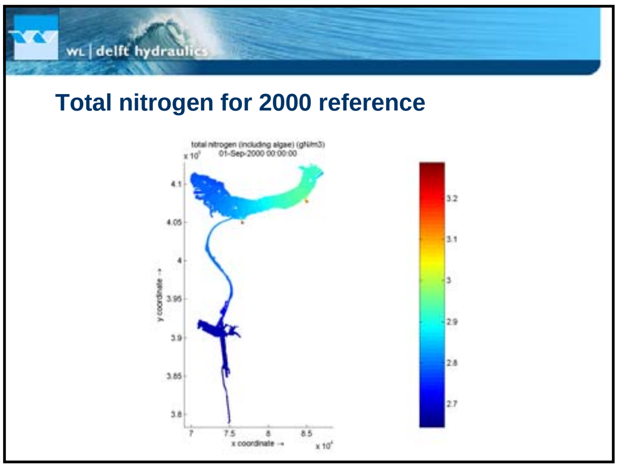
Reference-situation (3 nutrient load scenarios)



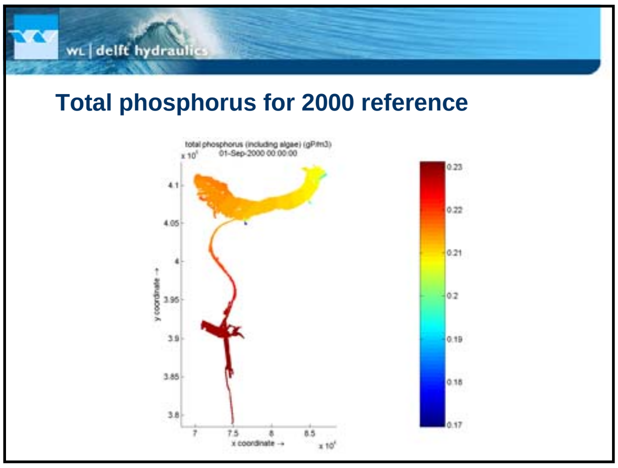
Locations to check space dependency



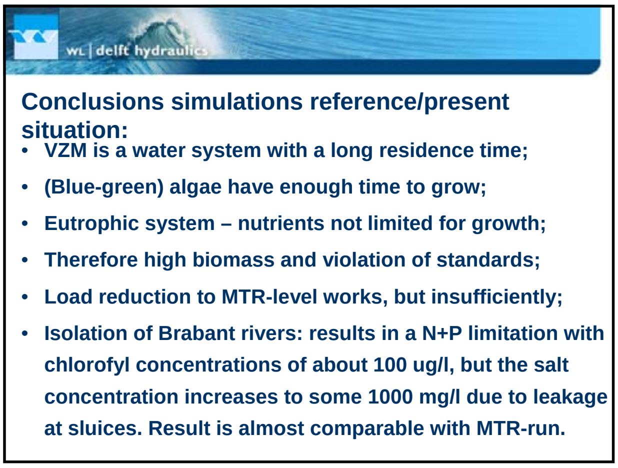
Chlorophyll-a for 2000 reference



Total nitrogen for 2000 reference

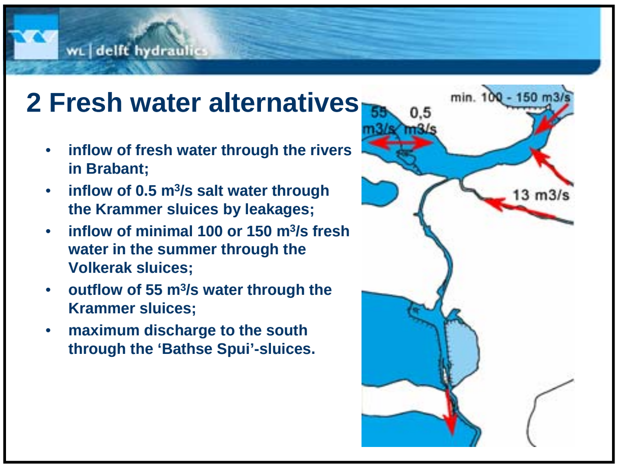


Total phosphorus for 2000 reference



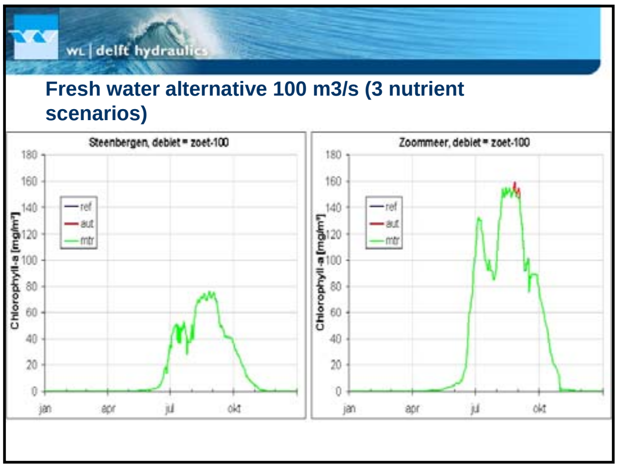
Conclusions simulations reference/present situation:

- VZM is a water system with a long residence time;
- (Blue-green) algae have enough time to grow;
- Eutrophic system – nutrients not limited for growth;
- Therefore high biomass and violation of standards;
- Load reduction to MTR-level works, but insufficiently;
- Isolation of Brabant rivers: results in a N+P limitation with chlorofyl concentrations of about 100 ug/l, but the salt concentration increases to some 1000 mg/l due to leakage at sluices. Result is almost comparable with MTR-run.

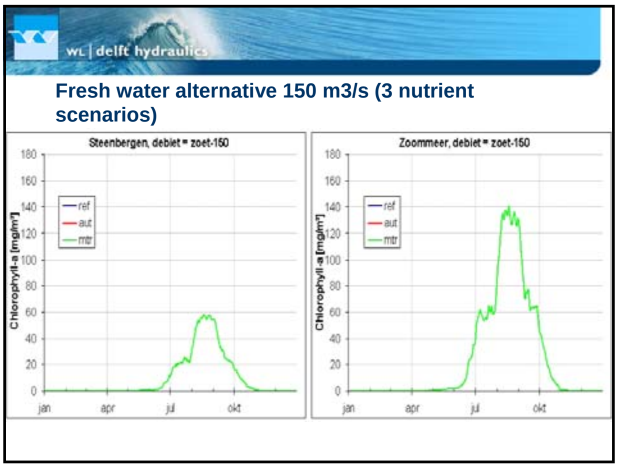


2 Fresh water alternatives

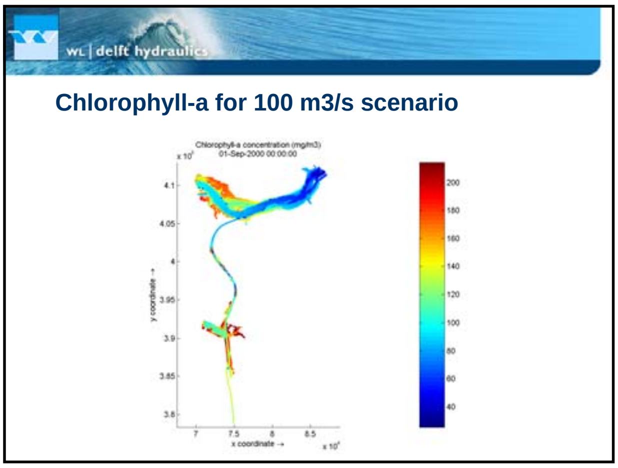
- inflow of fresh water through the rivers in Brabant;
- inflow of 0.5 m³/s salt water through the Krammer sluices by leakages;
- inflow of minimal 100 or 150 m³/s fresh water in the summer through the Volkerak sluices;
- outflow of 55 m³/s water through the Krammer sluices;
- maximum discharge to the south through the 'Bathse Spui'-sluices.



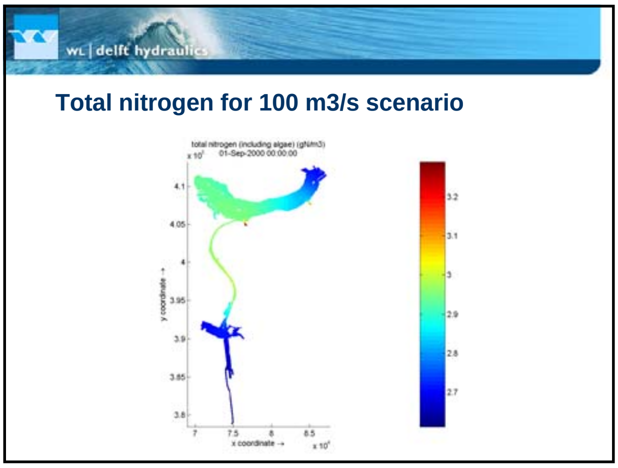
Fresh water alternative 100 m3/s (3 nutrient scenarios)



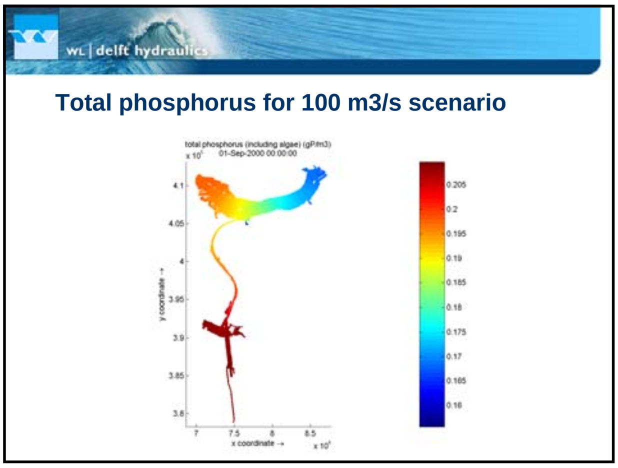
Fresh water alternative 150 m3/s (3 nutrient scenarios)



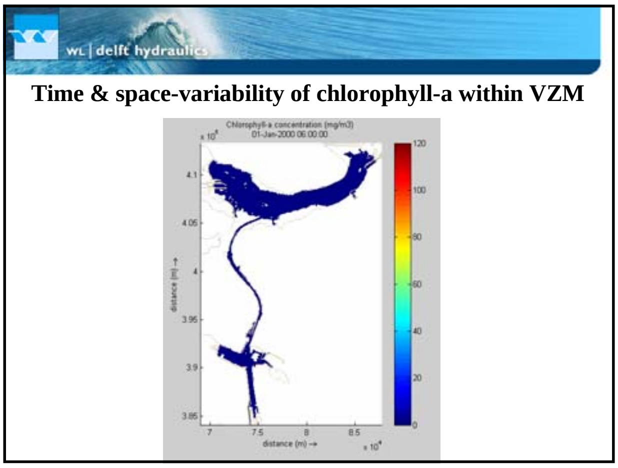
Chlorophyll-a for 100 m3/s scenario



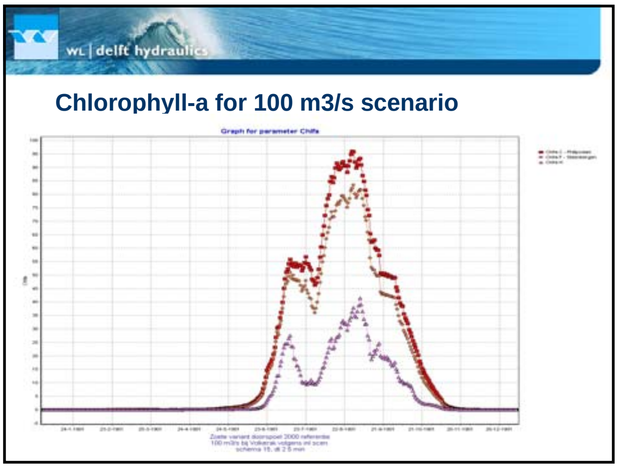
Total nitrogen for 100 m3/s scenario



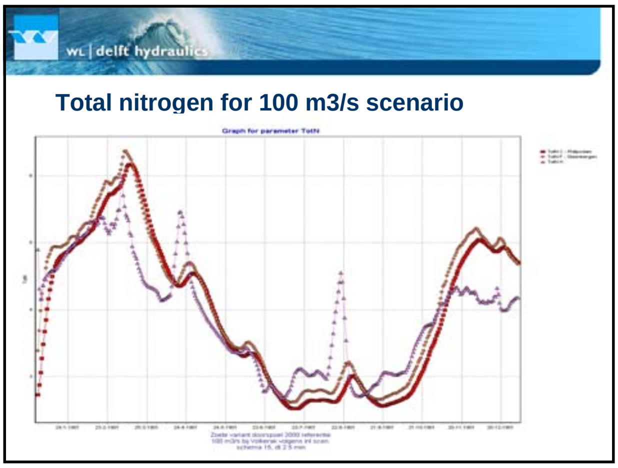
Total phosphorus for 100 m3/s scenario



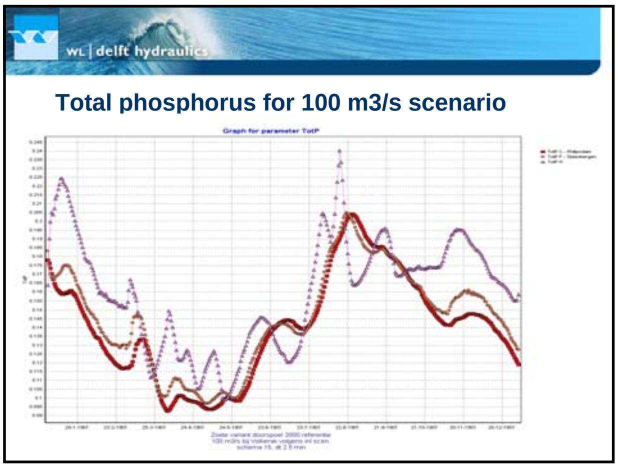
Time & space-variability of chlorophyll-a within VZM



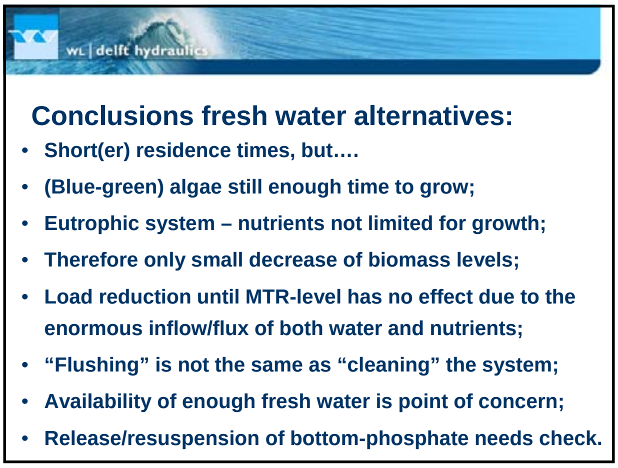
Chlorophyll-a for 100 m3/s scenario



Total nitrogen for 100 m3/s scenario

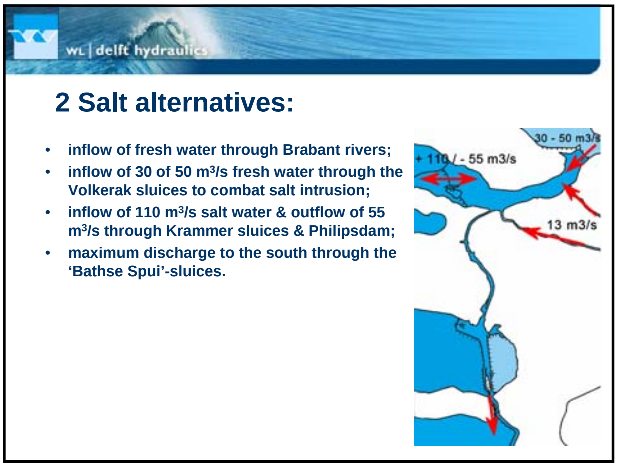


Total phosphorus for 100 m3/s scenario



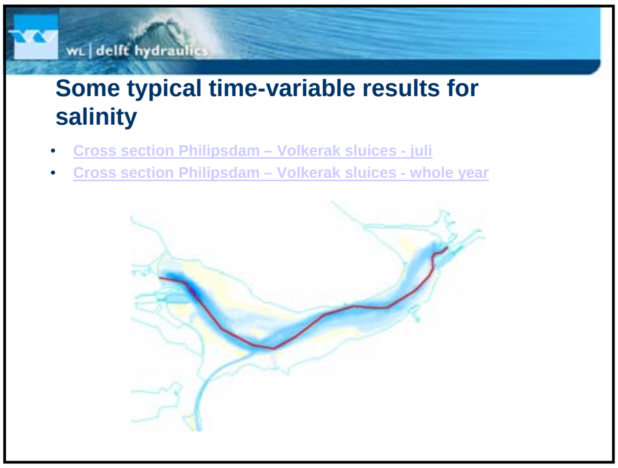
Conclusions fresh water alternatives:

- Short(er) residence times, but….
- (Blue-green) algae still enough time to grow;
- Eutrophic system – nutrients not limited for growth;
- Therefore only small decrease of biomass levels;
- Load reduction until MTR-level has no effect due to the enormous inflow/flux of both water and nutrients;
- “Flushing” is not the same as “cleaning” the system;
- Availability of enough fresh water is point of concern;
- Release/resuspension of bottom-phosphate needs check.



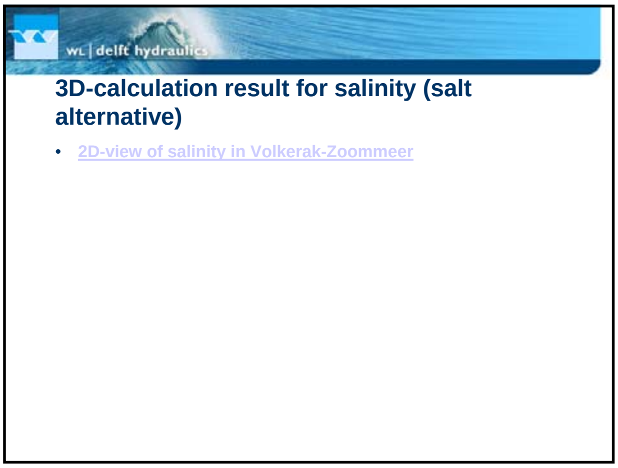
2 Salt alternatives:

- inflow of fresh water through Brabant rivers;
- inflow of 30 of 50 m³/s fresh water through the Volkerak sluices to combat salt intrusion;
- inflow of 110 m³/s salt water & outflow of 55 m³/s through Krammer sluices & Philipsdam;
- maximum discharge to the south through the ‘Bathse Spui’-sluices.



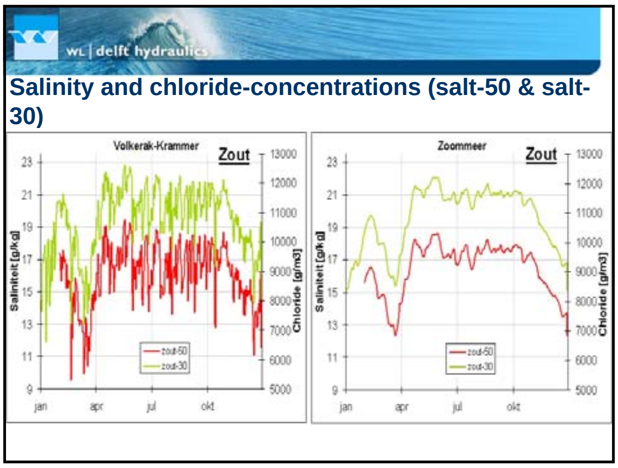
Some typical time-variable results for salinity

- Cross section Philipsdam – Volkerak sluices - juli
- Cross section Philipsdam – Volkerak sluices - whole year

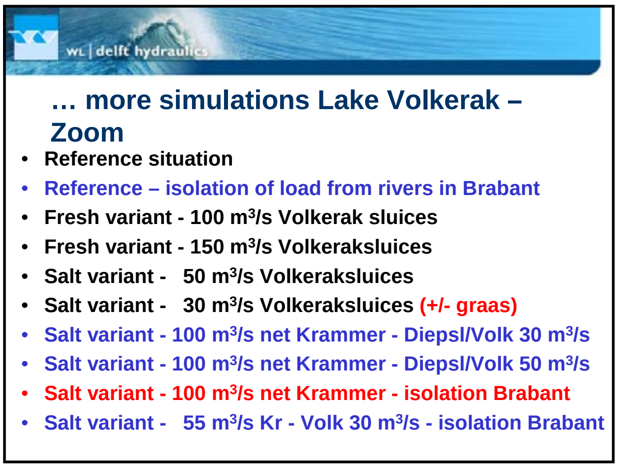


3D-calculation result for salinity (salt alternative)

- 2D-view of salinity in Volkerak-Zoommeer

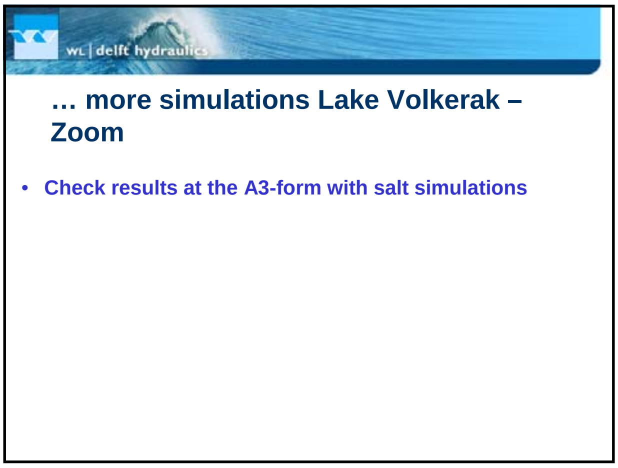


Salinity and chloride-concentrations (salt-50 & salt-30)



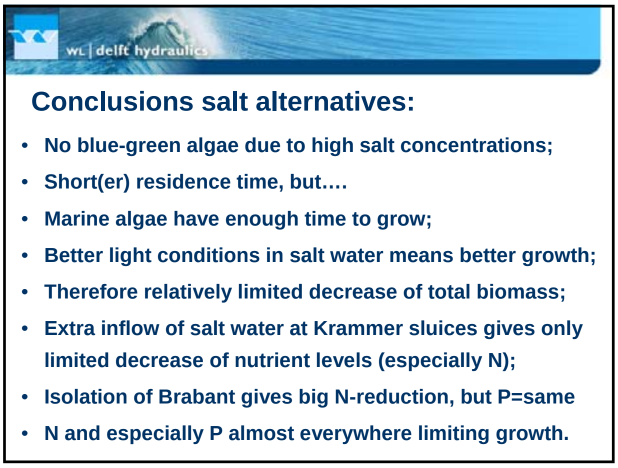
… more simulations Lake Volkerak – Zoom

- Reference situation
- Reference – isolation of load from rivers in Brabant
- Fresh variant - 100 m^3/s Volkerak sluices
- Fresh variant - 150 m^3/s Volkeraksluices
- Salt variant -   50 m^3/s Volkeraksluices
- Salt variant -   30 m^3/s Volkeraksluices (+/- graas)
- Salt variant - 100 m^3/s net Krammer - Diepsl/Volk 30 m^3/s
- Salt variant - 100 m^3/s net Krammer - Diepsl/Volk 50 m^3/s
- Salt variant - 100 m^3/s net Krammer - isolation Brabant
- Salt variant -   55 m^3/s Kr - Volk 30 m^3/s - isolation Brabant



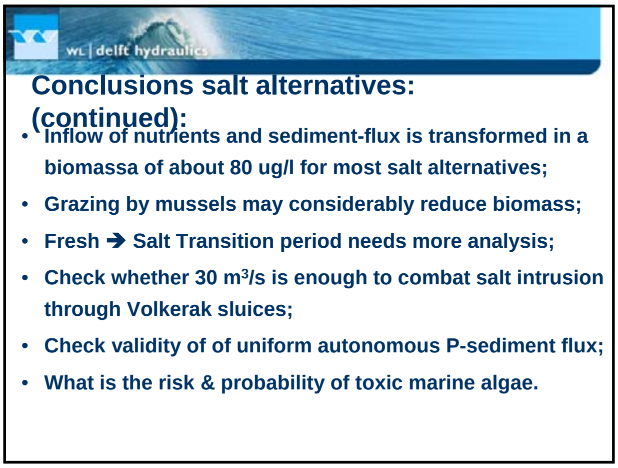
… more simulations Lake Volkerak – Zoom

- Check results at the A3-form with salt simulations



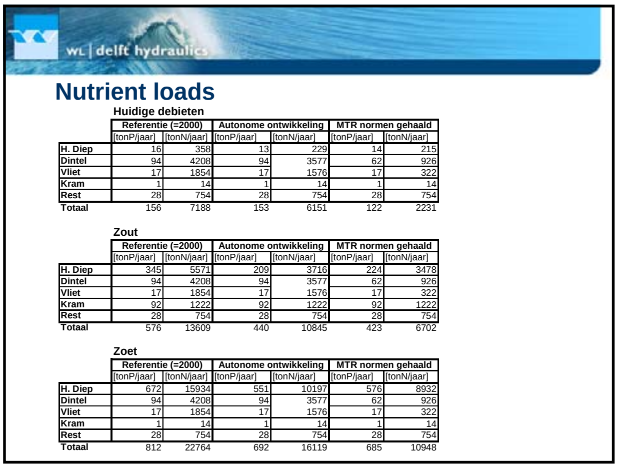
Conclusions salt alternatives:

- No blue-green algae due to high salt concentrations;
- Short(er) residence time, but….
- Marine algae have enough time to grow;
- Better light conditions in salt water means better growth;
- Therefore relatively limited decrease of total biomass;
- Extra inflow of salt water at Krammer sluices gives only limited decrease of nutrient levels (especially N);
- Isolation of Brabant gives big N-reduction, but P=same
- N and especially P almost everywhere limiting growth.



Conclusions salt alternatives: (continued):

- Inflow of nutrients and sediment-flux is transformed in a biomass of about 80 ug/l for most salt alternatives;
- Grazing by mussels may considerably reduce biomass;
- Fresh ➔ Salt Transition period needs more analysis;
- Check whether 30 m^3/s is enough to combat salt intrusion through Volkerak sluices;
- Check validity of of uniform autonomous P-sediment flux;
- What is the risk & probability of toxic marine algae.



Nutrient loads

Huidige debieten

	Referentie (=2000)		Autonome ontwikkeling		MTR normen gehaald	
	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]
H. Diep	16	358	13	229	14	215
Dintel	94	4208	94	3577	62	926
Vliet	17	1854	17	1576	17	322
Kram	1	14	1	14	1	14
Rest	28	754	28	754	28	754
Totaal	156	7188	153	6151	122	2231

Zout

	Referentie (=2000)		Autonome ontwikkeling		MTR normen gehaald	
	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]
H. Diep	345	5571	209	3716	224	3478
Dintel	94	4208	94	3577	62	926
Vliet	17	1854	17	1576	17	322
Kram	92	1222	92	1222	92	1222
Rest	28	754	28	754	28	754
Totaal	576	13609	440	10845	423	6702

Zoet

	Referentie (=2000)		Autonome ontwikkeling		MTR normen gehaald	
	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]	[tonP/jaar]	[tonN/jaar]
H. Diep	672	15934	551	10197	576	8932
Dintel	94	4208	94	3577	62	926
Vliet	17	1854	17	1576	17	322
Kram	1	14	1	14	1	14
Rest	28	754	28	754	28	754
Totaal	812	22764	692	16119	685	10948