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RESULTATEN PILOTS 2007

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stowa@stowa.nl WWW.stowa.nl
TEL 030 232 11 99 FAX 030 231 79 80
Arthur van Schendelstraat 816
POSTBUS 8090 3503 RB UTRECHT

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Uitgave
STOWA 2008
Arthur van Schendelstraat 816
Postbus 8090
3503 RB Utrecht
Tel 030 2321199
Fax: 030 2321766
e-mail: stowa@stowa.nl
http://www.stowa.nl

Auteurs
David Burger (Deltares)
Rolf Hulsbergen (Deltares)
Hans Los (Deltares)
Simon Groot (Deltares)
Bas Ibelings (Eawag)

Begeleidingscommissie:
Begeleidingscommissie:
Jasper Stroom (Hoogheemraadschap Rijnland), voorzitter
Wil van der Ende (Hoogheemraadschap Delfland)
Johan Oosterbaan (Hoogheemraadschap Delfland)
Eva de Bruin (Waternet)
Jeroen Postema (Rijkswaterstaat IJsselmeergebied)
en Tineke Burger (Rijkswaterstaat IJsselmeergebied)
Michelle Talsma (STOWA)
Wolf Mooij (NIOO)

Alleen digitaal beschikbaar

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TEN GELEIDE

Drijflagen van blauwalgen vormen een jaarlijks terugkerend probleem in een flink deel van de Nederlandse meren en plassen. Vooral bij zwemlocaties is de overlast groot. De zichtdiepte vermindert, er kan stankoverlast optreden en er kunnen hoge toxinegehaltes ontstaan. In de nieuwe EU zwemwaterrichtlijn worden blauwalgen genoemd als een gezondheidsrisico waar tijdig en adequaat mee omgegaan moet worden. Een modelinstrumentarium waarmee een algenbloei enkele dagen van tevoren kan worden voorspeld kan een waterbeheerder helpen het nemen van beslissingen om maatregelen te treffen en waarschuwingen te geven om recreanten te beschermen.

De doelstelling van dit project is om een waarschuwingssysteem te ontwikkelen dat drijflaagvorming door blauwalgen in kleine en grote binnenwateren kan voorspellen. Met het waarschuwingssysteem moet per meer of plas een aantal dagen vooruit voorspeld kunnen worden waar en wanneer drijflagen zullen ontstaan. Hiermee wordt voldaan aan de nieuwe zwemwaterrichtlijn waarin het voorkómen van blootstelling en het gebruiken van waarschuwingssystemen belangrijke onderdelen zijn.

Om te komen tot een werkend waarschuwingssysteem is in 2007 gestart met de bouw van het model en is het toegepast in een viertal meren. De resultaten van deze pilot studies treft u in dit rapport aan. Geconcludeerd is dat het voorspellingsmodel potentie heeft maar dat bij gebrek aan validatie gegevens de betrouwbaarheid van de voorspellingen nog te wensen overlaat. De (matige) zomer van 2007 was hier voor een deel debet aan. Door weinig zon, veel wind en neerslag zijn in beperkte mate (persistente) drijflagen tot ontwikkeling gekomen en daarmee weinig veldgegevens verzameld waarmee het model gevalideerd kan worden. In de zomer van 2008 zullen de pilots voortgezet worden om meer validatiegegevens te verkrijgen om de betrouwbaarheid van de modelvoorspellingen te verbeteren en ervaring op te doen met de bruikbaarheid van de voorspellingen in de praktijk.

Juli 2008,

J.M.J. Leenen
Directeur STOWA

SAMENVATTING

Overmatige groei van blauwalgen (cyano-bacteriën) is in de eutrofe meren in Nederland een groot probleem. Vooral tijdens de zomermaanden met stabiel weer en oplopende watertemperaturen, groeien blauwalgen snel en ontstaan door het opdrijvende vermogen van blauwalgen omvangrijke drijflagen aan het wateroppervlak. Onder invloed van een zwakke wind kunnen deze drijflagen naar de oevers worden getransporteerd om zich daar op te hopen. Afhankelijk van de locale omstandigheden kan een dergelijke algenbloei meerdere weken voor problemen zorgen.

Drijflagen van blauwalgen kunnen grote effecten hebben op aquatische systemen, waaronder een aanzienlijke vermindering van het doorzicht in de waterkolom, lage zuurstofgehalten, stank en een grote invloed op de belevingswaarde voor recreanten en omwonenden. Daarnaast produceren blauwalgen toxines waardoor drijflagen een direct gevaar kunnen vormen voor de gezondheid van recreanten en in het bijzonder van mensen die in direct contact komen met water, zoals zwemmers en surfers. Voor een goed waterbeheer en het minimaliseren van de gezondheidsrisico's die samenhangen met drijflagen van blauwalgen, meten de waterbeheerders de waterkwaliteit en het optreden van drijflagen. Bij grote drijflaagvorming kunnen er waarschuwingen worden gegeven of zwemverboden worden ingesteld. Als op basis van modelsimulaties een aantal dagen vooraf een voorspelling zou kunnen worden gegeven van het tijdstip en locatie van drijflagen, dan zou de waterbeheerder eerder gerichte maatregelen kunnen nemen en recreanten beter en op tijd kunnen informeren over de mogelijke gezondheidsrisico's.

In dit project is door Deltares een model opgezet waarmee het verschijnen en verdwijnen van drijflagen van blauwalgen middels 'Fuzzy Logic' technologie wordt beschreven. Het mede op 'Fuzzy Logic' gebaseerde model voorspelt drijflagen van blauwalgen door slimme combinatie van kwalitatieve expert-kennis over de vorming van drijflagen met beschikbare kwantitatieve gegevens van mogelijke verklarende variabelen. Met 'Fuzzy Logic' kan beschikbare kwantitatieve informatie worden gecombineerd met kwalitatieve expert-kennis die anders ongebruikt zou blijven. Deze alternatieve modelopzet is gekozen vanwege de onzekerheden en moeilijkheden bij de deterministische modellering van drijflagen.

Het drijflagenmodel is voor de periode van 1 juli tot 30 september 2007 getest met gegevens van de Delftse Hout, de Sloterplas, de Westeinderplassen en het Gooi/Eemmeer. De proefgebieden vervullen een belangrijke recreatiefunctie en hebben bovendien in de zomermaanden regelmatig (over)last van drijflagen van blauwalgen. Het uiteindelijke doel is om rond het drijflagenmodel een volledig operationeel waarschuwingssysteem te ontwikkelen waarmee drijflagen van blauwalgen tot vijf dagen van tevoren in zowel kleine als grote meren kunnen worden voorspeld. Het waarschuwingssysteem moet een minimale inzet en data van gebruikers koppelen aan een maximale bruikbaarheid van de geleverde informatie. De huidige modeltoepassingen hebben een karakteristieke rekentijd van één uur voor een simulatieperiode van twee weken.

De vergelijking van modelsimulaties met observaties in de vier proefgebieden spitst zich vooral toe op het moment waarop een drijflaag verschijnt, aanwezig is, of weer verdwijnt. Analyse van de resultaten geeft aan dat het 'Fuzzy Logic' principe, dat eerder werd toegepast op drijflaagvorming in het IJsselmeer, ook gebruikt kan worden in veel kleinere meren. De resultaten van de in de huidige studie uitgevoerde gevoeligheidsanalyse op de Fuzzy-parameters in het model geven aan dat wind de belangrijkste verklarende variabele in het model is voor het optreden van drijflagen. Vanwege deze directe relatie tussen drijflaagvorming en windsnelheid is het van belang dat windgegevens in m/s ter beschikking staan in plaats van de minder gedetailleerde Beaufort-schaal waarvan in deze studie moest worden uitgegaan.

Om bij veldmetingen in de proefgebieden een snelle visuele karakterisering te kunnen geven van een waargenomen drijflaag, is door algenexperts een maatlat gedefinieerd waarbij drijflagen worden ingedeeld in vier categorieën. Een aanduiding met categorie 2 of hoger impliceert een drijflaag. Door het geringe aantal waarnemingen van drijflagen dat beschikbaar is voor de calibratie van de Delftse Hout (13 maal een drijflaag van categorie 2 of hoger in de zomer van 2007) bleek een gedetailleerde calibratie niet mogelijk en moest worden volstaan met een gekozen set coefficienten waarbij een balans is gevonden tussen het aantal goed voorspelde drijflagen en het aantal onterecht voorspelde drijflagen. Met behulp van de 13 waargenomen kortstondige drijflagen in de Delftse Hout is in detail gekeken naar de momenten waarop drijflagen opkomen en verdwijnen. De aanwezigheid van drijflagen van categorie 2 of meer in de verschillende zones van de plas wordt vrij goed door het model gesimuleerd (10 van de 13 drijflagen), maar daar staat tegenover dat het aantal malen dat een drijflaag wordt voorspeld die niet is waargenomen aanzienlijk is.

Een gedetailleerde beschouwing van een aantal belangrijke invoergrootheden, zoals de drempelwaarde voor de biomassa waarboven men van een drijflaag spreekt, de coefficienten die het verschijnen en verdwijnen van drijflagen beschrijven en de relatie met de windsnelheid, geeft aan dat het aantal onterecht voorspelde drijflagen gereduceerd kan worden maar dat dit in de modeltoepassing voor de Delftse Hout ten koste gaat van het aantal correct voorspelde drijflagen. Een gewijzigde keuze van invoergrootheden geeft dus geen echte verbetering van de modelresultaten, ook al is deze observatie slechts gebaseerd op een beperkt aantal waarnemingen van drijflagen.

Voor het Gooimeer/Eemmeer, de Sloterplas en de Westeinderplassen kon het model niet volledig worden gecalibreerd en gevalideerd door een algeheel gebrek aan gegevens over drijflagen en daarnaast het lage blauwalgenbiomassa-niveau in de zomer in vergelijking met voorgaande jaren. Gebruikmakend van deze geringe hoeveelheid gegevensmateriaal en uitgaande van modelparameter ‘drijflaagvorming’ als indicator voor het optreden van drijflagen, presteerde de modeltoepassing voor deze meren niet zo goed als voor de Delftse Hout alhoewel meer calibratie-gegevens noodzakelijk zijn om dit nader te onderzoeken.

Om het drijflagenmodel blauwalgen verder te verbeteren en gereed te maken voor operationeel gebruik in een waarschuwingssysteem zijn een aantal aanbevelingen en aanvullende onderzoeksactiviteiten geformuleerd. De aanbevelingen zijn zowel gerelateerd aan de drijflagen-modelcode en gemodelleerde processen, als aan de beschikbaarheid van meer en gedetailleerdere veldgegevens afkomstig van de in 2008 uit te voeren bemonsteringscampagne voor drijflagen in dezelfde vier proefgebieden. Voor de meetcampagne worden naast de conventionele bemonsteringstechnieken een aantal alternatieve meetmethoden voorgesteld, waaronder het gebruik van foto’s, webcams, spectrale camera’s gemonteerd op boeien, en regelmatige luchtfoto’s bij optreden van algenbloei en drijflaagvorming.
Bij zowel drijflaagvorming als de windgedreven dispersie van drijflagen is behoefte aan kortdurende meetcampagnes, eventueel gecombineerd met remote sensing gerelateerde technieken, waarmee de dynamiek van drijflagen kan worden geanalyseerd. Daarnaast zijn

er voldoende gedetailleerde wekelijkse metingen nodig van de algenbiomassa en algensoortensamenstelling voor het slim resetten van het drijflagenmodel. Quasi real-time informatie over de blauwalgenbiomassa kan met in-situ fluoroprobes worden verzameld om gebruikt te worden bij de reset van het drijflagenmodel.

In de zomer van 2008 gaan de waterbeheerders opnieuw de drijflagen van blauwalgen in de vier proefgebieden meten in de verwachting dat er dan wel meerdaagse en omvangrijke drijflagen van blauwalgen zullen optreden. Met dergelijk nieuw gegevensmateriaal kan het drijflagenmodel beter worden gecalibreerd en kunnen de procesformuleringen in het model waar nodig worden aangepast.

DE STOWA IN HET KORT

De Stichting Toegepast Onderzoek Waterbeheer, kortweg STOWA, is het onderzoeksplatform van Nederlandse waterbeheerders. Deelnemers zijn alle beheerders van grondwater en oppervlaktewater in landelijk en stedelijk gebied, beheerders van installaties voor de zuivering van huishoudelijk afralwater en beheerders van waterkeringen. Dat zijn alle waterschappen, hoogheemraadschappen en zuiveringsschappen en de provincies.

De waterbeheerders gebruiken de STOWA voor het realiseren van toegepast technisch, natuurwetenschappelijk, bestuurlijk juridisch en sociaal-wetenschappelijk onderzoek dat voor hen van gemeenschappelijk belang is. Onderzoeksprogramma's komen tot stand op basis van inventarisaties van de behoefte bij de deelnemers. Onderzoekssuggesties van derden, zoals kennisinstituten en adviesbureaus. zijn van harte welkom. Deze suggesties toetst de STOWA aan de behoeften van de deelnemers.

De STOWA verricht zelf geen onderzoek, maar laat dit uitvoeren door gespecialiseerde instanties. De onderzoeken worden begeleid door begeleidingscommissies. Deze zijn samengesteld uit medewerkers van de deelnemers, zonodig aangevuld met andere deskundigen.

Het geld voor onderzoek, ontwikkeling, informatie en diensten brengen de deelnemers samen bijeen. Momenteel bedraagt het jaarlijkse budget zo'n zes miljoen euro.

U kunt de STOWA bereiken op telefoonnummer: 030 -2321199.
Ons adres luidt: STOWA, Postbus 8090, 3503 RB Utrecht.
Email: stowa@stowa.nl.

Website: www.stowa.nl

VOORSPELLINGSSYSTEEM BLAUWALGEN

RESULTATEN PILOTS 2007

CONTENTS

1

INLEIDING

In dit hoofdstuk worden de achterliggende redenen en directe aanleiding voor de uitvoer van het onderzoek naar efficiëntie en haalbaarheid van moerasbufferstroken in Nederland gepresenteerd. Tevens worden de verschillende mechanismen in bufferstroken die verantwoordelijk zijn voor de zuivering van nutriënten besproken en wordt aangegeven hoe het onderzoek is afgebakend.

1.1 SCUM PROBLEMS AND PREDICTION

High cyanobacterial (blue-green algae) biomass is a major problem in many eutrophic lakes in The Netherlands. Particularly during summer months when water column temperatures are warmer and weather patterns stable, cyanobacterial growth rates are high and cells may become highly buoyant leading to the formation of large scums on the water surface. Light winds may then transport the scum to the lake shoreline where the bloom continues to accumulate in the surface waters, under sheltered conditions. Dependent on climatic conditions and the stability of the water column, some blooms may persist for several weeks or even months.

Cyanobacterial scums have major impacts on aquatic systems, including a decline or complete loss of water column transparency, low oxygen concentrations, odour production and an overall decline in water quality and aesthetic value for recreational users and residents. Further, many cyanobacterial species have the ability to produce natural, intracellular toxins and during surface scum formation, toxin concentrations may increase by several orders of magnitude in a matter of just a few hours associated with the sudden increase in cyanobacterial biomass in the surface waters. The presence of a large scum along the shoreline may therefore represent a significant hazard to human health, particularly for recreational users coming in direct contact with the affected water such as swimmers.

In order to manage lake water quality and minimise potential health risks associated with the cyanobacterial blooms for recreational users, water managers carry out routine water sampling over the summer period when the development of surface scums is most likely to occur. As part of the European Swimming Directive, water samples are generally collected fortnightly although cyanobacteria cell counts and toxin analysis are currently not a mandatory part of the analyses.

Should large cyanobacterial scums be present, official warnings or closures are issued for the affected water body and beaches. For some water bodies, for example Almere Harbour, further management strategies are put into place to mitigate the spread of bloom events, including the mobilisation of surface skimmers, water jets and aeration barriers (WL l Delft Hydraulics 2007).

Cyanobacterial surface bloom formation is a highly dynamic process and cells have the ability to form a surface bloom over the course of only a few hours. Traditional sampling, especially over the fortnightly time scales as is currently carried out, is not sufficient to detect all possible surface blooms due to the limited sampling frequency and limited spatial resolution of the monitoring sites. Routine sampling on a more regular basis and at a greater spatial resolution for all lakes is not feasible and may still not capture all blooms present.

The ability to automatically forecast the timing and location of a surface cyanobacterial scum several days in advance would allow water managers to make better decisions to potentially mitigate scum transport into recreational zones, and better inform recreational users about potential health risks over the coming days.

As the formation and development of cyanobacterial scums is a complex and dynamic process, scums can not be easily predicted based on routine water quality monitoring alone. Complex water quality models may offer insights into the timing and development of bloom events in the water column as a whole, but require much site-specific data for parameterisation and calibration purposes.

In the late 1990's WL | Delft Hydraulics collaborated with RIZA to develop the model EcoFuzz (Ibelings et al, 2003), used to predict the appearance and disappearance of cyanobacterial surface blooms based on fuzzy logic modelling. Fuzzy logic was used to describe three governing conditions for surface bloom formation: (1) presence of existing cyanobacterial population (2) cell buoyancy and (3) water column stability. The model was applied to Lake IJssel, coupled with the water quality model Delwaq-BLOOM-Switch to estimate phytoplankton biomass. The model results were then compared with 12 years of NOAA-AVHRR (National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometers) satellite images for validation.

The EcoFuzz model showed very promising results with existing surface blooms in Lake IJssel predicted with a high degree of accuracy (Ibelings et al, 2003). However, it was unknown how well the model can simulate surface blooms in much smaller lakes in the Netherlands. The existing EcoFuzz model simulations also did not include simulations of shoreline scums, and was focused rather on the open waters of the lake where actual surface blooms were predicted only 5.4 % of the time. Surface scums may be expected to represent a greater problem on the shoreline of a water body, due to higher rates of cell accumulation associated with light wind transport of scums from the open waters. The shoreline of a water body is also more likely to be sheltered from the wind, and scums may persist longer in a more stable water column. Finally, the water quality model used in the study to calculate cyanobacterial biomass did not fully include vertical migration of cyanobacteria through buoyancy, which may affect the accuracy of the phytoplankton biomass calculations. Horizontal transport was incorporated as part of the existing EcoFuzz study, however, after scums were dispersed through wind action, scum biomass was not added back to the local population.

1.2 RESEARCH AIMS AND OBJECTIVES

The ultimate aim of this research is to develop a fully operational, stand alone early warning system for forecasting cyanobacterial surface scums in both small and large lake systems a few days to a week in advance. The system must be able to predict not only when surface scums develop, but also where the scums will occur, for example the shoreline location where risks of contact with the bloom are greatest for recreational users. This is of primary importance for meeting the future requirements of the European Union Bathing Water Directive, where minimising cyanobacterial exposure to recreational users and the potential use of a warning system is of primary importance. The final product must be easy to apply to different lake systems, with minimal input data and model recalibration, yet be highly reliable with an accurate forecast relative to what is actually observed in the lake. It is intended that the model must autonomously generate warnings on basis of the long term weather forecast, for up to seven days in advance.

The complete system, once incorporated into an operational warning system as part of a future study, will become an important management tool for various users, including at a Provincial level for issuing official lake warnings and closures and for communicating risks to the public, and at a lake management level (Water Boards) to prevent or minimise potential risks through the early implementation of management strategies, for example the automated activation of artificial mixing systems during scum-favourable conditions to prevent scum formation.

The overall research project is made up of three components:

1. Model code development to integrate the existing EcoFuzz model into Delft3D- FLOW, Delwaq and BLOOM II, followed by calibration and testing of the complete model instrumentation on four test locations.
2. Model code development to better describe the horizontal transport of cyanobacterial surface blooms;
3. Simulations using the complete model instrument over fortnightly reset periods for four pilot lakes between 1 July and 30 September 2008, to validate model output in respect to the timing and locality of scum formation on the basis of daily field data, and;
4. In a Phase 2 of the project (not part of this study), to develop an automated and fully operational early warning system for forecasting surface cyanobacterial blooms, based on the model development conducted in this study.

The current research described in this report is focused on Parts 1 and 2 of the above objectives. Part 3 is to be implemented as an additional study in the future if the results of the earlier phases are considered promising.

1.3 ORGANISATION AND PROJECT TEAMS

This research was commissioned by STOWA, on behalf of four Water Boards participating in the field trials: Hoogheemraadschap van Rijnland, Hoogheemraadschap van Delfland, Waternet and Rijkswaterstaat IJsselmeergebied. Although the research in the current study was carried out by Deltares (WL | Delft Hydraulics), representatives from each of the Water Boards formed an integral part of the research team to coordinate the field sampling programs for each of four test site locations. The research committee members representing the Water Boards, STOWA as well as NIOO were:

- Jasper Stroom (Hoogheemraadschap van Rijnland, Team Co-ordinator).
- Wil van der Ende and Johan Oosterbaan (Hoogheemraadschap van Delfland).
- Eva de Bruin (Waternet).
- Jeroen Postema and Tineke Burger (Rijkswaterstaat IJsselmeergebied).
- Michelle Talsma (STOWA).
- Wolf Mooij (NIOO).

Over the duration of the project, approximately monthly meetings were held between the research team of Deltares and the research committee to present and discuss the project results and progress to date. The main research team members and their contributions to this study were:

- Simon Groot (team leader).

- David Burger (development and implementation).
- Rolf Hulsbergen (computer programming 3D scum formation processes).
- Hans Los (cyanobacterial specialist and quality control).
- Bas Ibelings (Eawag, specialist cyanobacteria and Fuzzy logic modelling).

Additional computer programming support was provided by Arjan Markus and Jan van Beek.

1.4 WORK ACTIVITIES

The following research activities were carried out by Deltares as part of the current study:

1. Model development, modification and calibration, including:
   - Simulations of 3D hydrodynamics using Delft3D-FLOW;
   - Simulations of phytoplankton biomass using Delwaq-BLOOM;
   - Processes for cyanobacteria buoyancy and scum formation;
   - Processes for horizontal transport of cyanobacterial scums to the shoreline;
   - Processes for scum disappearance due to wind activity;
2. Testing of the complete model tool (Biomass - scum appearance - transport) for the period 1 July to 30 September 2007 on four test locations, based on the availability of physical-chemical water quality measurements and phytoplankton cell counts, and a model reset every two weeks;
3. Testing of the complete model tool based on forecasted climate data for one specific month, to be chosen in consultation with the lake managers,
4. Further testing of the complete model tool for Delftse Hout, to fully analyse model performance and improve the results, and;
5. Reporting.

1.5 PILOT LAKES

Four study lakes (Delftse Hout, Gooimeer-Eemmeer, Sloterplas and Westeinderplassen) were selected to conduct model simulation trials with the complete cyanobacterial bloom forecasting instrument. All four lakes are important for recreational activities, and feature frequent cyanobacterial surface blooms over the summer months. The lakes vary in size, depth and complexity to allow better testing and validation of the complete model instrumentation over a wider variety of systems.

1.5.1 DELFTSE HOUT

The Delftse Hout is a small (area 0.5 km^2), shallow (maximum depth 3 m) lake situated northwest of Delft. Management of the lake falls under the jurisdiction of Hoogheemraadschap van Delfland. The lake has no surface inflows, apart from overland runoff from a catchment primarily made up of recreational parkland. Delftse Hout is an important recreational lake, popular with swimmers over the summer period. Cyanobacterial blooms are frequent over this time, occasionally leading to the closure of the lake. There have been no detailed studies on the water quality of this lake, apart from routine sampling for nutrient and chlorophyll-a concentrations.

1.5.2 GOOIMEER AND EEMMEER

The Gooimeer (area 17.6 km^2) and Eemmeer (area 13.7 km^2) are two interconnected lakes adjacent to Lakes Nuldernauw and IJmeer. Both lakes have a long history of eutrophication, due to high external nutrient loads associated with intensive agricultural developments. Although water column nutrient concentrations continue to decline following significant reductions in external loads, cyanobacterial scums still frequently occur during summer months, particularly in the Gooimeer. High cyanobacterial biomass typically accumulates in areas along the northern shoreline of the Gooimeer, for example in the Almere yacht harbour and the recreational swimming beach Almere strand harbour. The phytoplankton community of the lake as a whole is not well documented, although summer cyanobacterial blooms are dominated by *Microcystis* and *Oscillatoria* species.

In 2006, the surface blooms persisted for several months, leading to many complaints from recreational users and members of the public. Apart from a major decline in the visual appeal of the Almere harbour and Strand harbour, the high concentrations of cyanobacteria cells in the surface waters also resulted in very low water clarity, low concentrations of dissolved oxygen, fish kills and a strong and highly unpleasant odour in the surrounding area. In December 2006 WL | Delft Hydraulics was commissioned to produce a management report to mitigate cyanobacterial blooms in the harbour for the City of Almere. A number of management strategies have now been implemented to prevent scums entering the harbour, including floating barriers, aeration barriers, skimmers and circulation pumps.

1.5.3 SLOTERPLAS

The Sloterplas is a small (area 1 km^2) yet deep (mean depth 15 m) sand mining lake situated in a predominantly urban catchment east of Amsterdam. External nutrient loads to the lake are high, and cyanobacterial blooms now occur frequently over the summer period, with scums persisting in a small harbour in the north part of the lake as well as the recreational swimming beaches on the north eastern shoreline. There is little information available on the water quality and phytoplankton community of the lake, although summer cyanobacteria species are dominated by *Oscillatoria* and *Microcystis* species. The lake is managed by Waternet.

1.5.4 WESTEINDERPLASSEN

The Westeinderplassen is a shallow (mean depth 2.8 m) lake with a surface area of 8.5 km^2. The lake morphology is complex, particularly in the northern reaches of the lake (Kleine Poel) which is made up of a series of small embayments featuring many islands and much urban development. The Kleine Poel is connected to the main basin of the lake (Grote Poel) via a series of small canals. The lake is directly connected to a large surface canal (Ringvaart), used to control the lakes water level. Cyanobacterial surface blooms occur almost annually in the lake each summer, dominated by *Microcystis* and *Anabaena* species. The scums are particular persistent around the northern shorelines of the main lake basin, as well as in the smaller urban basins. Management of the Westeinderplassen falls under the jurisdiction of Hoogheemraadschap Rijnland. There has been no previous water quality modelling studies on this lake.

1.5.5 DATA REQUIREMENTS

In order to fully carry out the field testing of the new model code on the four pilot lakes, the following data was requested from the Water Board responsible for each of the four study lakes for the period 1 July to 30 September 2007:

1. Phytoplankton cell counts and species biovolume, determined fortnightly from at least 2 locations.
2 Water column chlorophyll-a and dissolved and total nutrient concentrations, determined fortnightly from at least 1 location.
3 Water column temperature, collected fortnightly from at least 1 site.

4 Measurements of mean hourly wind speed, wind direction, relative humidity, percent cloud cover and hourly total radiation.
5 Light extinction coefficient, determined fortnightly.
6 Daily validation of bloom presence and absence along several shorelines around each lake, with blooms present ranked according to a scale of 1 to 4.
7 Daily forecasted climate data, including wind speed, wind direction, relative humidity, percent cloud cover and hourly total radiation.

In addition, information was requested on:
8 Lake bathymetry.
9 Indication of lake water balance and nutrient loads.

1.6 REPORT OVERVIEW

This research report is comprised of nine chapters. Chapter 1 provides a general introduction to the study, and presents the study aims, objectives and general research activities. A brief overview of cyanobacteria and algal bloom formation is provided in Chapter 2. Chapter 3 describes the existing models, and presents the complete modelling tool developed specifically for predicting cyanobacterial surface blooms in this study. Chapter 4 describes setup and implementation of the hydrodynamic model, and Chapter 6 the setup, implementation and results of the coupled water quality and fuzzy logic model. Additional water quality and phytoplankton biomass are presented in Chapter 7, while comparisons between simulations using hind and forecasted climate data on the model results are made in Chapter 8. Chapter 9 presents more detailed analysis of the model results and field data for the Delftse Hout, including further calibration of the most important model parameters to improve model results and scum predictions. The overall study conclusions and recommendations for future research are presented in Chapter 9.

2

CYANOBACTERIA AND BLOOM DYNAMICS

2.1 INTRODUCTION

Cyanobacteria, more commonly known as blue-green algae, are primitive prokaryotic organisms containing the photosynthetic pigment chlorophyll, giving them similar characteristics to plants. Cyanobacteria are found throughout both freshwater and marine ecosystems and are often especially prolific in eutrophic freshwater systems where water column concentrations of phosphorus and nitrogen are high. A number of features allow this species to out-compete other phytoplankton groups, including (Walsby, 1971; Reynolds and Walsby, 1975; Oliver and Ganf, 2000):

- Buoyancy in combination with high flotation rates, including the presence and regulation of air-filled structures (gas vacuoles) in some species, allowing surface bloom formation;
- Natural toxin production in some species;
- Nitrogen fixation of atmospheric nitrogen (N_2) through the use of specialised heterocyst cells during nitrogen-limited conditions;
- Reduced grazing pressure, associated with large cell sizes (colonies), production of allelopathic compounds and poor assimilation by grazers.

2.2 MECHANISMS OF CYANOBACTERIAL BLOOM FORMATION

Under certain environmental conditions, such as stable and warm climatic conditions as is normally observed during the summer months, cyanobacterial cells may become highly buoyant and form large blooms or scums in the surface waters of a lake or water body (Figure 2.1). At times, cell densities within the bloom may reach concentrations well over 100,000 cells per millilitre of water (Figure 2.2). Often light winds transport the buoyant cells to the shore line where the bloom continues to accumulate in the surface waters, visible as a large, green coloured scum (e.g., Figure 2.1). Dependent on climatic conditions and the stability of the water column, some blooms may persist for several weeks or even months. This has many implications for water quality, including:

- a major loss in water clarity;
- strong odours,
- a decline in dissolved oxygen concentrations, at times to zero;
- toxicity to recreational users and animals, and;
- loss in aquatic biodiversity.

Collectively, these factors contribute to an overall loss in the aesthetic, recreational and ecological value of the water body, such as observed in Figure 2.2.

FIGURE 2.1 MECHANISMS OF CYANOBACTERIAL BLOOM FORMATION. (1) CELLS ARE EVENLY DISTRIBUTED THROUGHOUT THE WATER COLUMN UNDER NORMAL WELL-MIXED CONDITIONS, (2) SUMMER BIOMASS INCREASES DUE TO HIGHER WATER COLUMN TEMPERATURES, NUTRIENTS AND LIGHT AVAILABILITY, WHICH MAY LEAD TO (3) THE FORMATION OF COLONIES AND FILAMENTS, (4) SURFACE BLOOM INITIALIZATION UNDER CALM AND LOW LIGHT CONDITIONS, (5) REGULATION OF CELLS DUE TO CARBOHYDRATE PRODUCTION AND SEDIMENTATION, (6A) ACCUMULATION OF BLOOM IN SURFACE WATERS, (6B) ACCUMULATION OF BLOOM ON LEE SHORELINE DUE TO LIGHT WINDS AND (6C) DISPERSAL OF CELLS IN THROUGHOUT THE SURFACE MIXED LAYER UNDER HIGH WIND CONDITIONS. KEY TW - TIME THAT WIND BLOWS, L - LAKE FETCH, CS - SURFACE CURRENT SPEED. CH_2O IS CARBOHYDRATE. FROM BURGER ET AL. (2003)

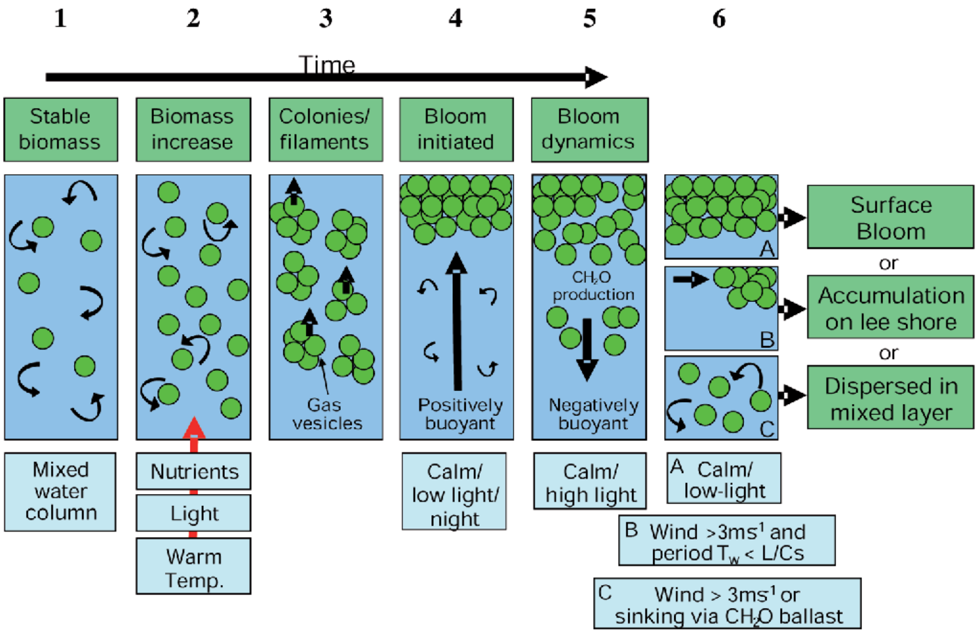
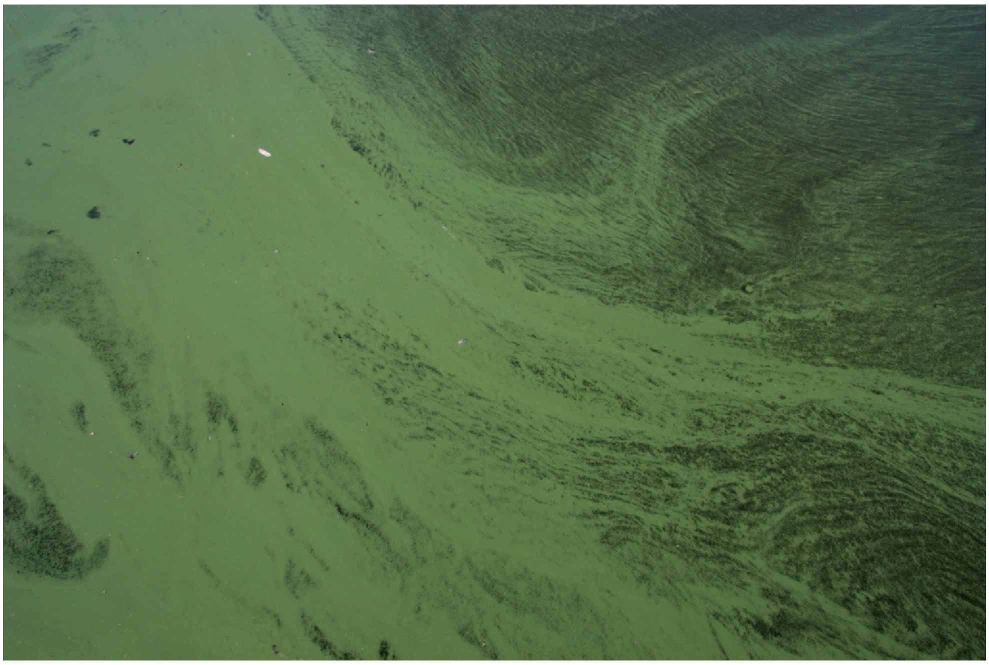


FIGURE 2.2 EXAMPLE OF A CYANOBACTERIAL SURFACE SCUM IN THE ALMERE HARBOUR



2.3 HUMAN HEALTH EFFECTS DUE TO CYANOBACTERIA EXPOSURE

Certain species of cyanobacteria have the ability to produce a wide range of natural, intracellular toxins under certain environmental conditions. At least 46 species have been demonstrated to cause toxic effects in vertebrates, with the most common toxin-producing genera in freshwater systems being *Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Microcystis*, and *Oscillatoria* (e.g. Chorus et al. 2000). In the Netherlands, common and potentially toxic cyanobacteria species dominating freshwater lakes over the summer period include *Anabaena flos aquae*, *Microsystis flos aquae* and *Microcystis viridis*. Although these species are known to be toxic, not all blooms and species strains are toxic and blooms can change from being non-toxic to toxic without a noticeable change in appearance. The presence and concentration of toxins and level of concentration is unpredictable and therefore cannot be accurately determined for all species and blooms. However, approximately 60% of cyanobacteria samples investigated have been found to contain toxins (Chorus et al., 2000).

The risks to human health by cyanotoxins in the water column and their effects are difficult to quantify as not all cyanobacterial blooms are toxic, toxicity may change suddenly due to changing environmental conditions, and many of the symptoms associated with exposure due to cyanotoxins are similar to those of other illnesses such as a common cold or flu, allergies or food poisoning. A wide range of toxins may be produced by cyanobacteria, and certain taxonomic groups may produce more than one type of toxin. The most dominant forms of toxins include microcystins, neurotoxins and cytotoxins.

The effects on human health following exposure through recreational activity is varied, but may include a combination of skin rashes and irritations, eye and ear irritation, runny nose or flu like symptoms, mouth ulcers, head aches, fevers, vomiting and gastroenteritis, and in chronic cases, liver damage. In high does, cyanotoxins can be acutely toxic.

2.4 CYANOBACTERIAL BLOOM MANAGEMENT

Reducing cyanobacterial surface blooms in eutrophic lakes is difficult, as the frequency of bloom formation is governed predominantly by climatic conditions, such as calm and warm weather. Two types of management strategies may be employed by water managers to manage cyanobacterial blooms and scums:

1. Control of total cyanobacterial biomass in an attempt to reduce the potential of surface scums occurring, and;
2. Prevention of surface scum formation or containment of the scum once already formed to reduce the impacts of the scum on water quality and recreational users.

Controlling cyanobacterial biomass is a long term management strategy which may not always be effective for reducing surface blooms. While reductions in external nutrient loading will ultimately lead to a decline in water column nutrient concentrations cyanobacteria growth in many lakes is limited by light rather than nutrients, and some species have the ability to thrive even under certain nutrient limited conditions. Furthermore, surface blooms may also form when concentrations of cyanobacterial species are low in the water column.

Management strategies to mitigate surface scums may be highly effective in the short term, but do nothing to reduce the overall problem of high cyanobacterial biomass. Management strategies to reduce scums may include artificial aeration to keep phytoplankton cells mixed throughout the water column thereby preventing scum formation, floating barriers to prevent scums from entering harbours and recreational swimming beaches, and removal of the scum through the use of skimmers and other devices.

3

MODEL DEVELOPMENT

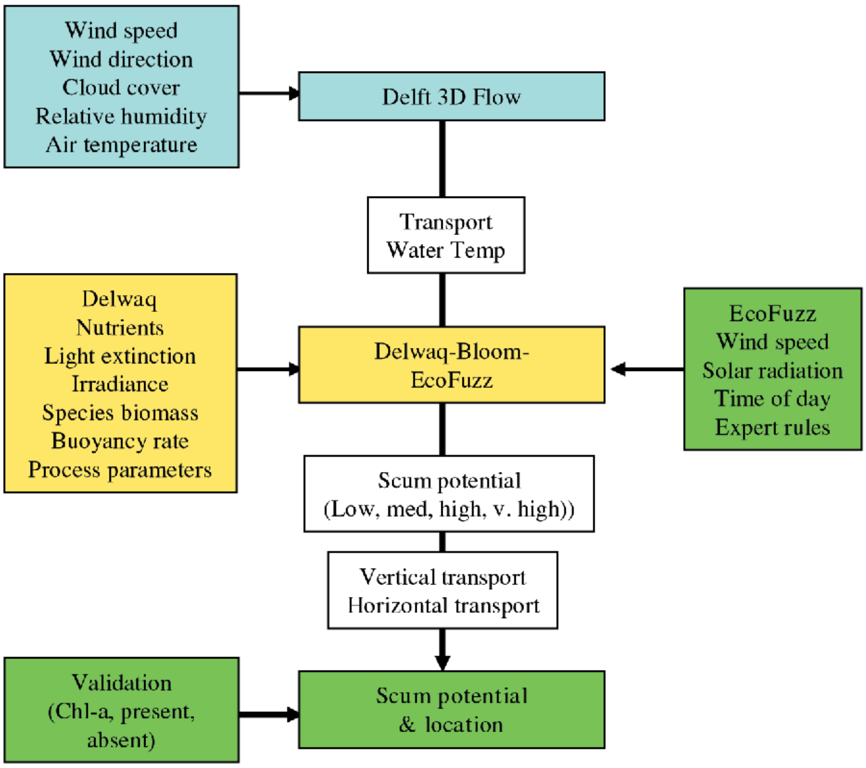
3.1 INTRODUCTION

The complete model instrumentation is based on four processes (Figure 3.1):

1. Simulations of lake hydrodynamics to model vertical and horizontal water velocities;
2. Quantification of cyanobacteria biomass in using a coupled water quality-phytoplankton model;
3. Determination of scum appearance and disappearance potential using the existing version of EcoFuzz;
4. Determination of scum formation and surface bloom transportation to the lake shoreline as part of the water quality model.

Based on the extensively validated models available at Deltares, the models Delft3D-FLOW, Delwaq, BLOOM II were used for the complete model instrumentation, coupled to and integrated with the model EcoFuzz (Figure 3.1).

FIGURE 3.1 SCHEMATISATION OF PROPOSED COMPLETE CYANOBACTERIAL EARLY WARNING SYSTEM



3.2 EXISTING MODELLING CAPABILITIES

3.2.1 DELFT3D-FLOW HYDRODYNAMICS MODEL

Delft3D-FLOW is a two and three-dimensional hydrodynamic and transport simulation model which calculates non-steady flow and transportation resulting from meteorological forcing data on a curvi-linear, boundary-fitted grid. Delft3D-FLOW solves the Navier Stokes equations for incompressible fluids, based on the Shallow Water and Boussinesq assumptions (WL | Delft Hydraulics, 2006). Delft3D-FLOW has been extensively developed, calibrated and validated for a wide variety of applications in both the freshwater and marine environment. The model is therefore well suited for simulating the hydrodynamics of the four pilot lakes in this study.

The results of flow and temperature simulated by Delft3D-FLOW can be directly coupled off-line (without feedback) to the water quality model Delwaq. Both models also utilise the same computational grid, including the horizontal and vertical grid structure and bathymetry.

3.2.2 DELWAQ WATER QUALITY MODEL

The model Delwaq (DELft WAter Quality) is a three dimensional water quality model which can be utilised for a wide range of water quality applications in both freshwater and marine environments. The model can be used for 2D or 3D computations (Delft3D-WAQ) or for 1D and 2D computations (Sobek-WQ).

A wide range of water quality substances can be modelled in Delwaq including nutrients, organic matter, suspended sediment, dissolved oxygen, phytoplankton species, bacteria and heavy metals. All substances are related to specific water quality processes, which are stored in the Delwaq process library. The list of available processes includes algal growth, nutrient cycling, organic matter mineralisation, sedimentation and resuspension and nutrient and heavy metal adsorption processes.
Delwaq calculates transportation of substances based on solving the following advection-diffusion-reaction equation on a predefined computational grid based:

$$\frac{\partial C}{\partial t} - \frac{\partial}{\partial x}\left[D_x \frac{\partial c}{\partial x} - u_x c\right] - \frac{\partial}{\partial y}\left[D_y \frac{\partial c}{\partial y} - u_y c\right] - \frac{\partial}{\partial z}\left[D_z \frac{\partial c}{\partial Z} - u_z c\right] = F\left[c, t\right]$$

where c is concentration, F the water quality process, D_x, D_y and D_z the dispersion coefficients and u_x, u_y, u_z velocity in the x, y, z directions. Extra transportation mechanisms such as sedimentation and resuspension can also be modelled using additional processes specified in the Delwaq process library. The model is described in more detail in WL | Delft Hydraulics 2006.

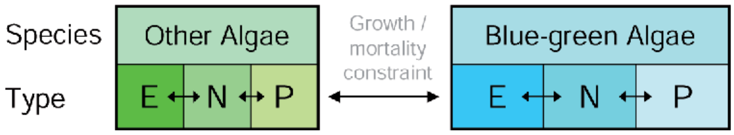
3.2.3 BLOOM PHYTOPLANKTON PRODUCTION MODEL

The phytoplankton primary production model BLOOM simulates changes in phytoplankton biomass and species composition in response to available water column nutrient concentration and light availability, as well as sedimentation, mortality and respiration processes. BLOOM can be run as a stand alone model with forced nutrient concentrations or be activated in the Delwaq process library for simultaneous computation with Delwaq to include the entire nutrient cycle and horizontal and vertical transport.

BLOOM is a multi-species algae model, with species competition based on an optimisation technique that distributes the available resources in terms of nutrients and light among all species present (WL, 1991 and 1992; Los and Brinkman, 1988). In BLOOM, each species is partitioned into three limitation types: phosphorus limited, nitrogen limited and energy (light) limited and in total, 15 types representing various species or taxonomic groups can be simulated in the model, which equates to 5 species (Figure 3.2). All potential limiting factors in terms of nutrient and light availability as well as additional growth limitations for each species and type is simulated in the model algorithm. The suitability of a species to a particular type is determined by the ratio of growth requirements and growth rate. An individual species or type can become dominant because it needs a relatively small amount of a limiting resource, or because it has high growth rates. For each model time step, the model optimisation procedure distributes all available resources among all algal types and (within growth and mortality constraints) species and calculates a new biomass for each species and type.

The coefficients used to describe the various species and type specific process rates in BLOOM are based on extensive literature searches and laboratory experiments (Zevenboom and Mur, 1981; Zevenboom et al., 1983; Zevenboom and Mur, 1984; Post et al., 1985; Riegman, 1992), as well as modelling applications over the last 20 years. A more detailed description of the model structure and process equations may be found in Los and Wijsman (2006) and Los (1991).

FIGURE 3.2 DIFFERENTIATION BETWEEN PHYTOPLANKTON SPECIES AND SPECIES TYPE IN THE MODEL BLOOM. E, N AND P REPRESENT TYPE ENERGY LIMITED, NITROGEN LIMITED AND PHOSPHORUS LIMITED, RESPECTIVELY



3.2.4 ECOFUZZ STAND ALONE MODEL

The model EcoFuzz, developed by WL | Delft Hydraulics in collaboration with RIZA, uses fuzzy logic to determine the likely chance of cyanobacterial surface bloom appearance and disappearance (see Ibelings et al, 2003). The model was developed to replace the uncertainties and difficulties associated with modelling surface bloom formation and disappearance deterministically. In the model, only bloom appearance and disappearance are simulated, not cyanobacterial biomass or surface bloom transportation. Therefore EcoFuzz must be linked to a primary production model to obtain cyanobacteria biomass estimates for model input.

EcoFuzz uses two steps of logical (fuzzy) inference to make a qualitative prediction on the degree of cyanobacterial surface bloom appearance (Figure 3.3). Water column stability and cell buoyancy are inferred from wind speed, time of day and irradiance, which in turn infers surface bloom appearance. Scum disappearance in turn also inferred from wind velocity, as well as irradiance. The model is described in more detail in Ibelings et al. (2003).

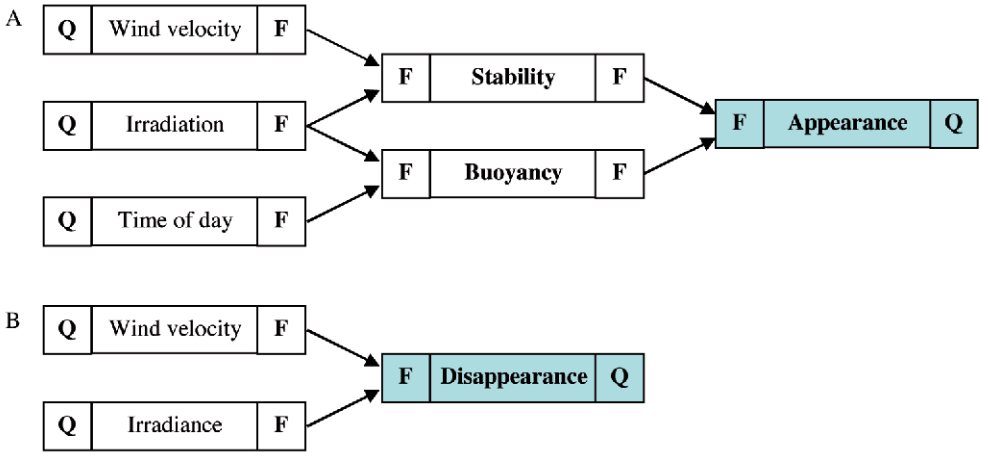
3.3 NEW MODEL DEVELOPMENTS

In order to expand the existing models of Delft3D-FLOW, Delwaq, BLOOM and EcoFuzz into an integrated modelling tool to predict cyanobacterial scum formation, transportation and disappearance, the following work activities were carried out:

- Implementation of EcoFuzz Visual Basic code into Fortran code and incorporation of the new code into the Delwaq process library;
- Development of new scum formation and buoyancy routines, including:
  - Coupling of EcoFuzz scum appearance and disappearance results with Delwaq-BLOOM into the Delwaq code, including the addition of a series of biomass and appearance thresholds to regulate the scum appearance process;

  - Development of a new buoyancy process in Delwaq to model cyanobacterial buoyancy;
  - Expansion of the total number of phytoplankton species represented in Delwaq-BLOOM to accommodate for scum algae;
  - Development of a new scum formation process in Delwaq to model creation and disappearance of scum algae;
- Development of new model code for surface bloom horizontal transport, including implementation of wind drag coefficient and grid-cell specific wind scaling factor to reflect localised differences in wind speed.

FIGURE 3.3 LOGICAL INFERENCE USED TO PREDICT SCUM APPEARANCE AND DISAPPEARANCE IN THE FUZZY LOGIC MODEL ECOFUZZ. THE WIND VELOCITY SCALES USED FOR THE SCUM APPEARANCE AND SCUM DISAPPEARANCE VARY



3.3.1 IMPLEMENTATION ECOFUZZ INTO DELWAQ

The original EcoFuzz model code was written in Visual Basic, which is not recognised by Delwaq. This code was rewritten in Fortran code to allow incorporation into the Delwaq process library. A number of additional changes were made in the Delwaq code to fully integrate the two models. Comparisons were made between output from the existing EcoFuzz stand alone model and the new Delwaq EcoFuzz model to ensure that all processes and results remained identical.

The existing input to EcoFuzz used to determine the membership functions remains unchanged. Input files for the following process parameters are now imported directly into the Delwaq user interface as time series text files:

- Mean hourly wind speed (m s^{-1}) (process VWindTemp).
- Total radiation for the past 6 hours (J cm^{2}) (process RadSurf6h).

The time of day, also required as input to EcoFuzz, is automatically read into the EcoFuzz process from the Delwaq time. The original expert rules used by EcoFuzz and contained in the Scum.rsy and Scum.rsc files remain unchanged, and both text files are automatically read by the Delwaq model during the model simulations.

Two output variables are calculated by the Delwaq-EcoFuzz model, as shown in (Figure 3.2):

1 Hourly scum appearance (process ScumApp);
2 Hourly scum disappearance (process ScumDis)

Both variables represent "defuzzified" values (see Ibelings et al, 2003), and range on a scale of 1 to 100. These values are further used by the new Delwaq scum appearance and disappearance routines to translate the output result into the formation or disappearance of a surface bloom in Delwaq-BLOOM.

3.3.2 DEVELOPMENT SCUM FORMATION AND BUOYANCY ROUTINES

In order to translate the appearance and disappearance results calculated by EcoFuzz into cyanobacterial bloom formation, several alterations and additions were made to the existing processes in the standard Delwaq code. Ecofuzz appearance is used to determine the chance of surface bloom formation, and is used in Delwaq to trigger a number of new processes to verify whether a surface bloom is indeed likely, and to start the bloom formation process.

Biomass and scum appearance thresholds

A number of thresholds have been implemented in Delwaq-BLOOM to filter the scum appearance value derived from EcoFuzz, and thereby regulate the scum formation process to ensure that a surface bloom occurs only when both the physical and biological conditions for bloom formation are favourable.

EcoFuzz calculates the likelihood of bloom formation based only on physical factors, and not the starting biomass of cyanobacteria. Cyanobacterial biomass may also be an important factor determining surface bloom formation as surface scum formation can be dependent on the number of cyanobacterial cells present in the water column. A cyanobacteria biomass threshold was therefore implemented as a Delwaq process parameter (CrCyano) to allow the concentration over which surface scums could form to be specified. This threshold can be varied per lake if required. A new output parameter was also created in Delwaq to calculate the total cyanobacteria biomass for each simulation step. Phytoplankton biomass is calculated by the model BLOOM for each Delwaq time step. Any threshold value can be specified in the model.

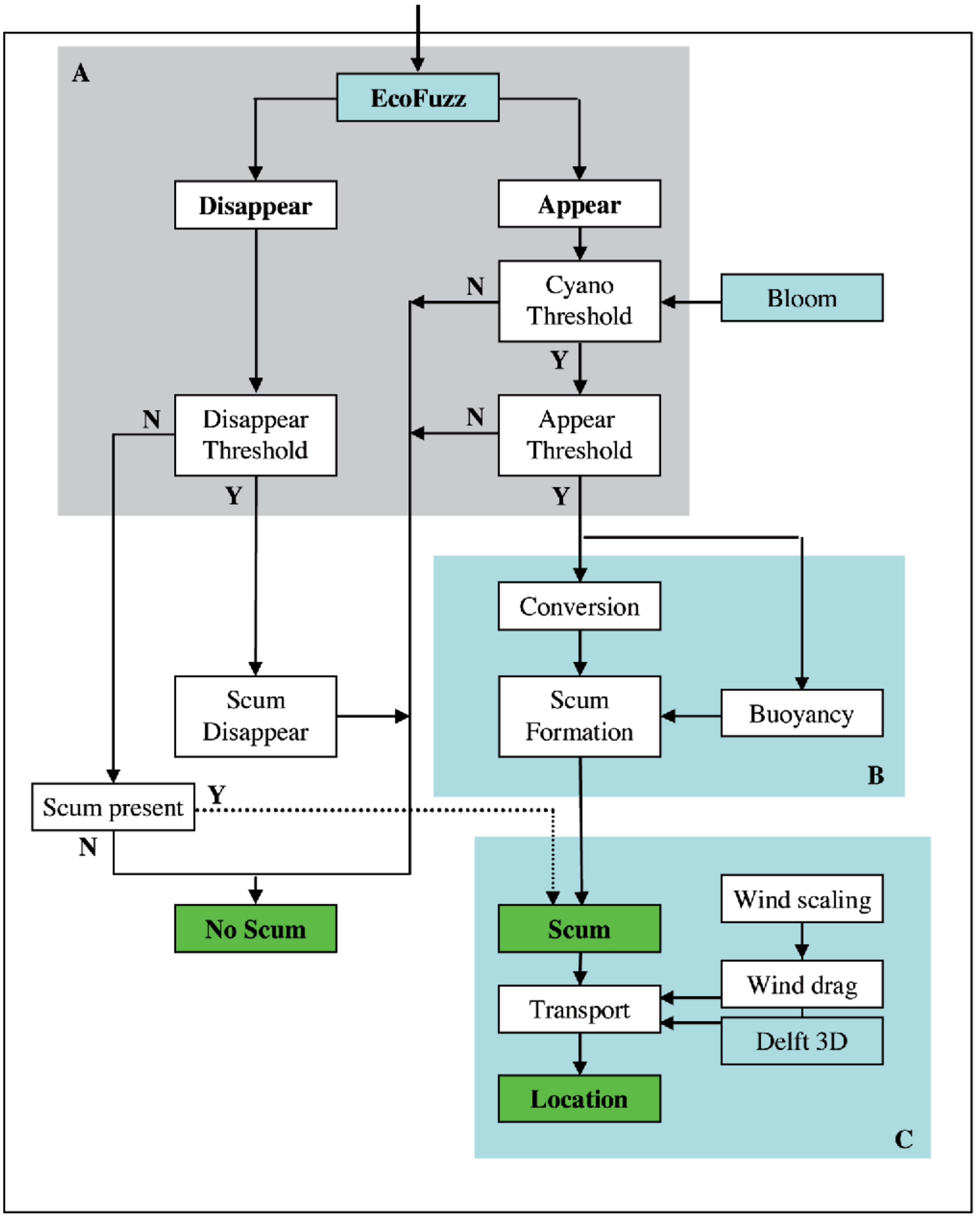
Although the cyanobacteria threshold is the most accurate biomass indicator for governing bloom formation in this study, a total chlorophyll-a threshold can also be used in the model (CrChlfa). A switch (SwEcoThres) in the Delwaq process list can be used to alternate between the cyanobacteria biomass threshold (value = 2) or chlorophyll-a threshold (value = 1). This threshold is expressed as ug Chl-a L^{-1} and any value can be specified in the model.

If the total cyanobacteria biomass in a given time step exceeds the specified threshold value, a second threshold value is used to determine if a surface bloom is likely to form based on the EcoFuzz appearance value (Figure 3.4). EcoFuzz rates the chance of surface bloom development on a scale of 1 (no scum) to 100 (very high chance of bloom). To ensure that the chance of surface bloom formation calculated by EcoFuzz was only translated to bloom formation in Delwaq under certain conditions, a scum appearance threshold value (Thres_App) can be specified as a Delwaq process parameter. Only if both the cyanobacteria biomass and appearance thresholds are exceeded will the buoyancy process be activated by the model.

Buoyancy process

The standard version of Delwaq-BLOOM does not include vertical migration of cyanobacterial species to the surface waters under bloom forming conditions, and the implementa-

FIGURE 3.4 SCHEMATISATION OF ECOFUZZ AND DELWAQ INTEGRATION AND PROCESSES, INCLUDING (A) SCUM APPEARANCE AND DISAPPEARANCE POTENTIAL, (B) SCUM FORMATION AND (C) SCUM TRANSPORT. EACH PROCESS IS DESCRIBED IN MORE DETAIL IN THE FOLLOWING SECTIONS BELOW. IN BRIEF, (1) A SCUM APPEAR AND SCUM DISAPPEAR VALUE ARE CALCULATED BY ECOFUZZ WITHIN DELWAQ. (2) IF CYANOBACTERIA BIOMASS EXCEEDS THE CYANOBACTERIA THRESHOLD, AND ECOFUZZ APPEARANCE VALUE EXCEEDS THE APPEARANCE THRESHOLD, THEN BLOOM-FORMING CYANOBACTERIAL CELLS ARE CONVERTED FROM THEIR NORMAL TYPE TO SURFACE BLOOM FORMING TYPE. (4) CYANOBACTERIAL SCUM FORMERS THEN RISE TO THE SURFACE TO FORM A SURFACE SCUM, BASED ON A NEGATIVE SEDIMENTATION VELOCITY. (5) THE SURFACE SCUM IS SUBJECT TO WIND TRANSPORTATION, DETERMINED BY THE CELL SPECIFIC WIND SCALING COEFFICIENT, WIND DRAG COEFFICIENT AND DELFT3D-FLOW OUTPUT. FOR SCUM DISAPPEARANCE, (I) THE ECOFUZZ DISAPPEARANCE VALUE IS COMPARED TO A SCUM DISAPPEARANCE THRESHOLD. (II) IF THE THRESHOLD IS EXCEEDED, THE SCUM DISAPPEARANCE ROUTINE IS ACTIVATED IF A SCUM EXISTS, AND ALL SCUM FORMING TYPES ARE REVERTED BACK TO THE NORMAL NON-SCUM FORM, MIXED THROUGHOUT THE WATER MIXED LAYER. (III) IF UNDER THE THRESHOLD, THE DISAPPEARANCE ROUTINE IS NOT ACTIVATED IN THE MODEL



tion of this new process into the Delwaq process library to translate the results of EcoFuzz into surface bloom formation or disappearance in Delwaq-BLOOM was a crucial part of the model development conducted in this study.

In order to differentiate between phytoplankton cells fully mixed in the water column and buoyant cells either in the process of forming a surface bloom or already present in the surface layers, a new algae type was created for all likely bloom forming cyanobacteria species. In the standard version of BLOOM, phytoplankton species are represented as various limitation types (E, N, P) depending on the growth limiting conditions in the water column.

For three dominant bloom forming cyanobacteria species (*Microcystis* sp, *Aphanizomenon* sp. and *Oscillatoria* (*Planktothrix*) sp.,), a new sub-species was created to differentiate between normal and floating states (Table 3.1). The BLOOM model coefficients used to characterise each species, including growth rates, nutrient uptake rates and mortality and respiration rates, were kept identical between the bloom forming and generic species type.

The list of phytoplankton species able to be modelled in BLOOM was expanded from 15 to 30 types to accommodate the new scum algal types, and allow for the inclusion of additional species and types at a later point if required. The Delwaq model code was reprogrammed to ensure that all new scum-forming types were also incorporated into all existing Delwaq sub-routines and processes, such as the routines for nutrient and organic matter cycling, light extinction, sedimentation, resuspension and transport.

TABLE 3.1 EXPANSION OF BLOOM SPECIES TYPES IN THE NEW MODEL INSTRUMENTATION

ExistingDelwaq-Bloom	New Delwaq-Bloom	
Generic	Generic	Bloom forming
Aphanizomenon E	Aphanizomenon E	Aphanizomenon Scum E
Aphanizomenon N	Aphanizomenon N	Aphanizomenon Scum N
Aphanizomenon P	Aphanizomenon P	Aphanizomenon Scum P
Freshwater diatoms E	Freshwater diatoms E	
Freshwater diatoms P	Freshwater diatoms P	
Chlorophytes E	Chlorophytes E	
Chlorophytes N	Chlorophytes N	
Chlorophytes P	Chlorophytes P	
Microcystis E	Microcystis E	Microcystis Scum E
Microcystis N	Microcystis N	Microcystis Scum N
Microcystis P	Microcystis P	Microcystis Scum P
Oscillatoria E	Oscillatoria E	Oscillatoria Scum E
Oscillatoria N	Oscillatoria N	Oscillatoria Scum N
Oscillatoria P	Oscillatoria P	Oscillatoria Scum P

If the scum appearance threshold is exceeded in the model, then the biomass associated with a particular cyanobacteria species is converted from its normal type to its scum forming type. The rate of conversion between the two types can be specified for each type as a Delwaq process parameter. For this study it was assumed that all cyanobacteria species were instantaneously converted to the scum forming type of each species.

Besides conversion from regular to scum algae, regular algae can also be subjected to a different vertical transport which is governed by a new buoyancy process implemented in Delwaq. The surface scum formation process is first regulated in the model by a scum appearance threshold (CrAppear) to regulate the conversion of non scum forming cyanobacterial species to their scum forming type if scum forming conditions are likely. If the buoyancy threshold is exceeded, all cells are transported to the surface layers using a type-specific negative sedimentation (buoyancy) rate, specified as a Delwaq process parameter. The rate at which these cells become buoyant can also be regulated through the buoyancy coefficient (BuoyCoeff) in the Delwaq process parameters.

Following activation of the buoyancy process, all scum forming species will eventually accumulate in the upper most layer where they will remain until the scum disappearance process is activated by the model. Growth and mortality rates for each cyanobacterial scum forming type are identical to the rates already defined for the non-scum type of the same species. While sedimentation is likely to occur for a certain proportion of cells in the surface bloom, due to a lack of literature values, this process was assumed to be minor and excluded in the model. The lack of sedimentation in the model does not result in the ongoing presence of surface scums, as the scums are dispersed as part of the scum disappearance process.

As part of the implementation of the scum process into Delwaq, all scum forming species were also incorporated into the existing light extinction process to simulate decreases in light availability for non-bloom forming species in the remaining water column under the scum.

3.3.3 HORIZONTAL TRANSPORT ROUTINES

The transportation of substances due to advection and dispersion within Delwaq is based on calculations of water velocity simulated in Delft3D-FLOW. As part of this study, two additional horizontal transport routines were developed with the Delwaq process library to better incorporate transportation of cyanobacterial surface blooms.

Scum horizontal transport

The horizontal transport of phytoplankton scums to the lake shoreline was simulated in the model based on the water velocities calculated in Delft3D-FLOW, and coupled to Delwaq.
A new wind drag process was implemented in the Delwaq process library to simulate additional wind drag ($V_{WindDrag}$) on cyanobacterial cells in the surface waters following bloom formation. Wind drag was calculated based on a wind drag coefficient ($F_{WindDrag}$, dimensionless), hourly wind speed (V_{Wind}) and direction relative to the grid orientation, using the following equation:

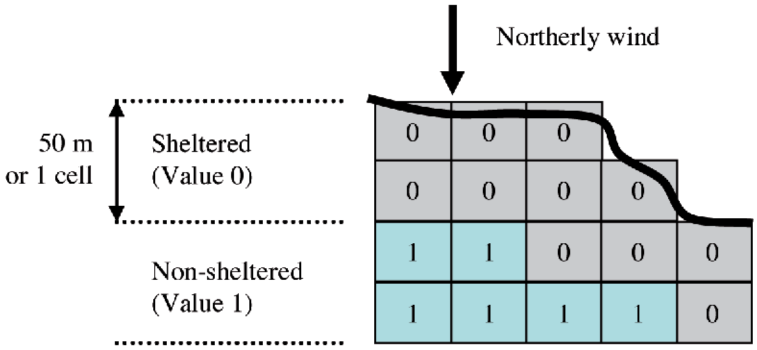
$$V_{WindDrag} = V_{Wind} \times F_{WindDrag} \times \text{cosine (grid angle)} \qquad \text{Equation 3.1}$$

Wind scaling

In order to better simulate the persistence of cyanobacterial surface scums in grid cells along the sheltered shoreline, which is dependent on wind direction, or within small harbours and embayments of the lake due to less wind exposure, the wind speed used for the wind drag calculation was scaled based on a grid cell-specific multiplication factor. This value was varied depending on the dominant wind direction, with eight wind directions specified in the model (NNE, ENE, ESE, SSE, SSW, WSW, WNW and NNW).

For each lake and wind direction, the grid cells directly adjacent to the leeward shoreline or all the cells in a small embayment or harbour were assumed to be sheltered from the wind, and given a multiplication factor (and therefore wind speed) of 0 (See Figure 3.3). The remaining grid cells were considered to be fully exposed to the wind, and were given a multiplication of 1. For this test study, the width of sheltered cells were assumed to be a distance of 50 m from the shoreline for all lakes, or a minimum of 1 cell wide. In sheltered regions such as harbours and small embayments, all cells were considered wind-sheltered, if the model grid was sufficiently fine enough to do so. These values can be altered by the user at any time should more detailed information on the localised effects of wind become available. The multiplication factor was used in calculation of the wind drag. This method was used as an approximation only for the potential effects of differences in wind fetch within the lake on horizontal surface scum transport.

FIGURE 3.5 INCORPORATION OF GRID AND WIND DIRECTION SPECIFIC WIND SCALING



3.3.4 SCUM DISAPPEARANCE

As for scum appearance, the scum disappearance routine is based on output from the model EcoFuzz, which is determined hourly by the model. If the scum disappearance value exceeds a given disappearance threshold value specified as a process parameter in Delwaq, then for each cyanobacteria species, biomass associated with the scum type will revert back to its normal type. The cells will then be distributed evenly throughout the water column, due to mixing as defined by Delwaq. The rate of transition between the scum and normal type can also be defined as a Delwaq process parameter.

If the scum disappearance threshold is not exceeded, then all cyanobacterial species will remain as type scum, with all cells remaining concentrated in the upper most layer of the water column. If there is no scum already present, than scum disappearance will have no effect on the cyanobacteria distribution in the water column. The scum disappearance threshold is intended as an extra calibration point in the model, used for additional fine-tuning of the model if required.

4

FLOW MODEL APPLICATION

4.1 INTRODUCTION

The accumulation of cyanobacterial surface scums along the shoreline of a water body is dependent on both vertical and horizontal transport, driven predominantly by meteorological conditions including wind speed and wind direction. In this study the three-dimensional hydrodynamic and transport simulation model Delft3D was used to calculate non-steady flow and transportation resulting from meteorological forcing data on a curvilinear, boundary-fitted grid. The results of the hydrodynamic simulations, including water velocities, water level and vertical eddy diffusivities and viscosities were then used as direct input to the water quality and ecological model Delft3D-Eco.

4.2 MODEL SETUP

4.2.1 LAND BOUNDARY

The land boundary files used to create a model grid for each of the four study lakes were supplied in GIS format by the relevant Water Board (Delfse Hout, Sloterplas, Westeinderplassen), or obtained from a previous modelling application (Gooimeer-Eemmeer). The land boundaries for all four lakes were compared with satellite images derived from Google Earth to ensure accuracy and that the key shoreline features were represented in the model boundary.

4.2.2 HORIZONTAL GRID SCHEMATISATION

Hydrodynamic grids were created for each lake based on the land boundary files provided by each water board. A semi-curvilinear grid construction was applied to ensure that the grid boundaries closely matched the land boundary, thereby avoiding a stair-case like schematisation and providing the most detail along the shorelines which represent the area of greatest interest for monitoring scum accumulation in this study. In order to maintain smoothness between consecutive grid cells and overall grid quality, the following criteria were observed (WL | Delft hydraulics, 2006):

- Orthogonality (cosine of angle between grid lines) generally less than 0.02.
- The aspect ratio ranges between grid cells of between 1 and 2.
- The ratio of adjacent grid cells of less than 1.2.

Model simulation times are largely governed by the total number of grid cells represented in the model. The overall aim of this study was to develop an early warning system for algal scums and relatively short model run times (< 1 hour) are therefore of primary importance when developing such a system. It was initially chosen to limit the grid resolution to a maximum of 1000 cells per layer, and a total of 5000 grid cells in the whole model application for each of the four pilot lakes. Following refinement of each lake grid, the final mean grid resolution for the four lakes range between 28 and 159 m (Table 3.1). A series of dry cells and thin dams were applied to each grid, where necessary, using satellite and aerial photographs to better represent the shore line and key features such as islands and harbour entrances. The final grids for all four lakes are represented in Figure 4.1.

For Delftse Hout, the large canal connected to the south-western part of the lake was considered an important feature of the lake and an area where algal blooms often occur. This was therefore included in the final model grid. For the Westeinderplassen, the large network of narrow canals situated in the North-eastern part of the lake were too complex to accurately schematise in the model, given the overall mean grid resolution of 79 m. This region was therefore represented as best as possible using a series of open grid cells between the various islands and open water areas.

TABLE 4.1 SUMMARY OF GRID SCHEMATISATION FOR THE FOUR STUDY LAKES

Lake	Lake area (km^2)	Grid size (m)	Cells/layer	Depth layers	Total cells
Delftse Hout	0.2	28	252	6	1512
Gooimeer/Eemmeer	30	159	1184	8	9472
Sloterplas	1	27	1367	11	15037
Westeinderplassen	8.5	79	1374	8	10992

4.2.3 VERTICAL GRID SCHEMATISATION

In Delft3D-FLOW, two vertical grid structures exist; the default sigma ( ) layer construction and the Z-layer construction. In the -layer, the thickness of each depth layer is represented as a fixed proportion of the total depth and accordingly the actual thickness of each layer varies with depth (Figure 3.2). In a Z-layer vertical grid construction, the thickness of each vertical layer remains constant irrespective of water column depth (Figure 3.2), and is therefore suggested to be better suited for use in small, shallow systems where stratification may be underestimated by a σ−layer model due to enhanced or incorrect transportation associated with sudden and large changes in layer thickness.

In this study, flow model simulations were first conducted using a -vertical grid construction due to concerns about the compatibility of the Z-layer flow model with the Eco model. The initial results of the -model suggested that mean water velocities in adjacent surface cells appeared to vary greatly due to large differences in the layer thickness between cells, leading to possible over or under estimations of transportation between cells, since scum algae would only accumulate in the top layer. Based on these results and the release of the new validated model code for coupling Z-layer grids with Delft-Eco, the Z-layer construction was subsequently used for all further simulations.

For all four lakes, the amount of layers were varied between 6 (Delfse Hout) and 11 (Sloterplas) (Table 4.1). The upper surface layer was kept reasonably fine (0.1 m), with layer thickness increasing by no more than 35 % with increasing depth.

FIGURE 4.1 SCHEMATIC REPRESENTATION OF THE DIFFERENCES BETWEEN A SIGMA (σ) AND Z-LAYER CONSTRUCTION FOR THE HYDRODYNAMIC FLOW MODEL

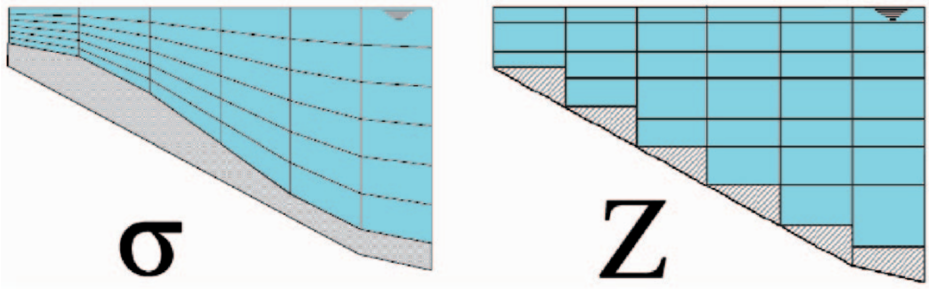


FIGURE 4.2 HYDRODYNAMIC GRID SCHEMATISATION FOR (A) DELFTSE HOUT AND (B) GOOIMEER-EEMMEER

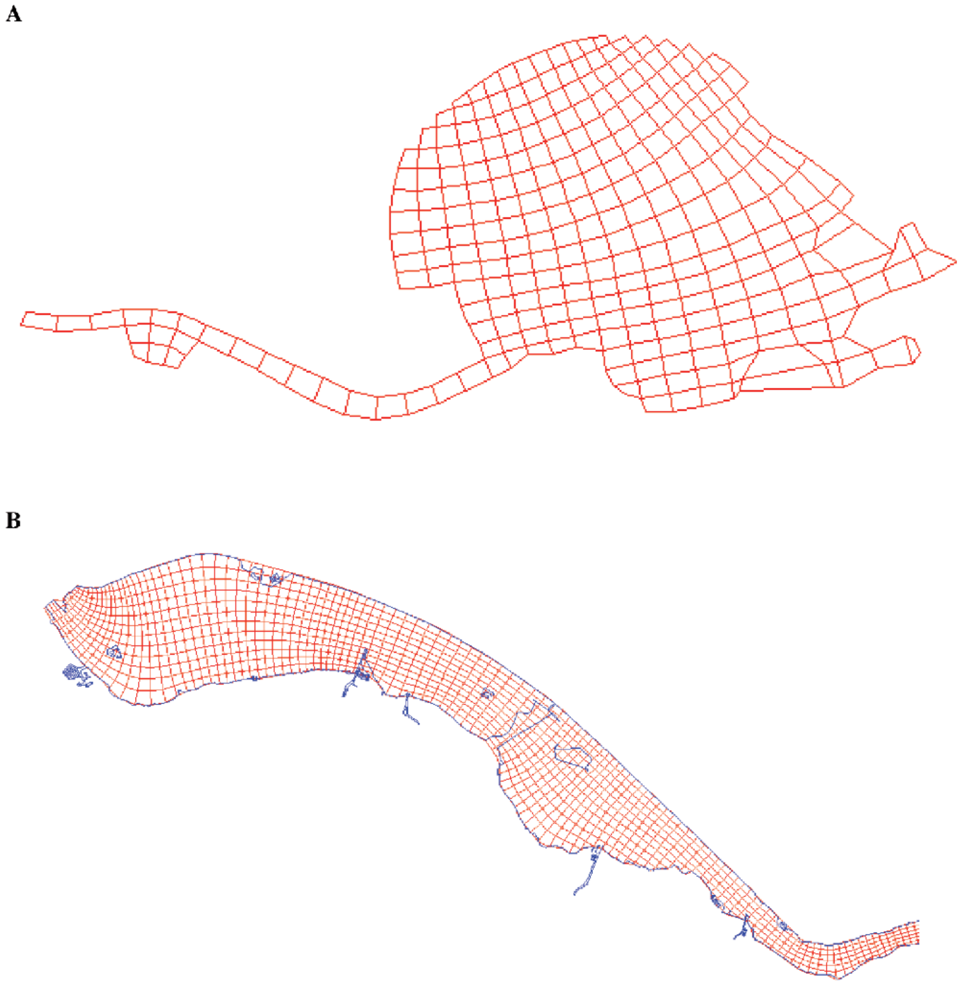
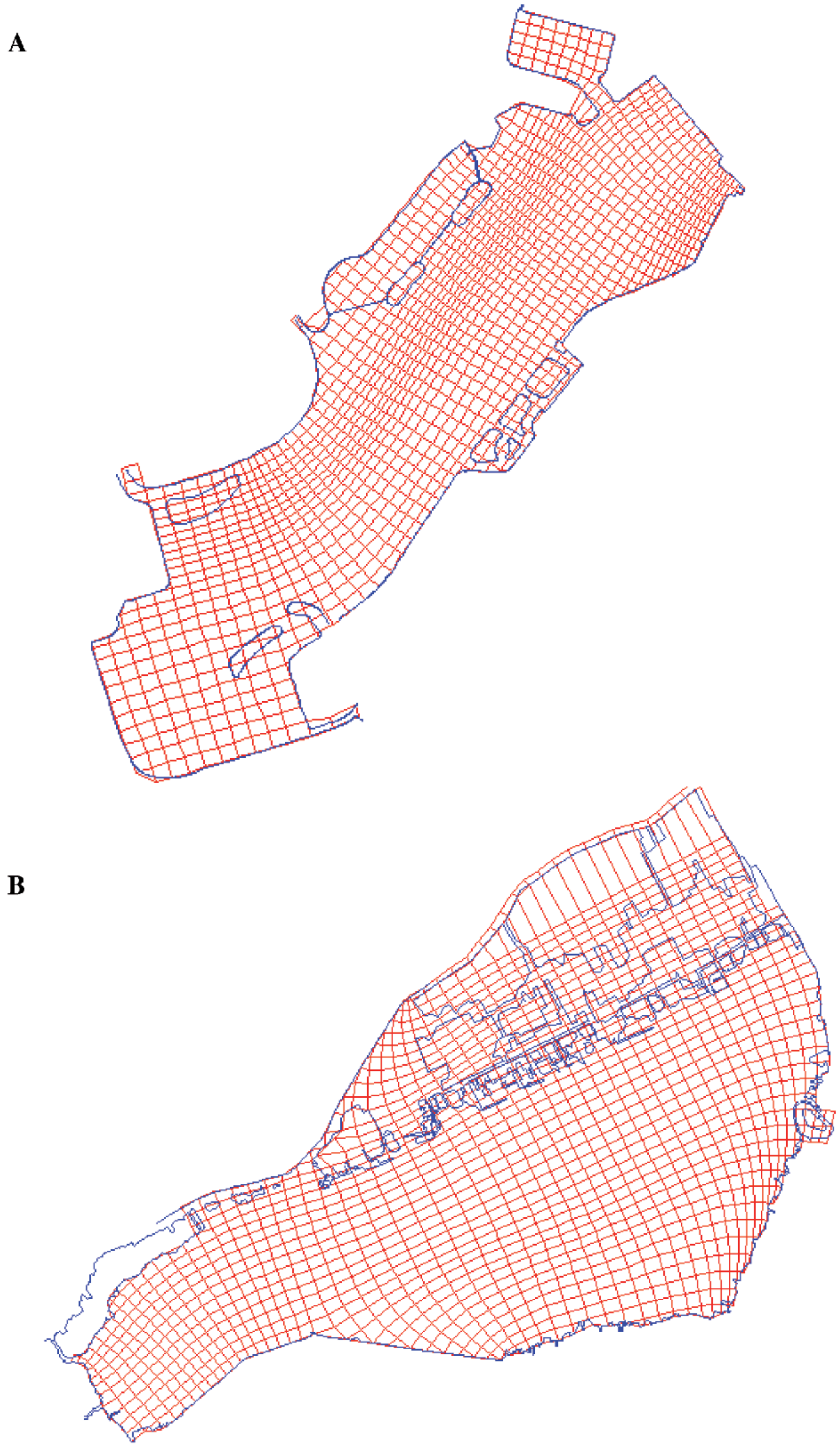


FIGURE 4.3 HYDRODYNAMIC GRID SCHEMATISATION FOR (A) SLOTERPLAS AND (B) WESTEINDERPLASSEN



4.2.4 BATHYMETRY

Bathymetry data for each lake was provided by the corresponding Water Board, with linear interpolation used to fill missing grid cell depths from the measured data. For Gooimeer/Eemmeer, which has a mean depth of 2 m but features some deep pits of up to 30 m in depth, it was assumed that the deep zones do not play a major role in regulating phytoplankton scums due to their relatively small water volume. Accordingly a maximum depth of 10 m was specified in the model. For Sloterplas, which has a mean depth of 15 m, it was assumed that the surface mixed layer (< 10 m) is most important for phytoplankton development and in the absence of detailed temperature profiles to calibrate the flow model, a maximum depth of 10 m was also specified for this lake.

4.2.5 FLOW BOUNDARIES

Due to the lack of available flow data and the intention to keep the overall algal scum warning tool as simple as possible, flow boundaries such as surface and sub-surface inflows and outflows were not modelled in this study. Due to the shallow nature of the lakes, wind transport is likely to be the dominant transport mechanism and the exclusion of surface inflows and outflows from the model is therefore not likely to have a significant influence on the flow simulation results. The effects of flow boundary exclusion in the water quality simulations are discussed in more detail in Chapter 5.

4.2.6 ADDITIONAL PARAMETERS AND PROCESSES

Wind

Mean hourly wind speed and direction were obtained either from Schiphol Airport (for Gooimeer-Eemmeer, Sloterplas, Westeinderplassen) or Rotterdam Airport (Delfse Hout), and applied uniformly as input to the model. A wind velocity dependent wind drag coefficient was applied in the model (Smith and Banke, 1975), reflecting increases in surface roughness associated with increasing wind velocities.

Heat exchange and temperature

Heat exchange was modelled using the Proctor Heat flux model, which calculates effective back radiation and heat losses due to evaporation and convection. Mean hourly air temperature, relative humidity and percent cloud cover were used as input to the model, derived either from Schiphol Airport (for Gooimeer-Eemmeer, Sloterplas, Westeinderplassen) or Rotterdam Airport (Delfse Hout).

Bottom roughness

Bottom roughness was specified in the model as a constant and uniform value over the whole surface area, based on a Chézy roughness formula and a coefficient of 65, which translates to a very smooth bottom.

Initial conditions

An initial uniform water column temperature was specified for the start date of the model, based on the most recently available field measurement for each lake. The initial water column level was specified at 0 m.

Simulation time step

Flow model simulations were carried out for all four lakes between 3 July and 30 September, 2007, with a time step of 1 minute and hourly model output.

FIGURE 4.4 HYDRODYNAMIC MODEL BATHYMETRY FOR (A) DELFTSE HOUT AND (B) GOOIMEER-EEMMEER

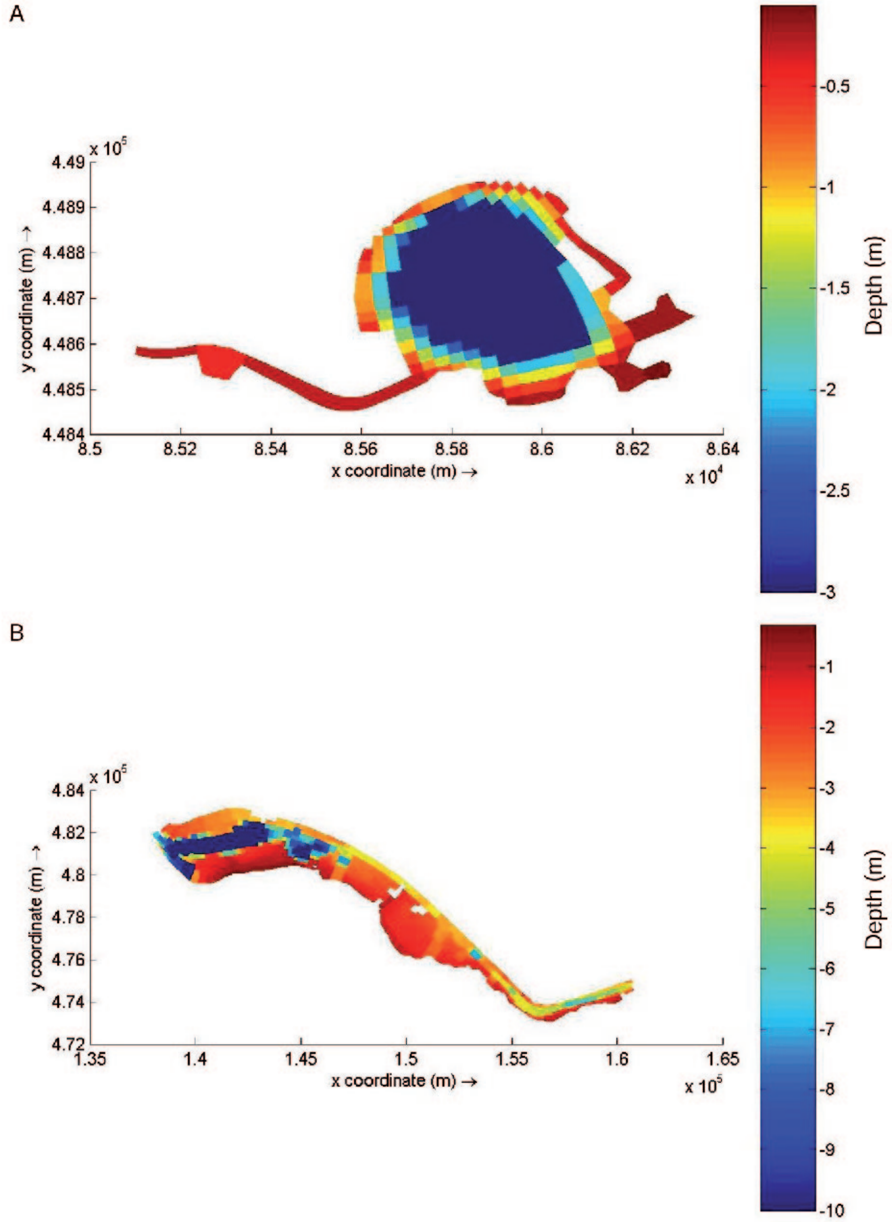


FIGURE 4.5 HYDRODYNAMIC MODEL BATHYMETRY FOR (A) SLOTERPLAS AND (B) WESTEINDERPLASSEN

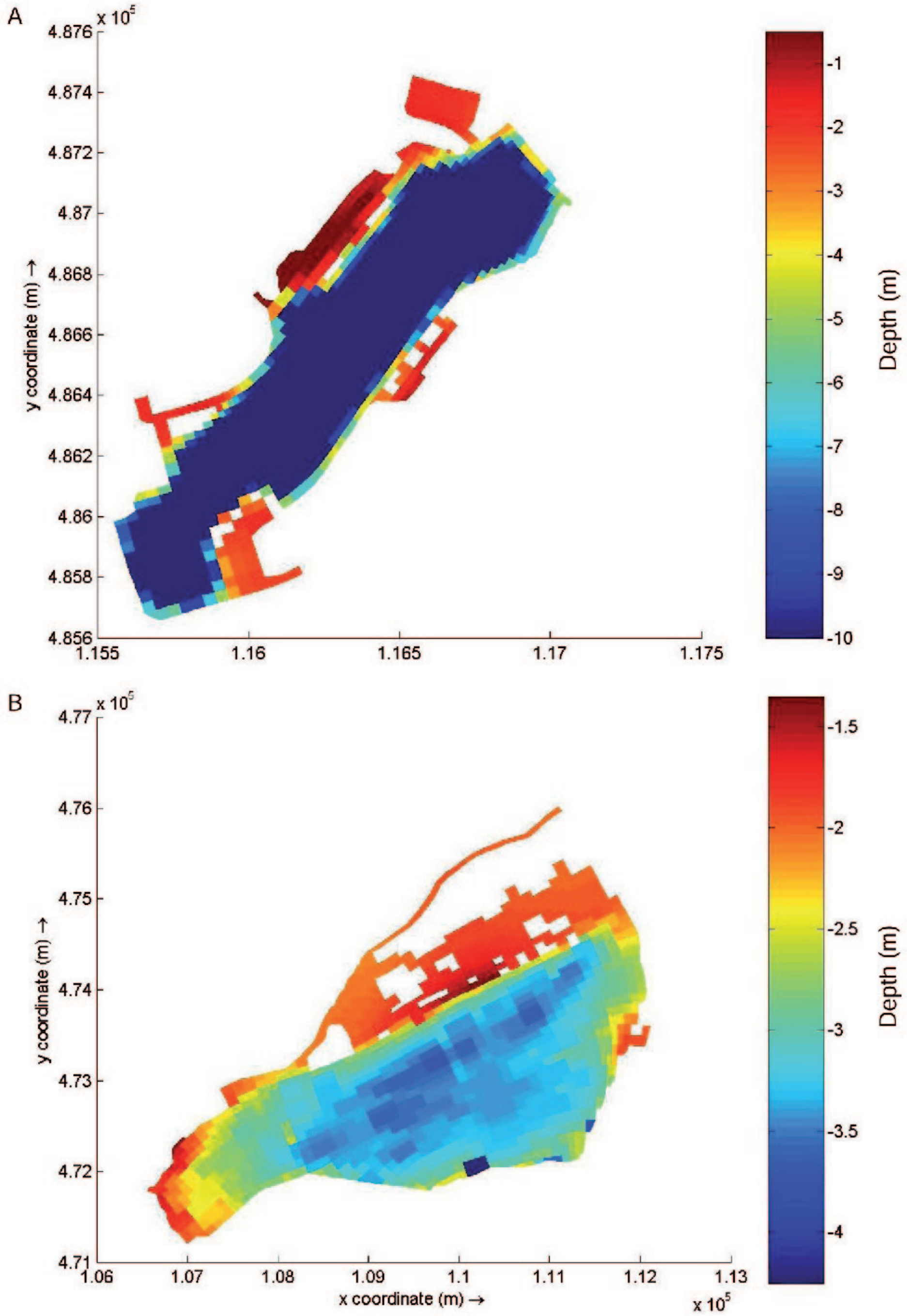
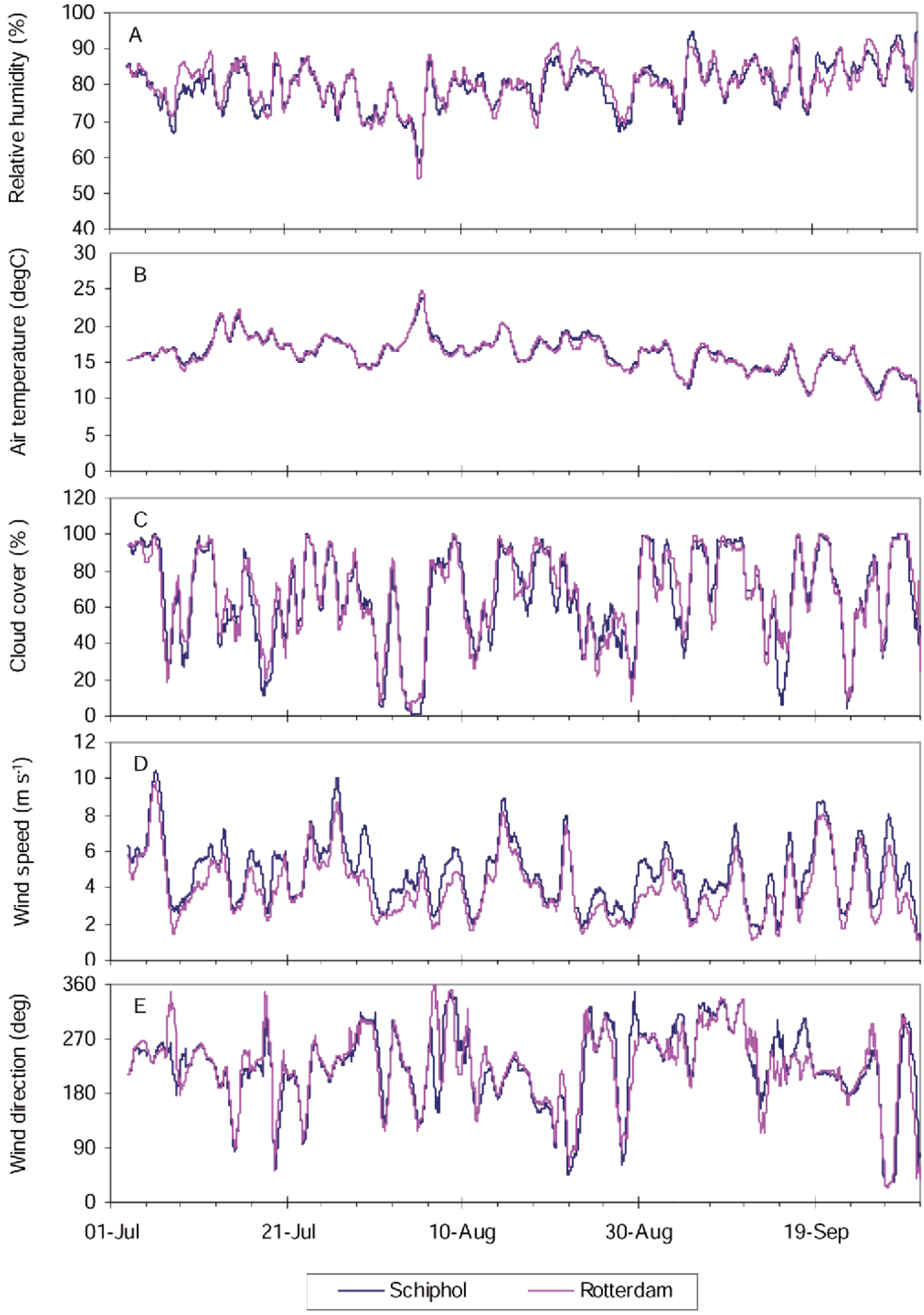


FIGURE 4.6 METEOROLOGICAL DATA USED AS INPUT TO DELFT3D-FLOW, INCLUDING (A) RELATIVE HUMIDITY, (B) AIR TEMPERATURE, (C) PERCENT CLOUD COVER, (D) WIND SPEED AND (E) WIND DIRECTION, FOR DELFTSE HOUT (STATION ROTTERDAM AIRPORT) AND GOOIMEER-EEMMEER, SLOTERPLAS AND WESTEINDERPLASSEN (STATION SCHIPHOL). A 24-HOUR RUNNING AVERAGE HAS BEEN APPLIED TO THE HOURLY DATA IN THIS FIGURE



4.3 FLOW RESULTS

In the absence of detailed validation data, the results of the hydrodynamic simulations were not validated as part of this study.

5

WATER QUALITY AND PHYTOPLANKTON MODELLING

5.1 INTRODUCTION TO WATER QUALITY MODEL SETUP

The main objective of the water quality modelling was to model cyanobacterial biomass, bloom development, scum formation and horizontal dispersion as simply, yet reliably as possible, without constructing a complete calibrated and validated water quality instrument. While the need for a water quality model to simulate phytoplankton biomass was recognised, a simplified approach was chosen in an attempt to reduce the amount of setup time and data requirements for initialising, forcing, calibrating and validating the model. This would also make the early warning tool more easily transferable to other lake systems and make the model less expensive to implement and maintain than a fully calibrated water quality model.

A simplified modelling approach does however have a number of potential drawbacks which may affect the accuracy of simulation results. Although cyanobacteria biomass and scums formation are the main focus of the modelling in this study, phytoplankton primary production is strongly coupled to water column nutrient availability, which along with light availability determines biomass. The nutrient balance of a lake is largely determined by external nutrient loads, derived either from surface inflows or groundwater sources. In many eutrophic lakes, internal nutrient loads derived from enhanced sediment nutrient release rates or wind resuspension may also be important.

A number of in-lake processes will lead to a decline in water column nutrient concentrations, including uptake of nutrients due to phytoplankton production and sedimentation of organic material. In the absence of nutrient inputs from external and internal sources, water column nutrient concentrations will likely decline to concentrations well below what is normally observed in the lake, and phytoplankton productivity will not continue in the model. Further, phytoplankton species composition is also governed by resource competition for nutrients.

In order to still accurately model phytoplankton biomass and species composition in the absence of a complete model setup with all nutrient sources and sinks accounted for, it was decided to periodically reset the model based on approximately fortnightly field measurements. It was assumed that the nutrient concentrations would vary little over the two weeks following the model reset, and therefore that phytoplankton biomass could be modelled accurately. As each model reset also included new phytoplankton biomass and therefore a new species composition, if the model simulations of biomass were inaccurate towards the end of the 2 weeks after the reset, this would also be corrected for.

5.2 FIELD DATA COLLECTION

Field measurements were conducted approximately every two weeks at multiple sites within each study lake to support model input requirements in terms of water column nutrient concentration, phytoplankton biomass, temperature and light extinction. All measurements, sample collections and subsequent laboratory analyses were completed by the relevant water board or its designated commercial laboratory. A data template, including notes on the best method of sampling, was provided to the water boards by Deltares prior to commencement of the monitoring program.

As accurate phytoplankton data were essential for resetting the model every two weeks, the phytoplankton analyses for all four study lakes was carried out by one organisation, Koeman en Bijkerk BV. Phytoplankton were enumerated to species level and expressed as biovolume.

5.2.1 DELFTSE HOUT

Water quality sampling was conducted approximately fortnightly (Table 5.1) at two sites in the Delftse Hout; Site OW203-111 (depth 2 m) and Site OW203-112 (depth 2 m) (Figure 5.1). Depth-integrated (0-2 m) water column samples were collected for subsequent analyses of soluble reactive phosphorus (PO_4), ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), total nitrogen (TN) and total phosphorus (TP). Water samples were also collected for chlorophyll-a analyses and phytoplankton enumeration. In addition, temperature profiles were collected at both sites at 0.5 m depth intervals. Light extinction coefficient (K_d) was determined from measurements of photosynthetically active radiation (PAR) collected at 0.2 m depth intervals to approximately 2.0 m.

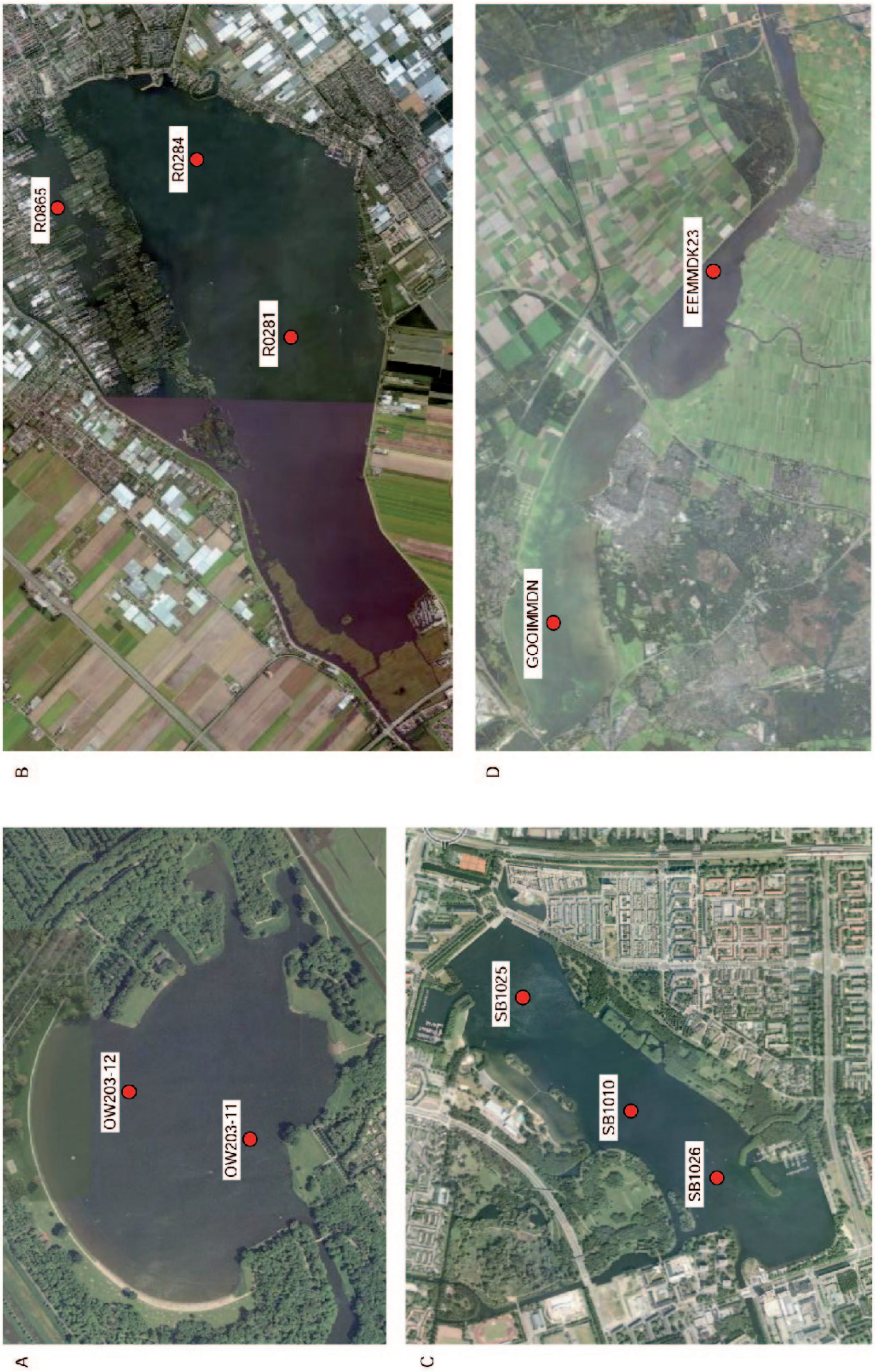
TABLE 5.1 WATER QUALITY SAMPLING DATES FOR DELFTSE HOUT (DH), GOOIMEER-EEMMEER (GE), SLOTERPLAS (SP) AND WESTEINDERPLASSEN (WP)

DH	GE	SP	WP
9-Jul	16-Jul	5-Jul	4-Jul
23-Jul	30-Jul	7-Jul	17-Jul
6-Aug	13-Aug	2-Aug	31-Jul
20-Aug	28-Aug	15-Aug	14-Aug
3-Sep	10-Sep	28-Aug	28-Aug
17-Sep	24-Sep	13-Sep	12-Sep
		26-Sep	25-Sep

5.2.2 GOOIMEER-EEMMEER

Physical-chemical water quality measurements were conducted at approximately monthly intervals in the Gooimeer (Site GOOIMMDN, depth 2 m) and Eemmeer (EEMMDK23, depth 2 m) (Figure 5.1, Table 5.1). At both sites, nutrient concentrations (PO_4, NH_4, NO_3, NO2, TP and total kjeldahl nitrogen) were analysed on depth integrated water samples (0-2 m). Temperature was also measured at depth 0.5 and 1.0 m in the Eemmeer. In addition, water samples were collected for chlorophyll-a analyses and phytoplankton enumeration from two additional sites in Gooimeer (Sites 1 and 2) and Eemmeer (Sites 3 and 4) approximately every two weeks from 16 July (Table 5.1). At the same sites, K_d was determined using PAR measurements generally collected every 0.1 m between the surface and bottom waters.

FIGURE 5.1 WATER QUALITY SAMPLING SITES IN (A) DELFTSE HOUT, (B) WESTEINDERPLASSEN, (C) SLOTERPLAS AND (D), GOOIMEER-EEMMEER



5.2.3 SLOTERPLAS

Physical-chemical water quality measurements were collected at one central lake site (Site SB1010, Figure 5.1) approximately fortnightly during the study period. Depth integrated samples of the surface mixed layer (0-8m) were collected for analyses of nutrients (PO_4, NH_4, NO_3, NO_2, TP and TN). Measurements of surface (depth 0.5 m) temperature were collected from the same site as well as profiles of PAR (0.5 m intervals between depth 0.5 and 2.5 m) for K_d determination. Concurrently, depth integrated (0-8 m) water samples were collected for phytoplankton enumeration and chlorophyll-a analyses from two additional sites (Site SB1025, and Site SB1026) (Figure 5.1).

5.2.4 WESTEINDERPLASSEN

Water quality measurements were collected approximately fortnightly at two mid lake sites (RO281, depth 3 m and RO284, depth 3 m) and at one embayment site (Kleine Poel Site RO865, depth 1.5 m) in the northern area of the lake. At all sites, nutrient concentrations (PO_4, NH_4, NO_3, NO_2, TP and TN) were determined from integrated water column samples collected over the whole water column. Additional samples were collected for chlorophyll-a analyses and phytoplankton enumeration using the same method. Temperature was measured concurrently at depths 0.5, 1, 2, and 3 m at sites RO281 and RO284, and at depths 0.5, 1.0 and 1.5 at Site RO865. PAR measurements were also collected from all sites at 0.25 m depth intervals between the surface and bottom for determination of K_d.

5.3 MODEL SETUP

5.3.1 HYDRODYNAMIC INPUT

The results of the hydrodynamic simulations, including water velocities, water level and vertical eddy diffusivities and viscosities were used as direct input to Delwaq. Water column temperature, calculated by the flow model, was also imported. Horizontal or vertical aggregation of the grid cells were not used, therefore the grid structure used by Delft-Eco was identical to that in Delft3D-FLOW.

5.3.2 MODEL SUBSTANCES AND PROCESSES

The most important water quality processes determining phytoplankton primary productivity are nutrient cycling and light availability. In this modelling application, nutrients in the detritus pools (detritus C, N, P) and dissolved pools (NH_4, NO_3, PO_4, Si) were simulated through inclusion of the following water quality processes:

- Mineralisation of detritus C, N, P;
- Sedimentation of organic material and nutrients;
- Extinction of visible light;
- Desorption of sediment adsorbed phosphorus;
- Mineralisation of sediment detritus C, N, P.

A full description of these processes and how they are modelled and incorporated into the Delwaq Process library can be found in WL | Delft Hydraulics (2005). In the absence of external nutrient loading, as well as limited information on the rates of other dominant processes in the water column, a number of processes were explicitly excluded from the model setup:

- Water column and sediment nitrification;
- Water column and sediment denitrification;
- Sediment resuspension;

- Phosphorus adsorption;
- Phosphate precipitation and dissolution in vivianite and apatite.

During preliminary model simulations, the inclusion of water column nitrification and denitrification processes led to very low levels of water column NH_4 and NO_3 concentrations relative to the field measurements. This could not be offset with enhanced water column and sediment detritus mineralisation rates, nor extremely low detritus sedimentation rates to maximise mineralisation occurring in the water column. While phytoplankton grazing and sediment resuspension are likely to be important in the four study lakes, this could not be validated with the data available, and both processes were deactivated in the model simulations. Phosphorus adsorption onto suspended sediment particles as well as the bottom sediments was also deactivated to maintain water column P concentrations in the absence of balanced nutrient loading.

5.3.3 PHYTOPLANKTON

Three phytoplankton taxonomic groups were simulated in the model; cyanobacteria, chlorophytes and diatoms. Cyanobacteria, the main focus of the study, were simulated to genus level while chlorophytes and diatoms were only simulated generally. For cyanobacteria, three species were specified, based on those most observed to have high biomass and form nuisance blooms in the four study lakes. These were *Microcystis* species, *Aphanizomenon* and *Oscillatoria* species. The parameters used to characterise each species, including growth and mortality rates and nutrient uptake rates for each species and each limitation type, were based on the standard values already defined in the BLOOM model (see Los, 1991 for a complete description).

In addition to the water quality processes already described, a number of additional phytoplankton processes were also modelled. These processes, many of which have been developed into the Delwaq model specifically for this application, are described in more detail in Section 3. They include:

- Phytoplankton primary production (BLOOM model);
- Scum appearance;
- Scum formation;
- Scum horizontal dispersion;
- Scum disappearance.

Due to a lack of detailed data, phytoplankton grazing was not included in the model application for any of the four pilot lakes. The potential effects of grazing by zooplankton species or mussel populations on the model results therefore remain unknown.

5.3.4 PHYTOPLANKTON INITIAL CONDITIONS

Algal concentrations used to prescribe the initial starting conditions for each species or taxonomic group in the model resets were based on field measurements of chlorophyll-a concentration and estimates of species biovolume derived from cell counts. For each lake and restart date, the mean total chlorophyll-a concentration was proportioned into each model taxonomic group (chlorophytes and diatoms) or species (*Microcystis* sp, *Aphanizomenon* sp., *Oscillatoria* sp.) based on the total measured biovolume for each group or species.

For the cyanobacteria, additional minor species not directly represented in the model were assigned to one of the three modelled species based on their morphology. For example, counts of *Anabaena* sp., a filamentous species, were included as *Aphanizomenon* sp. The biovolume of all species not in the cyanobacteria, chlorophytes or diatom taxonomic groups were divided equally between chlorophytes and diatoms.

The resulting chlorophyll-a concentration for each input group was then divided by the Carbon:chlorophyll-a ratio to obtain an estimate of carbon biomass for direct input to the model. Although it is well known that C-chlorophyll-a ratios vary between taxonomic groups and individual species, values documented in the literature also suggest a high degree of variability within a species due to changing nutrient limitation states and light availability. An average Carbon:chlorophyll-a ratio of 40 was therefore assigned for all phytoplankton species and groups in this study.

5.3.5 NUTRIENT INITIAL CONDITIONS

Concentrations of PO_4, NH_4, NO_3, and NO_2 obtained from the field program were used as direct input to the model. Dissolved silica concentrations were not collected as part of the routine modelling so were assumed to be 1.0 mg L^{-1} for all lakes over the duration of the study. Silica was measured at three sites on one occasion in Westeinderplassen (14 August, 2007) and were found to be between 1.0 and 1.3 mg L^{-1}. Concentrations of adsorbed ortho phosphorus (AAP) were assumed to be 0 mg L^{-1} for all lakes.

Concentrations of particulate (detritus) carbon (DetC), nitrogen (DetN), phosphorus (DetP) and silica (DetSi) were estimated using a combination of field measurements and algal stochiometry, as defined in the following equations:

DetC = TC − AlgalC	Equation 4.1
DetN = TN − NH_4 − NO_3 − NO_2 − AlgalN	Equation 4.2
DetP = TP − PO_4 − AlgalP	Equation 4.3
DetSi = AlgalSi	Equation 4.4

Where TC is total carbon and AlgalC, AlgalN, AlgalP and AlgalSi the concentration of C, N, P and Si within the phytoplankton biomass, estimated as (Los, 1991):

AlgalC = Chl-a x 0.029	Equation 4.5
AlgalN = Biomass x C:N ratio	Equation 4.6
AlgalP = Biomass x C:P ratio	Equation 4.7
AlgalSi = Chl-a x 0.016	Equation 4.8

For AlgalN and AlgalP, the biomass of each algal species and type, as estimated from the chlorophyll-a concentration, was multiplied by the corresponding C:N or C:P ratio for each species and type, as used by the BLOOM model. For AlgalSi, chlorophyll-a represents only the Chlorophyll-a associated with total diatom biomass. Total carbon concentrations were not available for the four lakes so was assumed to be a constant of 4.0 mg L^{-1} throughout the study period. All parameters were recalculated with every model reset.

5.3.6 ECOFUZZ MODEL INPUT

Three parameters were used as input to the EcoFuzz model;

- Time of day (h);
- Mean hourly wind speed (m s^{-1}), and;
- Total irradiance for the previous 6 hours (J cm^{-2})

The time of day was derived directly from the Delwaq model time step. Mean hourly wind speed and irradiance were derived either from the Rotterdam airport climate station (Delftse Hout) or the Schiphol climate station (Gooimeer-Eemmeer, Sloterplas, Westeinderplassen) (Figure 5.2). Mean hourly wind direction, required as input to the new surface bloom transportation process, was also derived from the Rotterdam airport climate station or Schiphol climate stations (Figure 5.2).

For all basis simulations, the membership functions used in EcoFuzz to determine the appearance and disappearance of surface cyanobacterial blooms were derived directly from the existing simulations of the IJsselmeer (Ibelings et al., 2003) (Figure 5.3). A sensitivity analyses on these functions is further presented in Section 7.3.

5.3.7 MODEL TIME STEPS AND SIMULATION PERIODS

All Delwaq simulations were conducted using a computational and output time step of 1 hour, to ensure that simulations times would remain sufficiently short for use in an operational early warning system. The BLOOM and EcoFuzz models, run simultaneously within Delwaq, were also run on the same time step.

TABLE 5.2 MODEL SIMULATION START AND END DATES FOR DELFTSE HOUT (DH), GOOIMEER-EEMMEER (GE), SLOTERPLAS (SP) AND WESTEINDERPLASSEN (WP)

	DH		GE		SP		WP	
Run	Start	End	Start	End	Start	End	Start	End
1	9-Jul	22-Jul	16-Jul	29-Jul	5-Jul	16-Jul	4-Jul	16-Jul
2	23-Jul	5-Aug	30-Jul	12-Aug	17-Jul	1-Aug	17-Jul	30-Jul
3	6-Aug	19-Aug	13-Aug	27-Aug	2-Aug	14-Aug	31-Jul	13-Aug
4	20-Aug	2-Sep	28-Aug	9-Sep	15-Aug	27-Aug	14-Aug	27-Aug
5	3-Sep	16-Sep	10-Sep	23-Sep	28-Aug	12-Sep	28-Aug	11-Sep
6	17-Se	30-Sep	24-Sep	30-Sep	13-Sep	25-Sep	12-Sep	24-Sep
7					26-Sep	30-Sep	25-Sep	30-Sep

FIGURE 5.2 IRRADIANCE (6 HOURLY TOTAL) AND MEAN HOURLY WIND SPEED AND DIRECTION FROM SCHIPHOL AND ROTTERDAM CLIMATE STATIONS, USED AS INPUT TO DELWAQ-ECOFUZZ. NOTE WIND SPEED AND WIND DIRECTION REPRESENT A 6-HOUR RUNNING MEAN IN THIS FIGURE

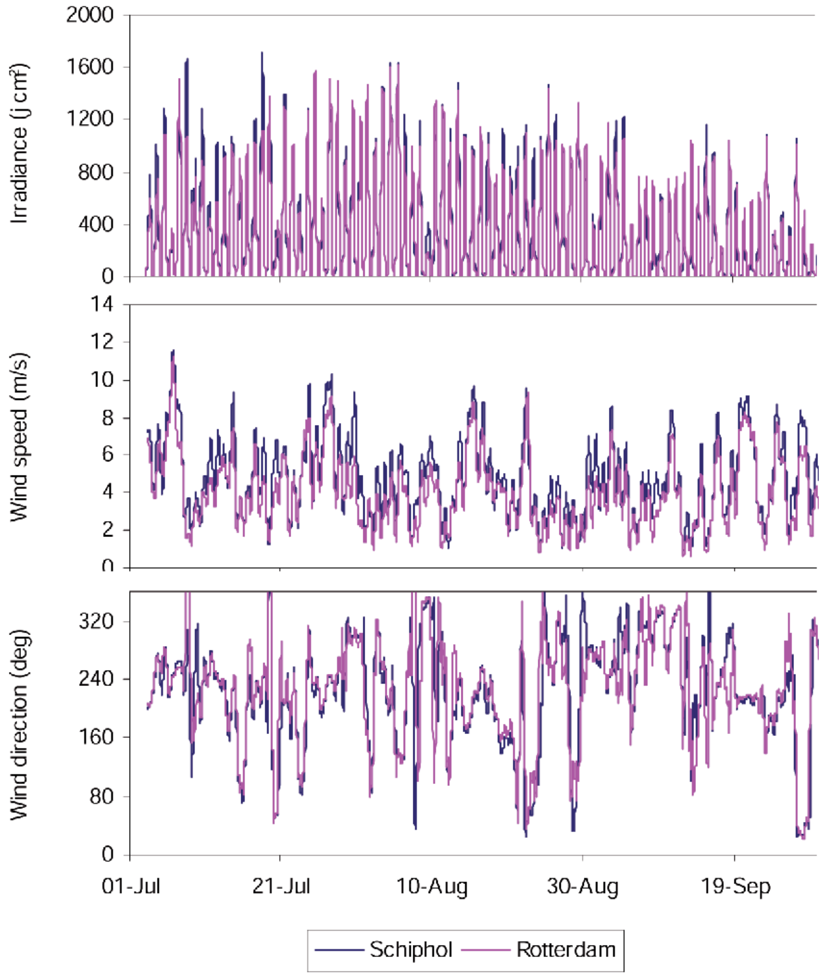
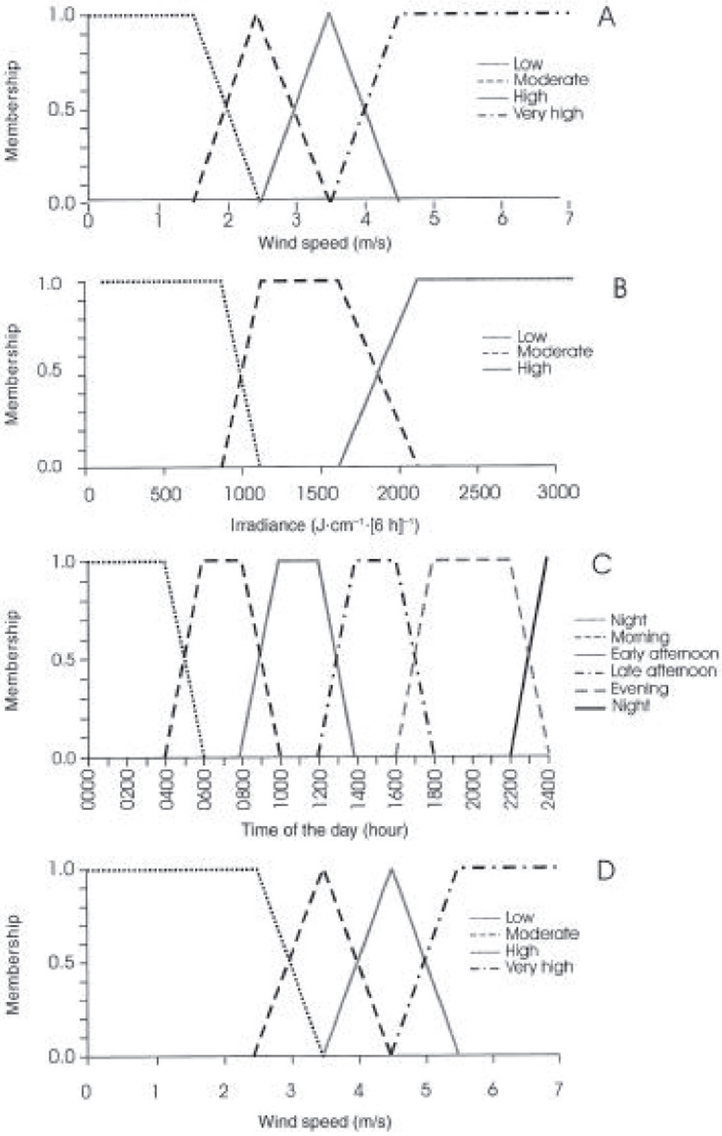


FIGURE 5.3 MEMBERSHIP FUNCTIONS USED BY ECOFUZZ TO DETERMINE APPEARANCE OF SURFACE BLOOMS: (A) MEAN HOURLY WIND SPEED, (B) CUMULATIVE IRRADIANCE FLUX OVER THE PAST 6 HOURS, (C) TIME OF DAY AND (D) MEAN HOURLY WIND SPEED FOR GOVERNING SURFACE BLOOM DISAPPEARANCE (FROM IBELINGS ET AL., 2003)



5.4 MODEL VALIDATION

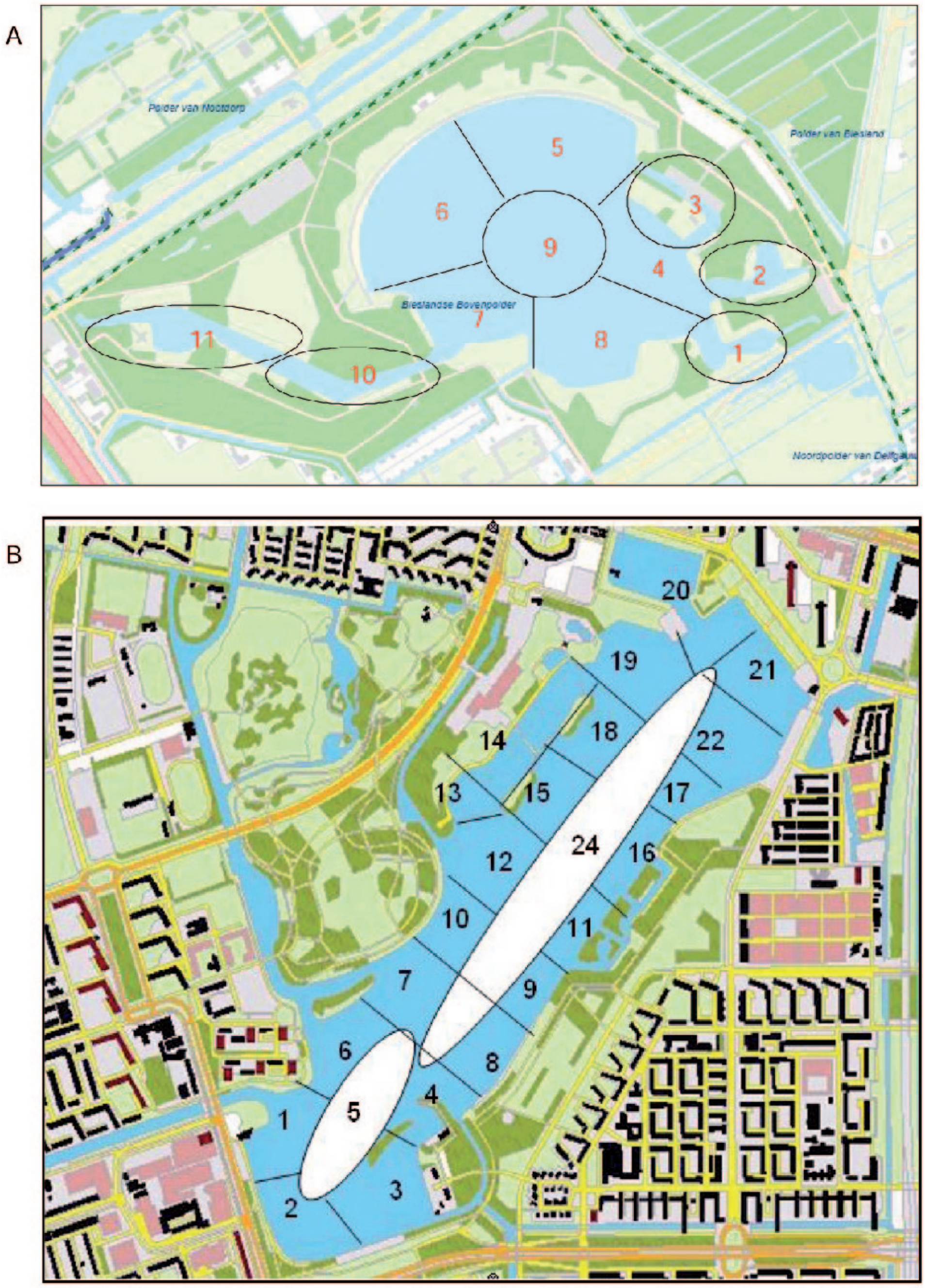
Validation of the model instrumentation under scum and no scum conditions is an important aspect of the model calibration and validation. As an early warning tool, not only must the model predict the moment that cyanobacterial surface scums occur, but also the location of the scum within the lake, so that a warning can be issued for a particular shoreline or area if the need exists. Further, the moments that cyanobacterial scums are not present are equally as important for validating the results of the model simulations.

5.4.1 SCUM FIELD SURVEY METHODS

It was intended that spatial validation data be collected daily for each of the four lakes over the entire study period between 1 July to 30 September 2007. The collection of this data was largely reliant on input from dedicated members of the public either living on the lake shore or regularly using the lake for recreational or commercial activities. Where daily surveys were completed, the presence or absence of a scum was recorded as well as the location of the scum along a particular shoreline or area within the lake.

To obtain as much detail as possible on the spatial distribution of scum development, two lakes (Delftse Hout and Sloterplas), were divided into a number of zones reflecting different shorelines where scums may or may not occur, depending on the predominant wind direction (Figure 5.4). Particularly for Delftse Hout, the presence or absence of scums in each of these zones were included as part of the daily surveys.

FIGURE 5.4 **SHORELINES LOCATIONS USED IN DAILY VALIDATION SURVEYS FOR (A) DELFSE HOUT AND (B) SLOTERPLAS. NOTE NOT ALL LOCATIONS WERE SAMPLED EACH DAY**



Bloom categories

In order to provide detail on the cyanobacterial scums when present, a score chart was defined to provide a fast, visual estimate of bloom intensity in the absence of more detailed field measurements such as chlorophyll-a concentrations and phytoplankton cell counts. Four categories were assigned based on expert judgement and recorded as part of the daily surveys when surface scums were present (Figure 5.5):

Category 1 Colonial cells or filaments present in the surface waters but visibility through the water column is generally not obscured. There are no large, inter-connected surface scums (> 10 cm^2) and there is no odour present;

Category 2 A large number of cells and filaments are present in the surface waters with water column visibility obscured in places. Inter-connected patches (> 10 cm^2) of scums exist but there is no odour present;

Category 3 Very high densities of cells and filaments present on the water surface and water column visibility is mostly but not completely obscured. Coloured surface scums are bright green and not easily mixed back into the water column. Foam may be potentially present and odours are absent or slight;

Category 4 Very high densities of cells and filaments present on the surface and water column visibility is completely obscured by a consistent thick, scum layer coloured between green and light blue. Surface foam is potentially present and a strong odour is also present.

5.4.2 USE OF VALIDATION DATA TO ASSESS MODEL PERFORMANCE

The results of the model simulations were compared to the field data as follows:

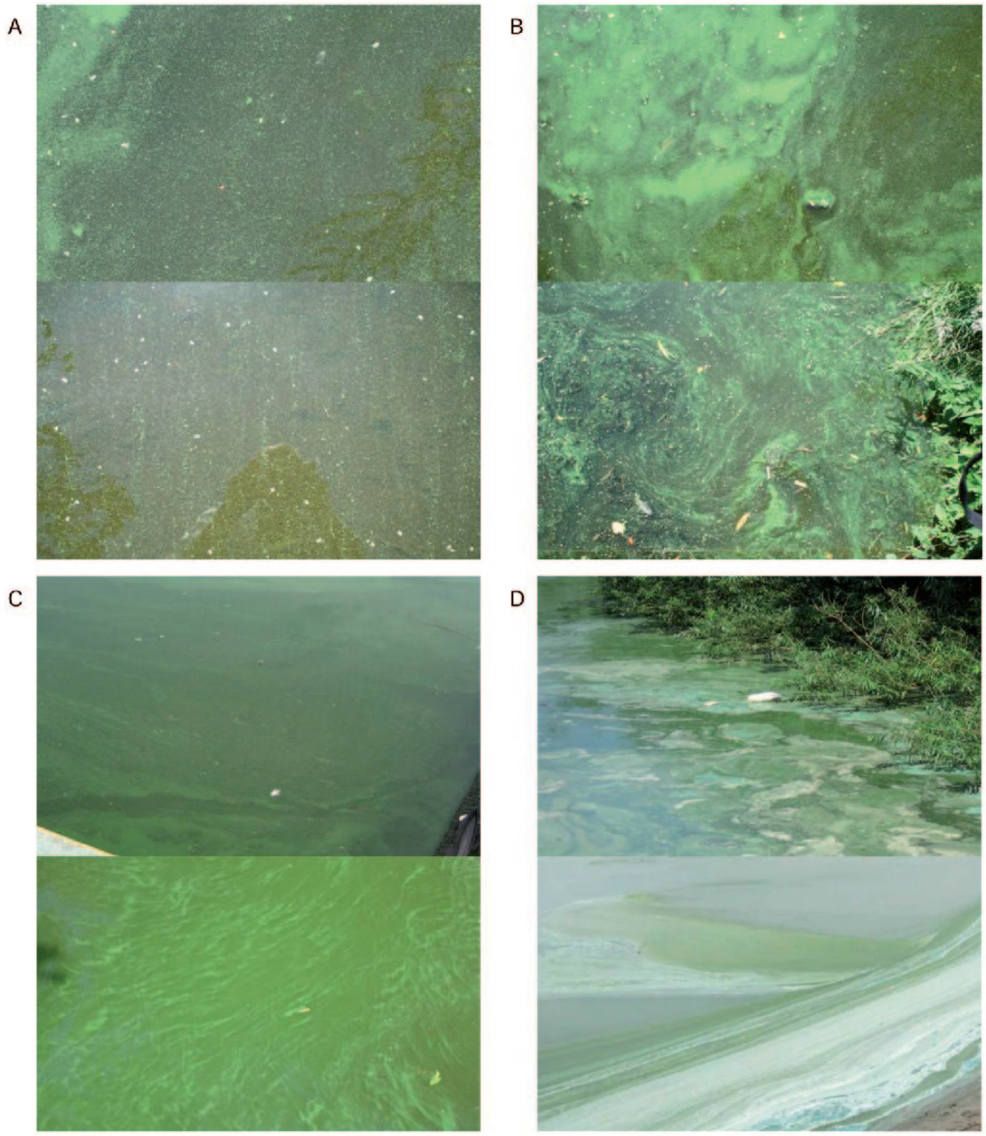
1 Scum appearance:
- Model scum appearance compared to field scum presence.

2 Scum location:
- Visual comparisons of scum location each day.

Model output of scum appearance was used to quantitatively assess model accuracy relative to the field data. Scum appearance was chosen as this parameter indicates if a surface scum will occur in the model before the scum is further subjected to the transport processes, making the end result more difficult to interpret. The scum appearance results were assessed on a daily basis, for example if model scum appearance was greater than the appearance threshold specified in the model for any time step on that day, than a scum will be recorded for that day. For the field data, scum presence represents a scum present for any shoreline on the lake for that entire day.

To assess scum location predictions, the validation data available was used to make a spatial map for each of the four lakes, showing the presence and absence of scums, as well as the category of scum if present for each day of the study period. Field scums were only visually represented on the very shoreline of a lake on each plot, unless the survey data noted that the scum was present over the whole surface area of the lake. These images were then used to make visual comparisons between the field data and model simulations. The results of the complete model tool include the result of both scum appearance and disappearance.

FIGURE 5.5 CYANOBACTERIAL SCUM CATEGORIES DEFINED IN THE STUDY: (A) CATEGORY 1, (B) CATEGORY 2, (C) CATEGORY 3 AND (D) CATEGORY 4



5.4.3 VALIDATION DATA AVAILABILITY

Due to a lack of interest or time by the public, the validation data collected from each lake was often incomplete or absent for many days or particular locations within each lake.

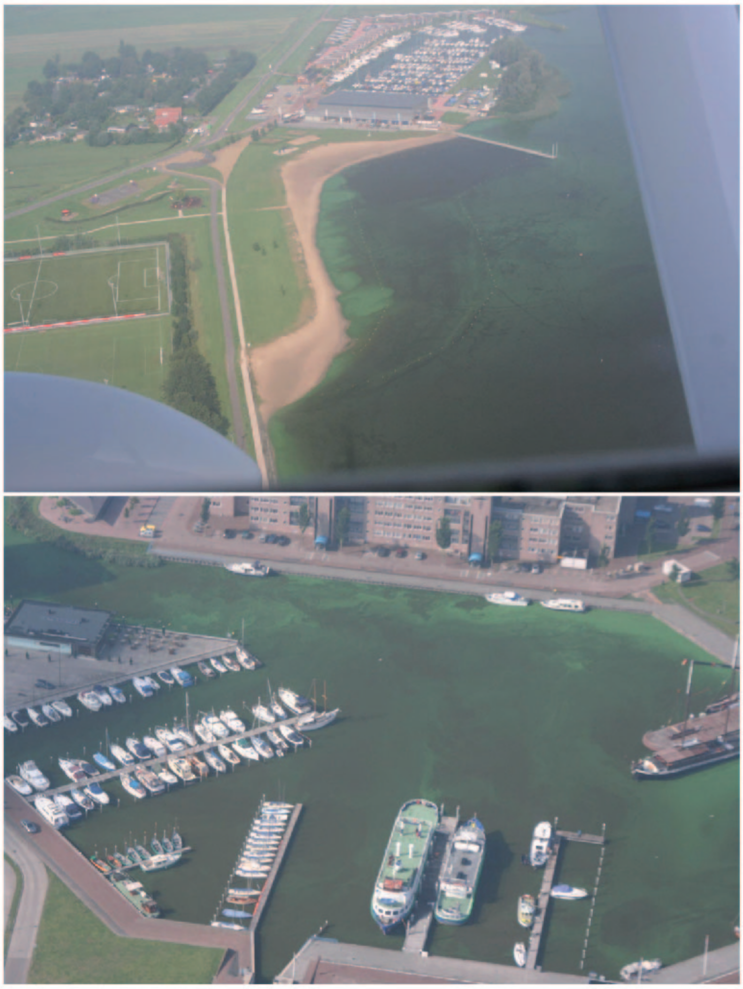
Delftse Hout

The validation data collected was most complete for Delftse Hout, where observations were recorded for every lake shore on every week day and some weekends at around 11:00 am each day. Seven categories were used to define the intensity of scums (Category 0.5, 1, 1.5, 2, 2.5, 3, 4) based on the original categories defined in Section 4.4.1.

Gooimeer-Eemmeer

For Gooimeer-Eemmeer, daily validation data were not collected for any day over the study period, although a series of aerial photographs were taken on 14 days between 1 July and 30 September 2007. On some flights, several hundred photographs were taken of the whole shoreline of both interconnected lakes. While the photographs provide excellent evidence for the presence or absence of surface scums for the survey dates in question, it was not always easy to determine the precise location of the blooms when present, particularly in the absence of any notable shoreline features to allow the exact location of the photograph to be pin-pointed. Further, on some overcast days, it was also difficult to differentiate between surface cyanobacterial scums and suspended sediment plumes, although this was normally the case in the middle of the lake rather than on the shorelines which are the focus of this study. As it was not possible to estimate the intensity of the bloom from the aerial photographs (Figure 5.6), it was assumed that all visible blooms were Category 4.

FIGURE 5.6 EXAMPLE OF AERIAL PHOTOGRAPHS SHOWING SURFACE BLOOM PRESENCE IN THE GOOIMEER-EEMMEER



Sloterplas

Only one location was surveyed intensively in Sloterplas: Zone 20, a small harbour located in the Northern part of the lake. Validation data was collected daily between 1 July and 20 August at this site, although a minimum scum category of 0.5 was recorded for most days. Further Zones 11, 13 and 16 were surveyed on four days throughout the study period.

Westeinderplassen

Validation data collected from the Westeinderplassen were based on boat surveys, with the presence or absence of scums recorded at several locations on each survey day, depending on the route travelled. Scum presence or absence was noted specifically on 18 days over the study period, although one boat operator noted no scums present for every day in August and September. The boat surveys were mostly carried out in the northern regions of the lake, between the northern part of the Grote Poel, Kleine Poel and Ringvaart. Thirteen locations were specifically named in the survey results, and these were translated to the area of nearest shoreline for the final model comparison. In addition, a map of all known scum locations between 1 July and 30 September was provided by Hoogheemraadschap Rijnland.

6

MODEL SIMULATION RESULTS

6.1 WATER QUALITY SIMULATIONS

Based on the available reset data, model simulations were carried out over at least 6 different time periods between 1 June and 30 September 2007. In order to calibrate the model for each lake, multiple simulations were conducted, focusing on water column nutrient concentration and phytoplankton biomass and species composition.

6.1.1 NUTRIENT CONCENTRATIONS

Water column nutrient concentrations were difficult to simulate accurately in all four study lakes despite the fortnightly model reset. Particularly for the dissolved nutrients (PO_4, NH_4, NO_3), which represent the nutrient form taken up by phytoplankton for growth, water column concentrations continued to decline after the simulation start date and model reset in many of the lakes (e.g. Figure 6.1). A number of methods were used to “artificially” add nutrients to each system through manipulation of the mineralisation rate constants and other process parameters but this appeared to have limited effect, or created undesirable results elsewhere.

Model simulations of nutrient concentrations appeared to be the most accurate in the Delftse Hout, most likely due to the lack of any large external load to the lake (Figure 6.1). Therefore the absence of external loading in the model simulations is likely to have only a minor effect. Water column concentrations of NH_4 and NO_3 were generally below the detection limit in the field data, and a minimum threshold was used to reflect this in the model simulations. Concentrations of PO_4 in the water column were relatively stable throughout the 2-weekly simulations, and in some cases even increased, due to little uptake by the nitrogen limited phytoplankton and the presence of internal loading. A large increase in PO_4 concentration observed in the field measurements from mid August were considered unusual but appeared to be real across all sites and relative to the TP concentration.

Measured water column concentrations of dissolved nutrients were much higher in the Eemmeer than in the Gooimeer (Figure 6.2 and 6.3), and for this reason it was decided to model the two lakes based on different starting conditions for each model reset. Model simulations of water column nutrient concentrations generally showed a rapid decrease for the Eemmeer, and more gradual decrease in the Gooimeer, following each model reset. In the Gooimeer, NH_4 concentrations increased with each model reset.

In the Sloterplas, simulations of water column PO_4 decreased during the model runs in July, and remained more stable for the remaining model periods (Figure 6.4). Concentrations of NO_3 were often at or below the threshold in both the model simulations and field data, while concentrations of NH_4 generally increased after each model reset.

In the Westeinderplassen, water column concentrations of PO_4 nearly always became limiting and well below the mean measured water column concentration, while NH4 fluctuated rapidly depending on the phytoplankton biomass (Figure 6.5).

FIGURE 6.1 MODEL (LINE) SIMULATIONS OF (A) TOTAL NITROGEN (TN), (B) TOTAL PHOSPHORUS (TP), (C) AMMONIUM ($_{NH4}$), (D) NITRATE (NO_3) AND (E) PHOSPHATE (PO_4) FOR DELFTSE HOUT, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

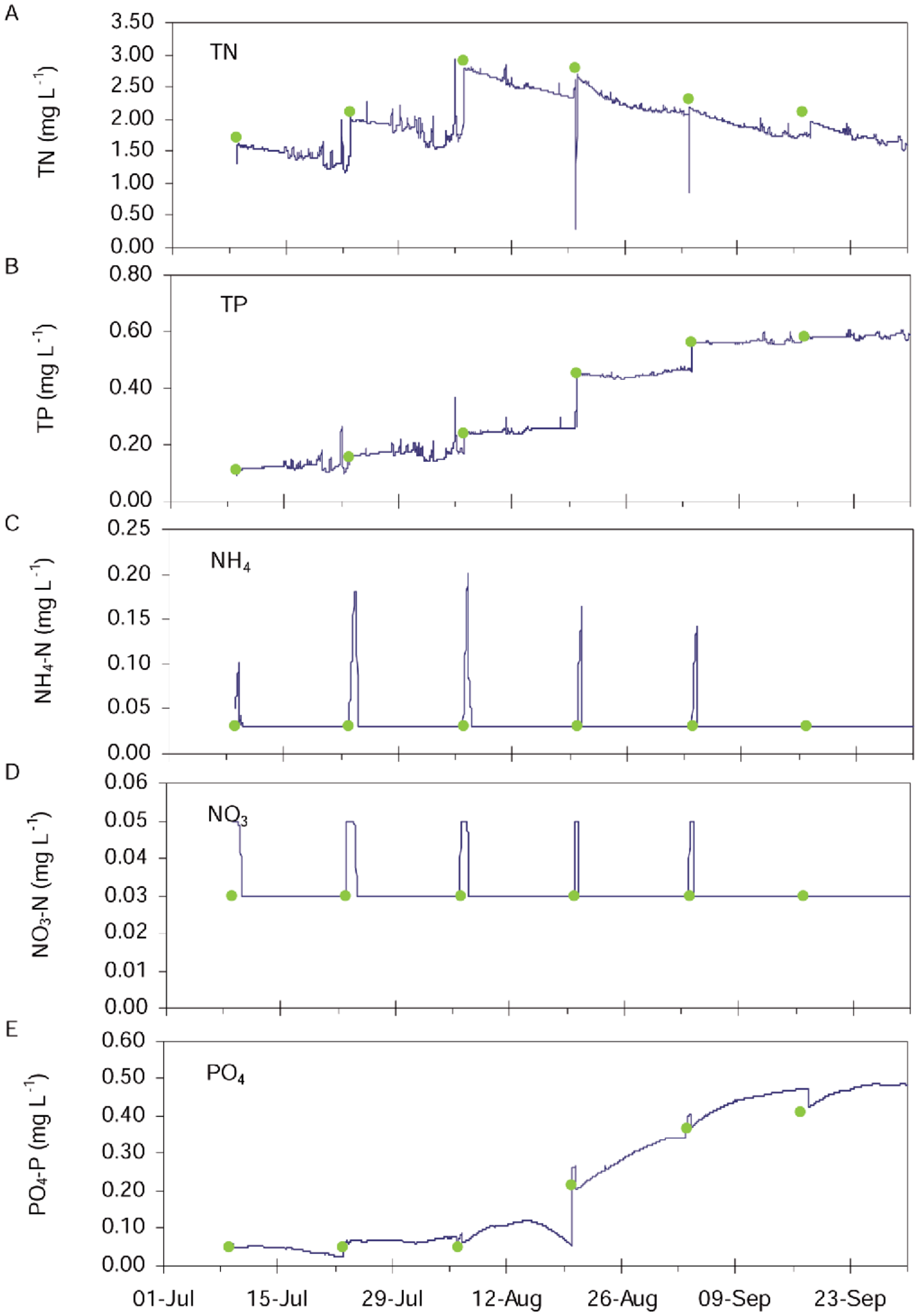


FIGURE 6.2 MODEL (LINE) SIMULATIONS OF (A) TOTAL NITROGEN (TN), (B) TOTAL PHOSPHORUS (TP), (C) AMMONIUM (NH_4), (D) NITRATE (NO_3) AND (E) PHOSPHATE (PO_4) FOR GOOIMEER, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

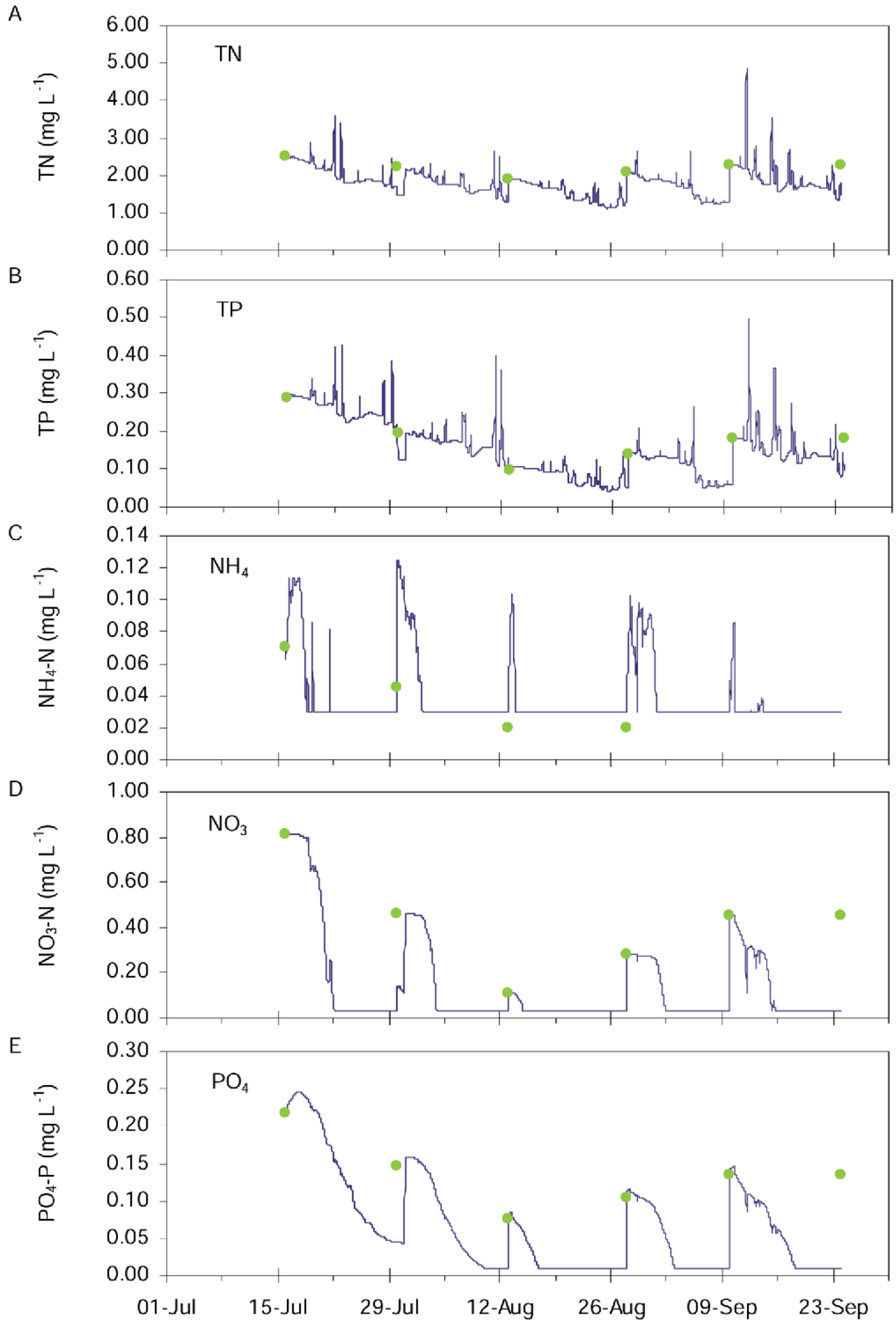


FIGURE 6.3 MODEL (LINE) SIMULATIONS OF (A) TOTAL NITROGEN (TN), (B) TOTAL PHOSPHORUS (TP), (C) AMMONIUM (NH_4), (D) NITRATE (NO_3) AND (E) PHOSPHATE (PO_4) FOR EEMMEER, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

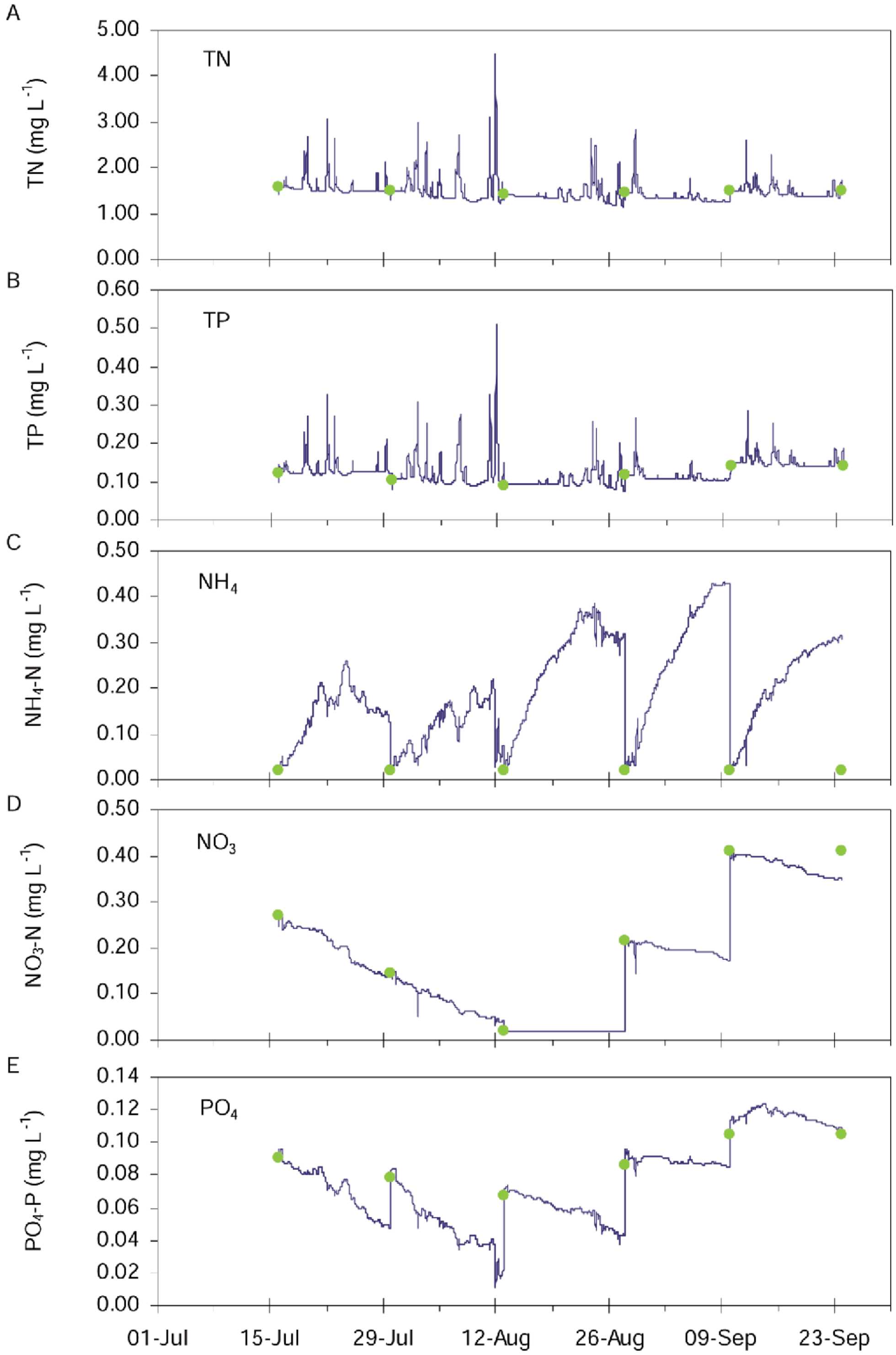


FIGURE 6.4 MODEL (LINE) SIMULATIONS OF (A) TOTAL NITROGEN (TN), (B) TOTAL PHOSPHORUS (TP), (C) AMMONIUM (NH_4), (D) NITRATE (NO_3) AND (E) PHOSPHATE (PO_4) FOR SLOTERPLAS, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

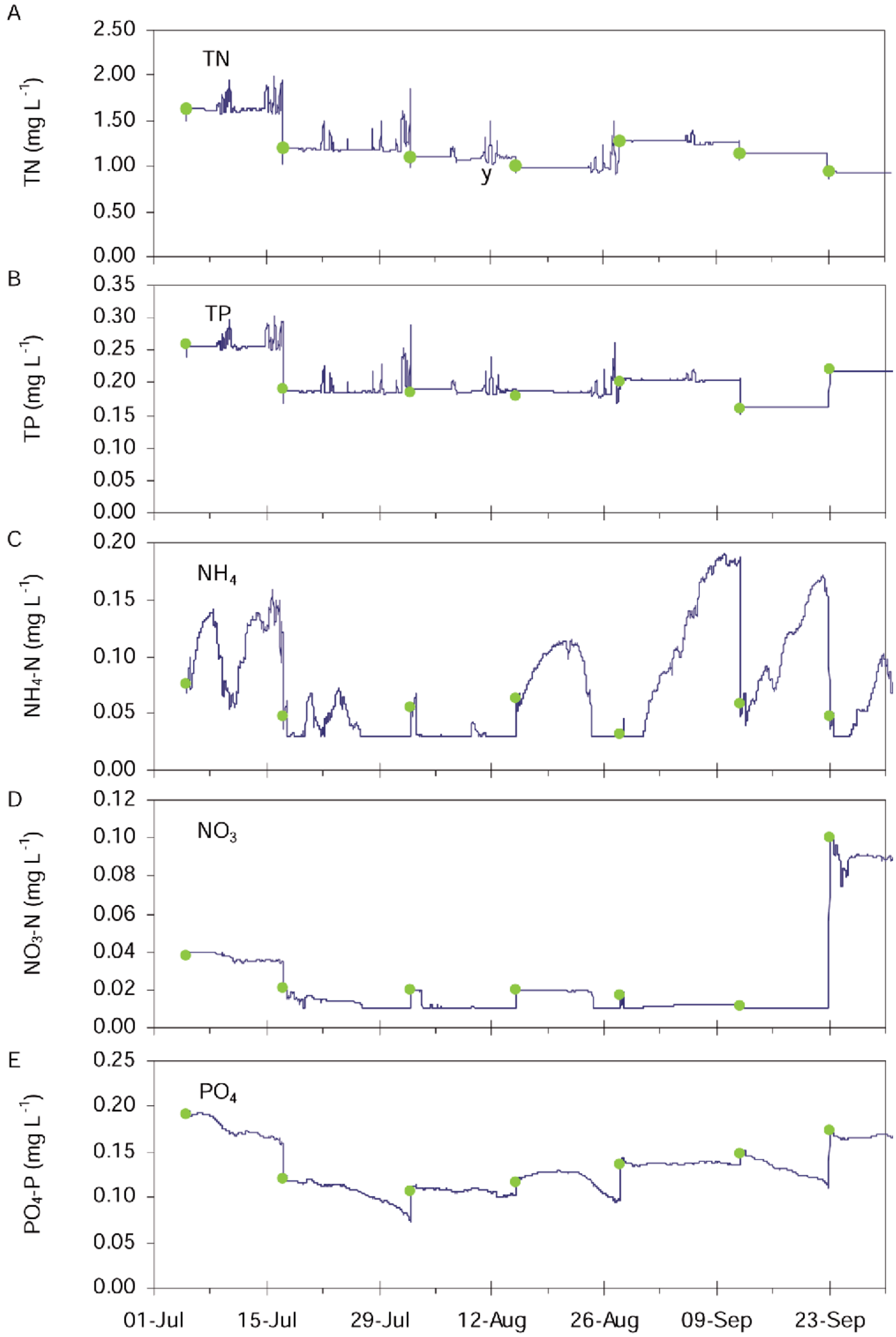
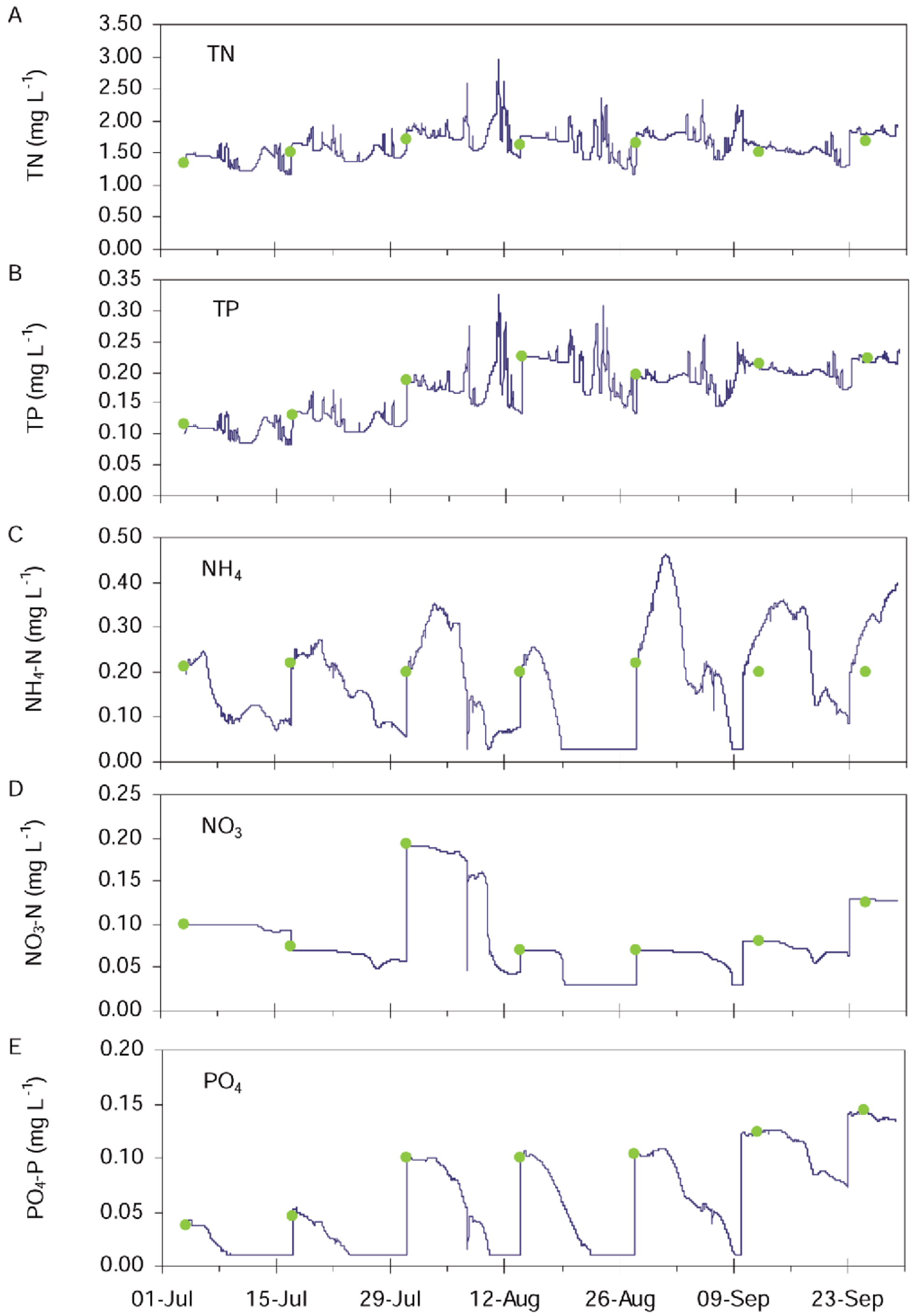


FIGURE 6.5 MODEL (LINE) SIMULATIONS OF (A) TOTAL NITROGEN (TN), (B) TOTAL PHOSPHORUS (TP), (C) AMMONIUM (NH_4), (D) NITRATE (NO_3) AND (E) PHOSPHATE (PO_4) FOR WESTEINDERPLASSEN, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL



6.1.2 PHYTOPLANKTON FIELD MEASUREMENTS

Phytoplankton cell counts conducted fortnightly in each study lake are shown in Figure 6.6. Phytoplankton biovolume was greatest in the Delftse Hout, and dynoflagelate species (*Ceratium sp.*) dominated the phytoplankton biomass from mid August. *Anabaena* and *Microcystis* species were the most dominant cyanobacteria group present in the lake, both reaching high biomass in late July.

Phytoplankton biovolume was greater in the Eemmeer than Gooimeer, with cyanobacteria species (*Microcystis* sp.) dominating the phytoplankton species composition over the whole study period (Figure 6.6). Cyanobacteria also dominated the species composition in the Sloterplas (Figure 6.6), while in the Westeinderplassen both chlorophytes and cyanobacteria biovolume were high (Figure 6.6). In both lakes, *Microcystis* sp. dominated the cyanobacteria.

6.1.3 PHYTOPLANKTON MODEL SIMULATIONS

Model simulations of phytoplankton biomass showed large deviations from the initial concentrations used to reset the model for each model simulation period. As a result, in all model simulations the species composition also changed over the duration of the simulation following each reset.

In the Delftse Hout, concentrations of diatoms, which represented the largest phytoplankton biomass in the lake, decreased rapidly over the course of the reset (Figure 6.5). Cyanobacteria biomass showed a large increase over the same time scales (Figure 6.5). A similar trend was observed in the Gooimeer and Eemmeer (Figure 6.6) and Sloterplas (Figure 6.7), with cyanobacteria biomass always increasing during each simulation while diatom and chlorophyte biomass nearly always decreased.

In the Westeinderplassen, diatom biomass decreased while chlorophyte biomass increased exponentially (Figure 6.7). Cyanobacteria biomass reached biomass values many times greater than the original starting concentration towards the end of each reset period. Additional calibration with the light extinction coefficient as well as the nutrient loading suggests that other factors play an important role in regulating the total biomass in the Westeinderplassen, possibly zooplankton grazing.

In all lakes, model simulations led to an increase in cyanobacteria biomass over the model reset period. Concentrations at the end of the reset would at times reach values 6-10 times greater than the starting concentration. This was due to a perceived decline in competition from other phytoplankton groups by the model, following their gradual loss from the system.

FIGURE 6.6 PHYTOPLANKTON (LEFT) AND SPECIES (RIGHT) COMPOSITION FOR (A) DELFTSE HOUT, (B) EEMMEER AND (C) GOOIMEER, JULY-SEPTEMBER 2007

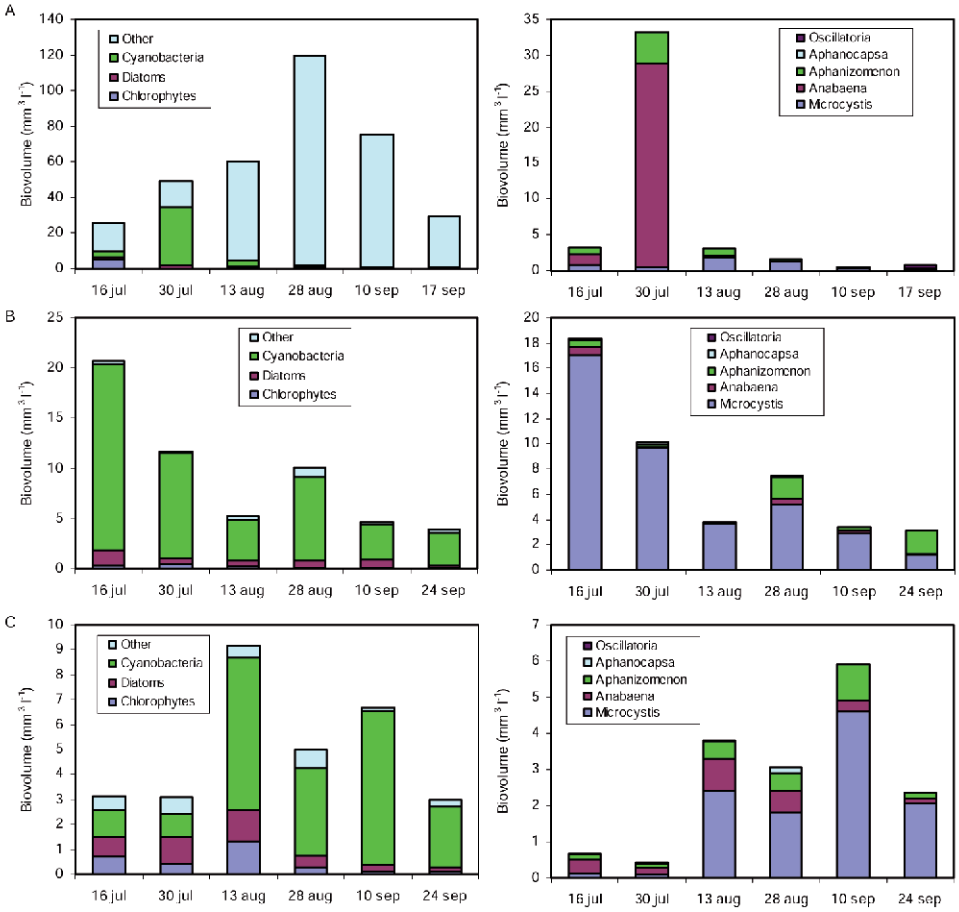


FIGURE 6.7 PHYTOPLANKTON (LEFT) AND SPECIES (RIGHT) COMPOSITION FOR (A) SLOTERPLAS AND (B), WESTEINDERPLASSEN, JULY-SEPTEMBER 2007

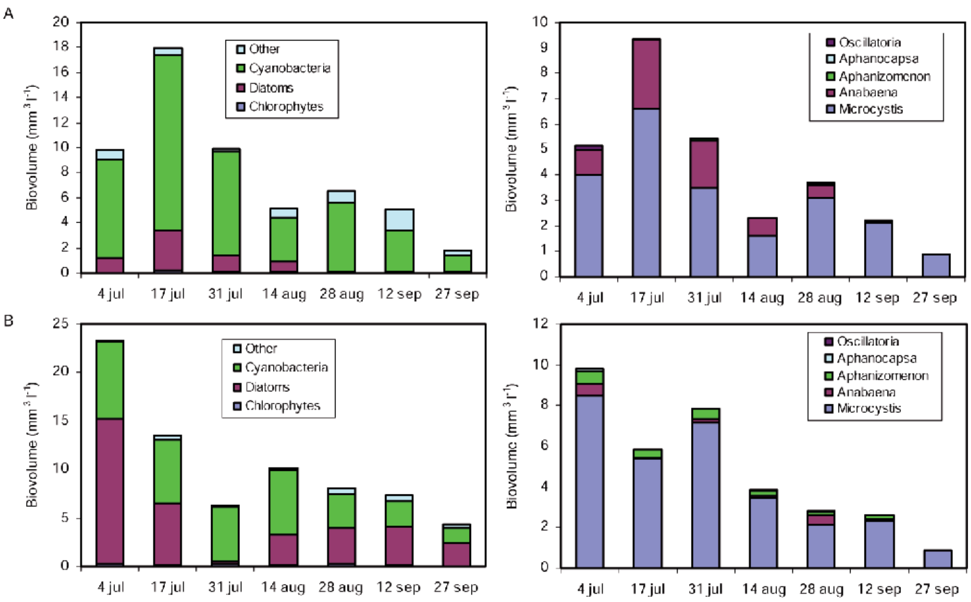


FIGURE 6.8 MODEL (LINE) SIMULATIONS OF (A) CYANOBACTERIA (CYANO), (B) DIATOM AND (C) CHLOROPHYTES (GREENS) BIOMASS FOR DELFTSE HOUT, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

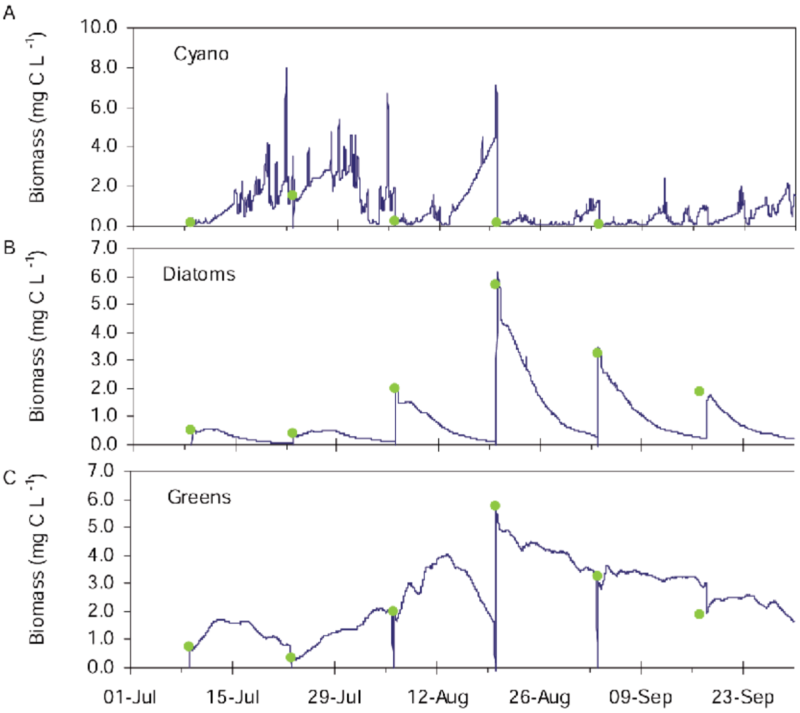


FIGURE 6.9 MODEL (LINE) SIMULATIONS OF (A) CYANOBACTERIA (CYANO), (B) DIATOM AND (C) CHLOROPHYTES (GREENS) BIOMASS FOR GOOIMEER AND EEMMEER, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

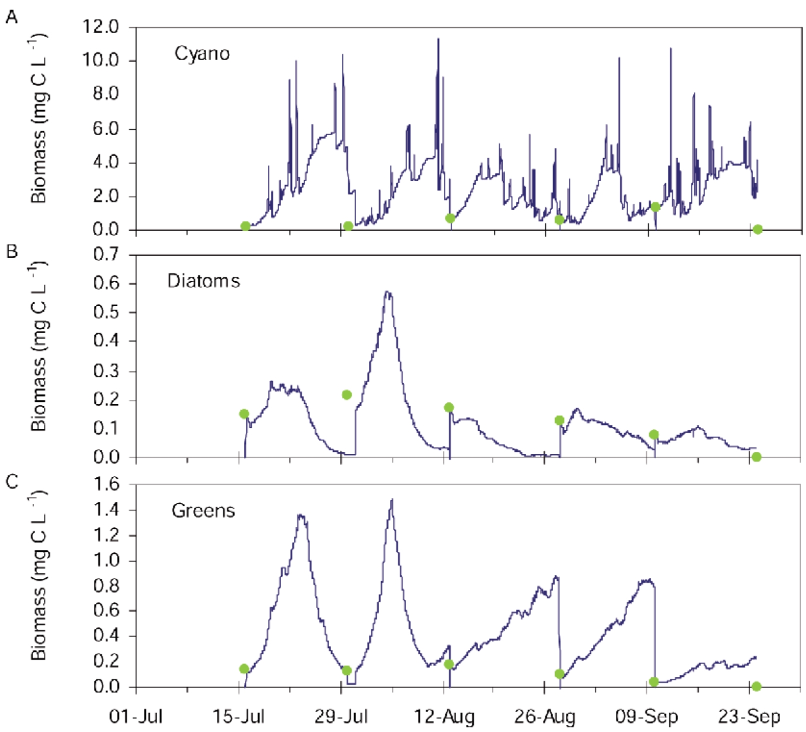


FIGURE 6.10 MODEL (LINE) SIMULATIONS OF (A) CYANOBACTERIA (CYANO), (B) DIATOM AND (C) CHLOROPHYTES (GREENS) BIOMASS FOR SLOTERPLAS, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

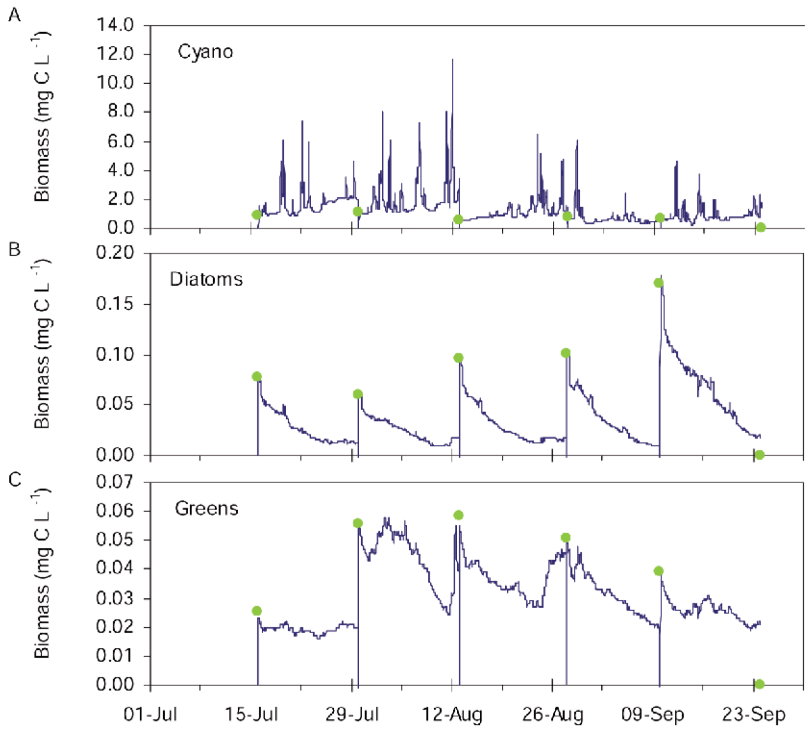


FIGURE 6.11 MODEL (LINE) SIMULATIONS OF (A) CYANOBACTERIA (CYANO), (B) DIATOM AND (C) CHLOROPHYTES (GREENS) BIOMASS FOR SLOTERPLAS, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL

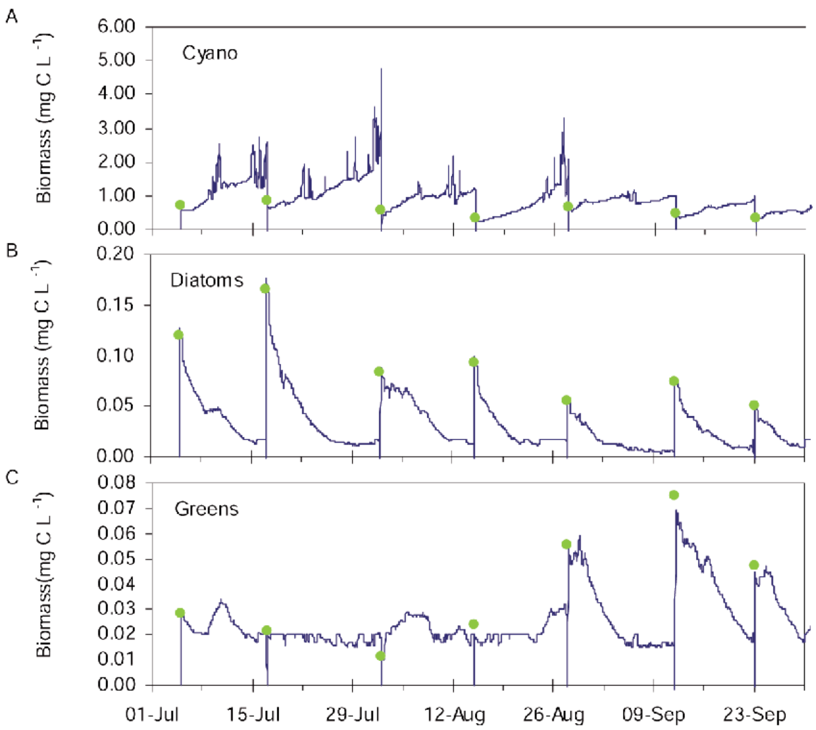
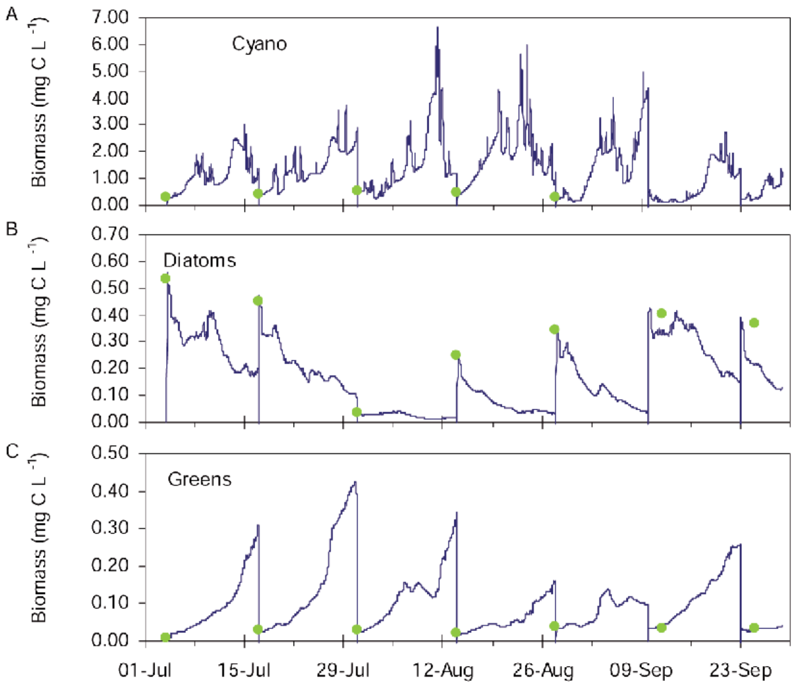


FIGURE 6.12 MODEL (LINE) SIMULATIONS OF (A) CYANOBACTERIA (CYANO), (B) DIATOM AND (C) CHLOROPHYTES (GREENS) BIOMASS FOR WESTEINDERPLASSEN, OVER THE PERIOD JUNE-SEPTEMBER 2007. THE POINTS REPRESENT THE FIELD MEASUREMENTS USED TO PERIODICALLY RESET THE MODEL



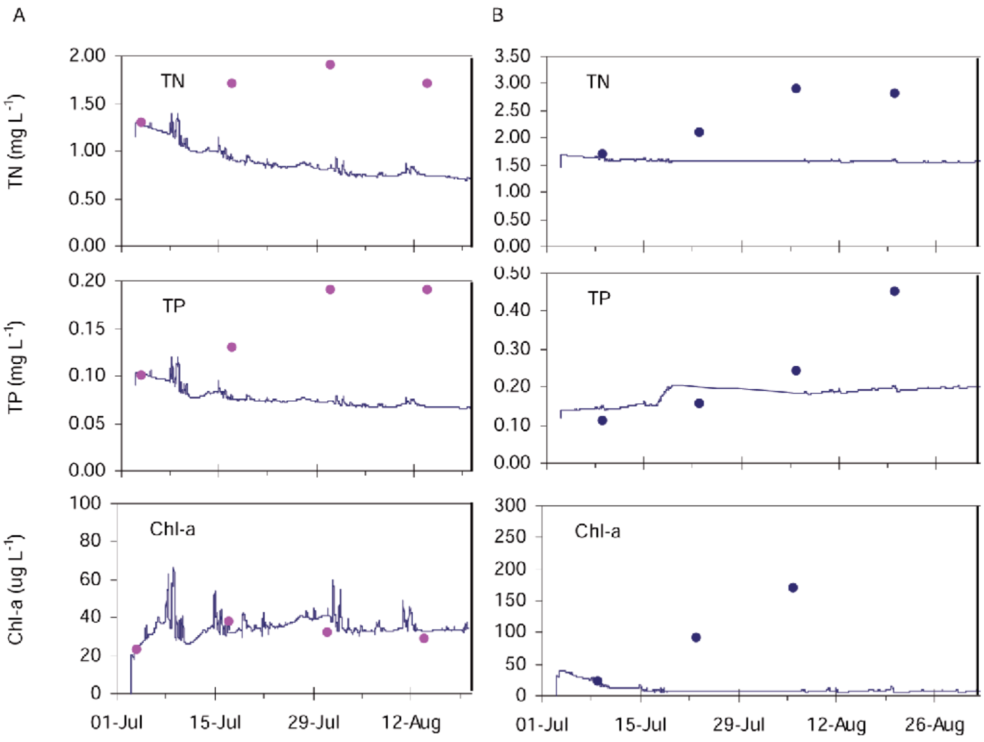
6.1.4 SIMULATIONS IN ABSENCE OF MODEL RESET

Simulations were also conducted to determine if the fortnightly reset was indeed required over a long time scale. Model simulations over July and August were made for each lake using only the first field measurements as initial starting conditions, with no further resets applied to correct the model.

The results of these simulations suggest that in the absence of a validated nutrient balance, the water column nutrient concentrations and chlorophyll-a are difficult to simulate. For example, in the Westeinderplassen, TN and TP concentrations rapidly declined to well below the observed field measurements (Figure 6.13). In the Delftse Hout, TP concentrations were reasonable over the first month in comparison to the field values (Figure 6.13), while concentrations of TN and chlorophyll-a were well below the actual measurements.

The results of these simulations verify that in the absence of a validated nutrient balance, a model reset is essential to accurately simulate the both the water column nutrient concentrations and phytoplankton biomass simultaneously.

FIGURE 6.13 CONTINUOUS MODEL SIMULATIONS OF TOTAL NITROGEN (TN), TOTAL PHOSPHORUS (TP) AND CHLOROPHYLL-A CONCENTRATIONS (CHL-A) FOR (A) WESTEINDERPLASSEN AND (B) DELFTSE HOUT



6.2 SURFACE BLOOM FORMATION

6.2.1 ECOFUZZ SCUM APPEARANCE AND DISAPPEARANCE

Cyanobacterial bloom formation and disappearance were simulated concurrently with the water quality and phytoplankton simulations. The results of scum appearance and disappearance, simulated in EcoFuzz before cyanobacterial biomass is taken into account, suggest that there was ample opportunity for scum formation over the full duration of the study period based on the water column stability and buoyancy alone (Figures 6.14 & 6.15). Maximum scum appearance values of 92.5 were frequent for all lakes over the whole study duration. There was also little difference in the output of disappearance over time, with no clear trends present over the study period (Figure 6.16).

The meteorological data used as input to the model were derived from two different sources: Rotterdam airport for Delftse Hout and Schiphol airport for Gooimeer-Eemmeer, Sloterplas and Westeinderplassen. The results of scum appearance and disappearance therefore differed slightly between the lakes (Figure 6.16). Scum appearance was more frequent and at times higher for the simulations conducted using the Rotterdam Airport climate data (Delftse Hout) (Figure 6.16).

FIGURE 6.14 SCUM APPEARANCE BASED ON CLIMATE DATA INPUT FROM (A) ROTTERDAM AIRPORT (FOR DELFTSE HOUT) AND (B), SCHIPHOL AIRPORT (FOR GOOIMEER-EEMMEER, SLOTERPLAS, AND WESTEINDERPLASSEN), JULY TO SEPTEMBER 2007

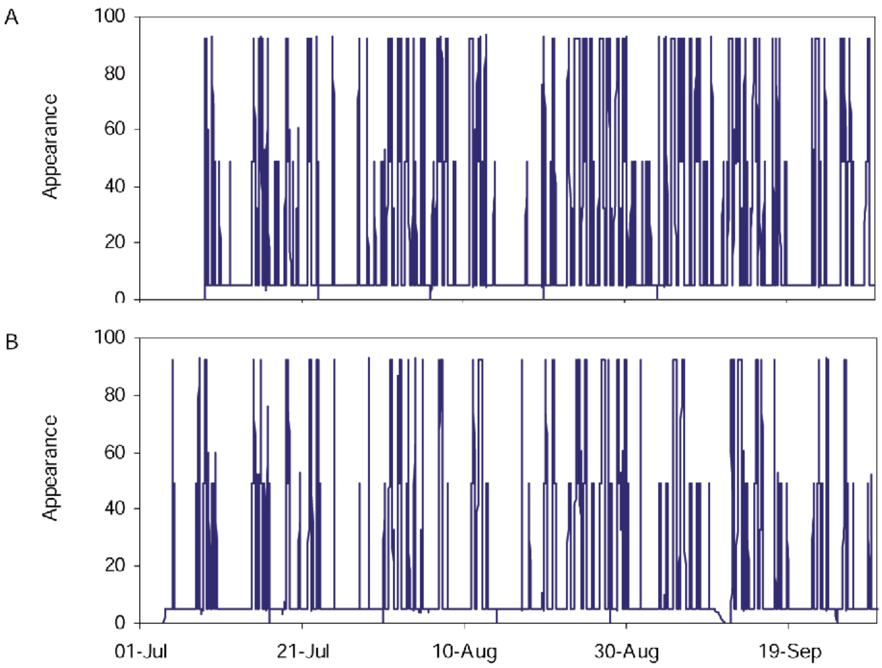
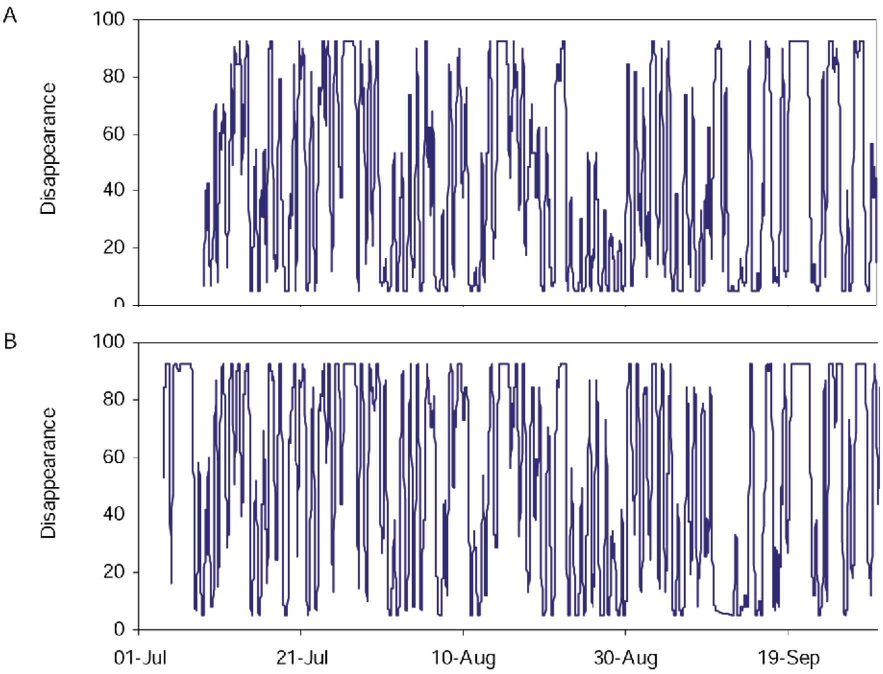
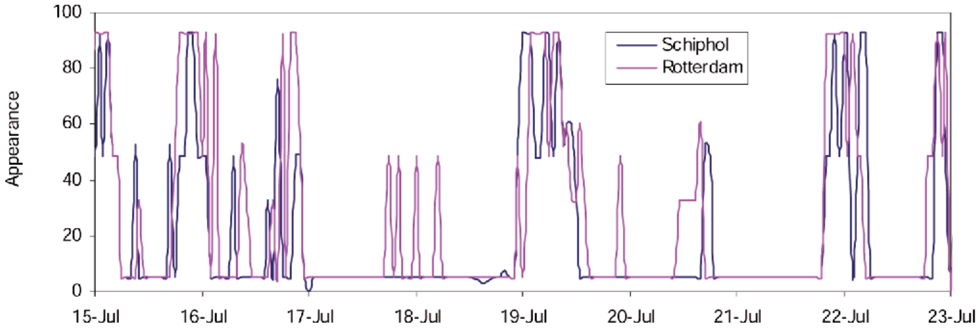


FIGURE 6.15 SCUM DISAPPEARANCE BASED ON CLIMATE DATA INPUT FROM (A) ROTTERDAM AIRPORT (FOR DELFTSE HOUT) AND (B), SCHIPHOL AIRPORT (FOR GOOIMEER-EEMMEER, SLOTERPLAS, AND WESTEINDERPLASSEN), JULY TO SEPTEMBER 2007. NOTE A 6-HOURLY RUNNING AVERAGE HAS BEEN APPLIED TO MAKE TRENDS MORE VISIBLE IN THE FIGURE



There appeared to be a slight diurnal trend in model output for scum appearance, with high values often occurring in the early morning, between the hours of 12:00 and approximately 4:00 (Figure 6.16).

FIGURE 6.16 COMPARISON BETWEEN SCUM APPEARANCE OUTPUT FOR CLIMATE DATA INPUT FROM ROTTERDAM AIRPORT (FOR DELFTSE HOUT) AND SCHIPHOL AIRPORT (FOR GOOIMEER-EEMMEER, SLOTERPLAS AND WESTEINDERPLASSEN), 15-23 JULY, 2007



Model calibrations to improve output of surface scum formation were focused on the scum appearance and disappearance thresholds which control when a surface scum appears and disappears in the model simulations. The scum appearance or disappearance value generated by EcoFuzz must exceed a certain threshold before the scum appearance process is activated in Delwaq. These values have a range of 0 to 100 % in the model, and were calibrated between 20 and 90 % in the simulations. Calibration was based on visual comparisons between the model output and available field data. For three of the lakes (Gooimeer-Eemmeer, Sloterplas and Westeinderplassen) this could not be calibrated fully as there was little validation data available or few surface blooms had been observed. A threshold appearance value of 40 was used for all lakes in the final simulations (Table 6.1). For the disappearance threshold, a value of 80 was used for all lakes apart from the Westeinderplassen. In this lake a much lower value of 40 was applied, to ensure that the blooms were not immediately dispersed in the model.

TABLE 6.1 APPEARANCE AND DISAPPEARANCE THRESHOLDS, AS WELL AS THE WIND DRAG FACTOR, USED TO CALIBRATE DELFTSE HOUT (DH), GOOIMEER-EEMMEER (GE), SLOTERPLAS (SP) AND WESTEINDERPLASSEN (WP). A FULL DESCRIPTION OF THE PARAMETERS AND HOW THEY ARE IMPLEMENTED IN THE MODEL IS PROVIDED IN SECTION 3

Parameter	Symbol	Unit	Range	DH	GE	SP	WP
Thresholdappearance	Thres_App	%	0-100	40	40	40	40
Threshold disappearance	Thres_Dis	%	0-100	80	80	80	40
Wind drag factor	FWindDrag	Dimensionless	1-10	5	1	0.2	0.5

6.2.2 MODEL SIMULATIONS VERSUS FIELD VALIDATION DATA

The results of the cyanobacterial surface bloom appearance conducted with the complete model instrumentation are compared to the field validation data available for each of the four study lakes in Figure 6.18. Scum appearance was used to assess the model results, as this could be easily quantified for the whole lake for comparison with the field data. Scum appearance and disappearance are not coupled in the appearance output, and it was therefore assumed that scum disappearance occurred when scum appearance did not. For the field validation data for Delftse Hout and Sloterplas, where values of 0.5 were often recorded, any bloom category less than 1 was assumed to be no bloom present for the purpose of this study.

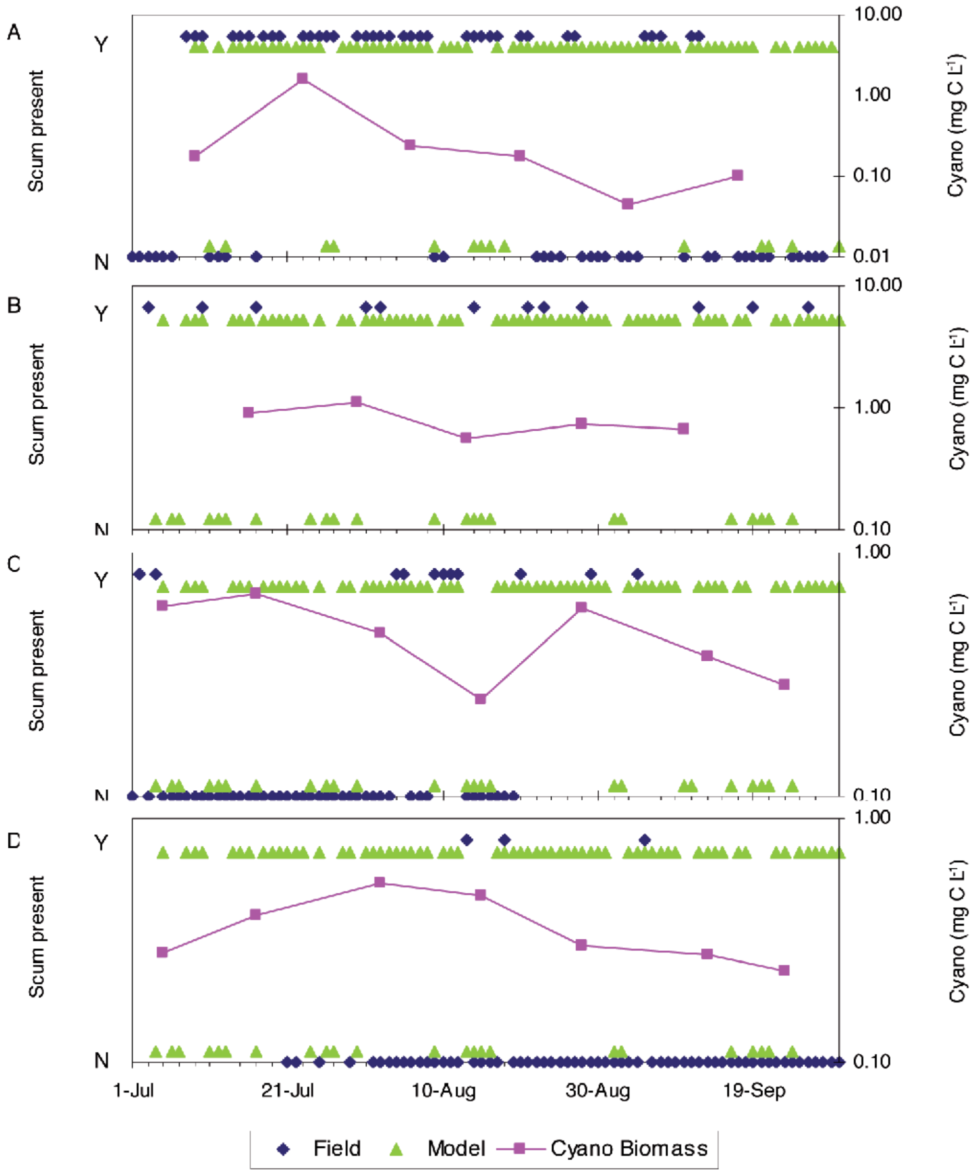
For the Delftse Hout, which had the most available validation data, bloom appearance was simulated accurately by the model 82 % of the time (see Table 6.2). Bloom disappearance, inferred from no scum appearance, however, was only estimated correctly by the model 23 % of the time. Overall, the model output was correct relative to the field data for only 55 % of the time. No data was available for validation for 16 days over the modelling period. In the Gooimeer-Eemmeer, despite the limited field validation data available (9 days over the whole model period), surface bloom appearance were accurately simulated by the model 78 % of the time (Table 6.2. The overall model results were correct 80 % of the time for both scum appearance and absence, although more data would be required to validate this performance.

In Sloterplas, bloom appearance was simulated accurately 80 % of the time although blooms were predicted 26 times by the model when according to the limited field data they were not present. However, the field data from Sloterplas was typically only for one small location (the harbour) and therefore blooms may have occurred in the lake but not observed in the validation data available. For both scum presence and absence, the model was correct only 44 % of the time relative to the field data. In the Westeinderplassen, there was also not enough data to assess the model performance accurately. However, blooms were generally not observed in the lake over the summer period. Based on the data available, the model simulations predicted bloom presence on 2 of the 3 days that they were also observed in the field. However, the model also predicted bloom appearance on 49 days when the validation suggested there were no blooms present. Overall model accuracy for the Westeinderplassen was only 21 % relative to the field data.

TABLE 6.2 COMPARISONS BETWEEN OUTPUT OF MODEL SCUM APPEARANCE AND FIELD VALIDATION DATA FOR CYANOBACTERIAL BLOOM PRESENCE AND ABSENCE FOR DELFTSE HOUT (DH), GOOIMEER-EEMMEER (GE), SLOTERPLAS (SP) AND WESTEINDERPLASSEN (WP). MODEL CORRECT AND INCORRECT REPRESENTS THE TOTAL DAYS ON WHICH MODEL CORRECTIONS FOR BOTH SCUM PRESENCE AND ABSENCE WERE CORRECT. NO DATA REPRESENTS DAYS WHICH WERE SIMULATED IN THE MODEL FOR WHICH THERE WAS NO FIELD DATA AVAILABLE TO VALIDATE THE RESULTS

			Field	Model	Model	No Data
Lake	**Model**	**Bloom present**	**Bloom absent**	**Correct**	**Incorrect**	
DH	Bloom present	28	23			
	Bloom absent	6	7			
	Total	34	30	35	29	16
GE	Bloom present	7	0			
	Bloom absent	2	1			
	Total	9	1	8	2	67
SP	Bloom present	8	26			
	Bloom absent	2	14			
	Total	10	40	22	28	39
WP	Bloom present	2	49			
	Bloom absent	1	11			
	Total	3	60	13	50	25

FIGURE 6.17 DAILY COMPARISON BETWEEN SCUM PRESENCE (Y) AND ABSENCE (N) FOR THE AVAILABLE VALIDATION DATA (FIELD) AND MODE SIMULATIONS (MODEL), FOR (A) DELFTSE HOUT), (B) GOOIMEER-EEMMEER, (C) SLOTERPLAS AND (D) WEST-EINDERPLASSEN), JULY – SEPTEMBER 2007. MODEL OUTPUT FOR SCUM PRESENCE WAS INFERRED FROM SCUM APPEARANCE. FIELD MEASUREMENTS OF CYANOBACTERIA BIOMASS (CYANO, ON LOG SCALE) ARE ALSO SHOWN FOR EACH LAKE. MISSING DATA POINTS FOR THE FIELD VALIDATIONS ARE NOT SHOWN (SEE TABLE 6.1)



6.3 SURFACE BLOOM HORIZONTAL TRANSPORT

Assessment of model performance for horizontal surface bloom transportation was not trivial for a many reasons, including:

- A general lack of validation data for three of the four study lakes (Gooimeer-Eemmeer, Sloterplas and Westeinderplassen;
- Not all shorelines were included in the field survey on the days for which validation data was collected (Sloterplas and Westeinderplassen);
- The validation data represents only a small time period over the day, while the model simulations are conducted hourly;
- Simulations of water quality nutrient concentrations and phytoplankton biomass and species composition was not good in the model simulations.

In order to make comparisons of the spatial distribution of phytoplankton surface blooms between the field validation data and model simulations, a series of maps were made for each lake. Shorelines where blooms had been visualised were shaded based on the category of surface bloom observed. Output from the model was then visually inspected for the days for which validation data was available. The model output represents a mean daily location, while the field data represents only one moment during the day.

Calibration of cyanobacterial surface bloom wind dispersal in the model was largely determined using the wind drag coefficient. Although this parameter is dimensionless, calibrations were conducted between a range of 0 (no wind dispersal) and 10 (high wind dispersal). Calibration was made by visually comparing the model output with the field validation data available. The final wind drag coefficients specified in the model are given in Table 6.1.

The results show indicate that the accumulation of surface blooms along the lee shoreline of the dominant wind is well simulated by the new model code. For the Delftse Hout, cyanobacteria accumulation was typically along the North east and North western shorelines in the model simulations, as well as in the South west and long canal in the South west. A series of plots showing the model results and actual field validation data are shown in Figures 6.18-23. The model results indicate a clear accumulation of cyanobacterial biomass along the lake shorelines which compare well with what is seen in the field for most days.

Model simulations of the Gooimeer and Eemmeer also appeared to reflect what generally occurs in the lake, although the validation data was extremely limited over the duration of the study (only 9 days). The model simulations of 23 August and 12 September capture the exact location of surface blooms observed in the aerial photographs, although on other days the timing of the bloom location appears to be incorrect (Figures 6.21-23). For example, on 2 and 21 August the model simulations over the whole day suggest that the bloom was most dominant along the southern shoreline of the Gooimeer, while the photographs show accumulation along the Almere harbour front and the northern shoreline (Figures 6.21). However, it was extremely difficult to fully validate all the aerial photographs collected each survey day, as many photos did not show any recognisable land features making the exact location in the lake difficult to pinpoint. Also, the validation data represents only the presence of a bloom around mid day, while the model simulations represent the spatial distribution over the whole day. It may be possible that wind activity during the course of the day rapidly redistributed surface blooms in the Gooimeer, alternating between the northern and southern shorelines depending on the dominant direction.

The aerial photographs of the Gooimeer often showed the presence of a permanent surface bloom in the Almere Harbour. Due to the large model grid size, the Almere harbour is not well represented in the model simulations, and therefore surface blooms in the model simulations do not readily accumulate in this location.

In the Sloterplas, the model often showed an accumulation of cyanobacterial blooms in the harbour in the northern part of the lake, as well as the recreational swimming beach along the north western shoreline (Figs. 6.23-24). The field validation data available was primarily for the harbour, where blooms of category 0-1 were recorded nearly every day. Two large blooms were (category 3) were also observed along the mid-eastern shoreline (11 August), and this was also captured by the model simulations.

Surface bloom accumulation was more difficult to calibrate in the Westeinderplassen than in some of the other lakes, due to the complexity of the lake morphology and hydrodynamics in the Northern basins, as well as the lack of field data to validate the model. The small number of blooms which were recorded in the lake were typically centred around the small canals intersected the Grote and Kleine Poel (Figures 6.25). These canals are not well represented in the model, due to the chosen model grid size. Model simulations showed an increase in biomass in the Grote Poel on many days, although it is uncertain to what extent this really happened (Figures. 6.25).

The results of model simulations conducted with varying wind drag coefficients suggest that this parameter is very important for the overall calibration of the complete model instrument. For example in the Gooimeer-Eemmeer, the difference in model simulations conducted wind drag coefficient 0 and 1 is shown in Figure 6.26. Without the wind drag process, surface scums do not accumulate on the shoreline of the lake, but rather remain spread out over a large surface area in the middle of the lake.

FIGURE 6.18 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN DELFTSE HOUT

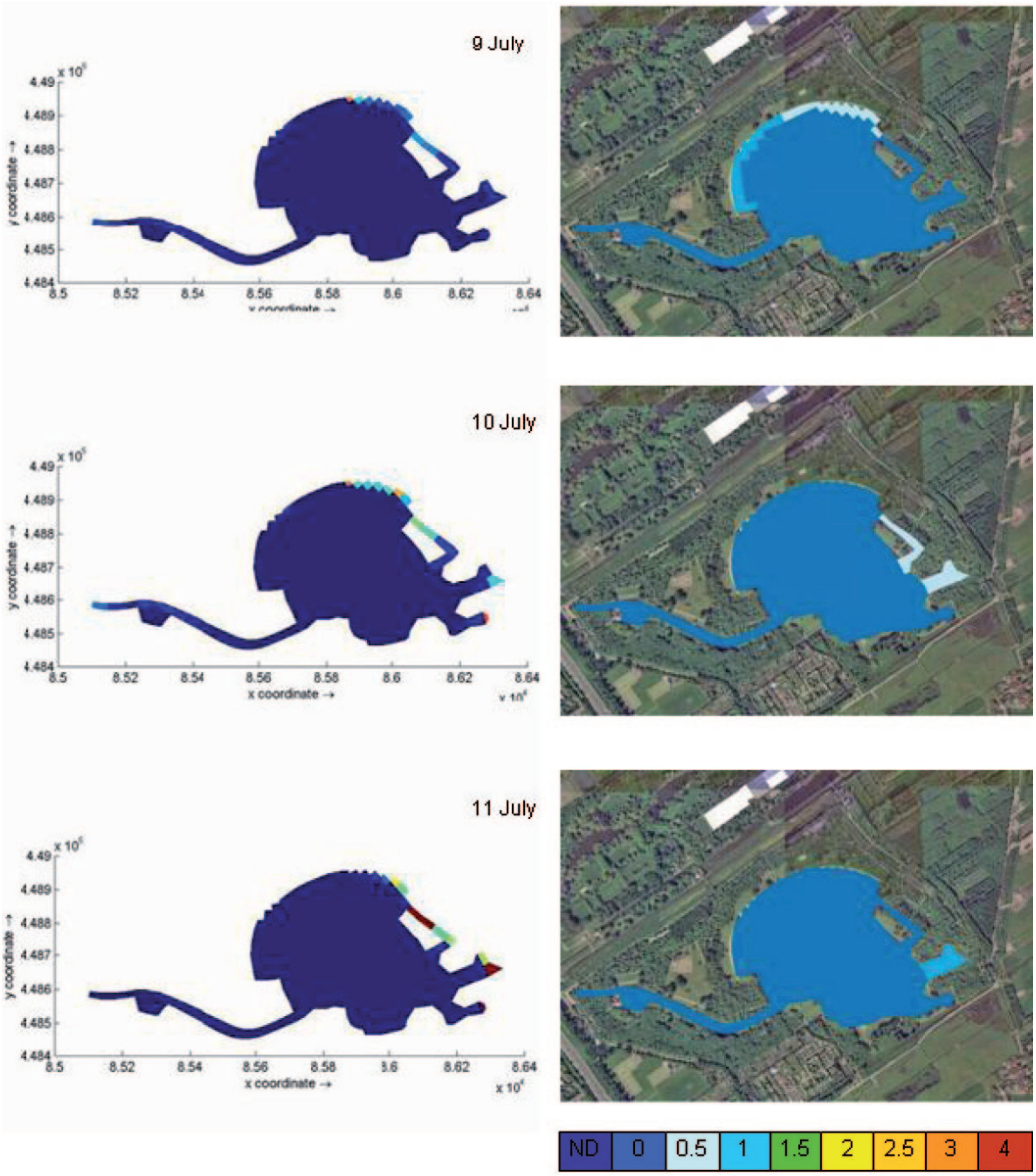


FIGURE 6.19 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN DELFTSE HOUT

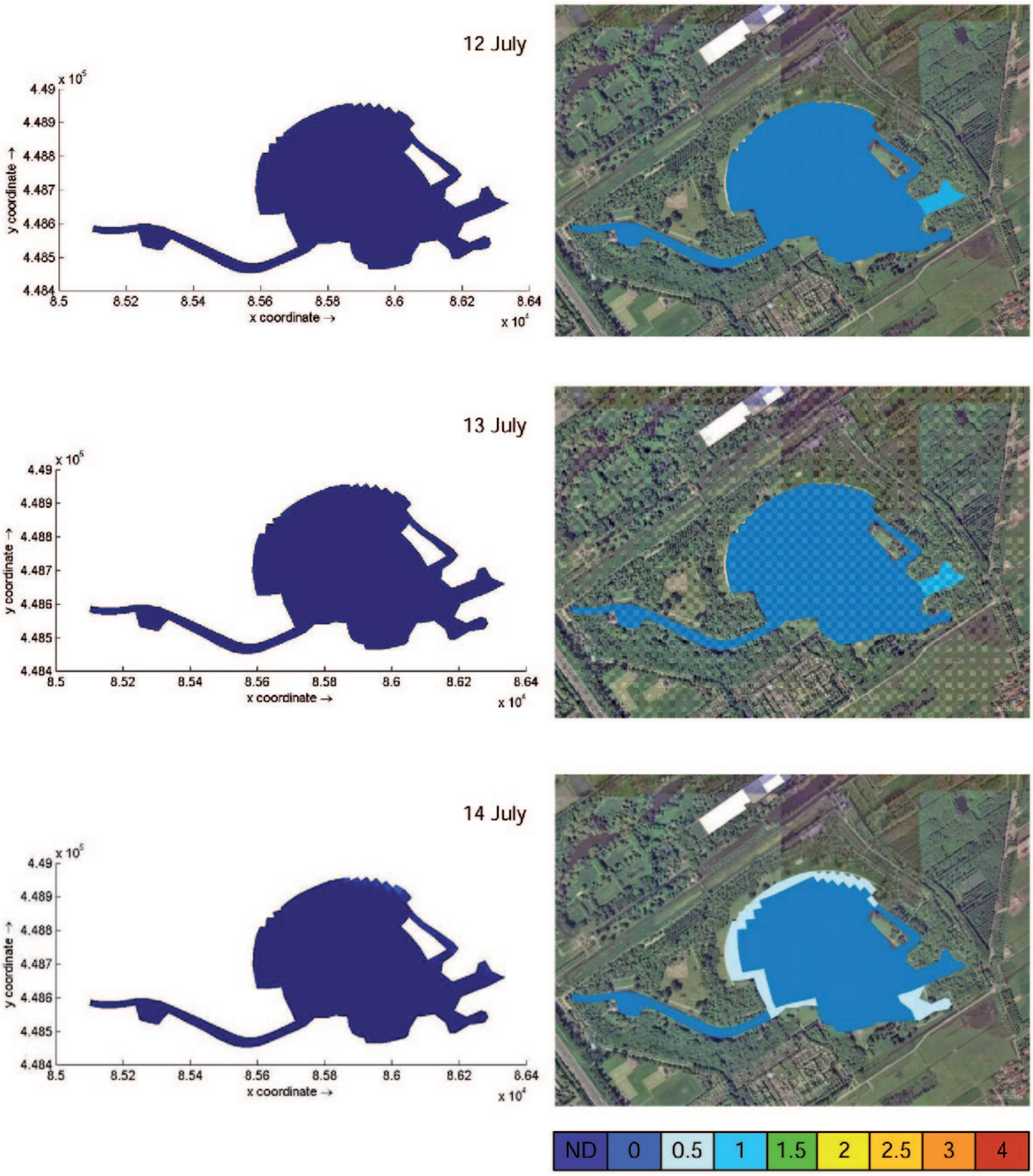


FIGURE 6.20 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN DELFTSE HOUT

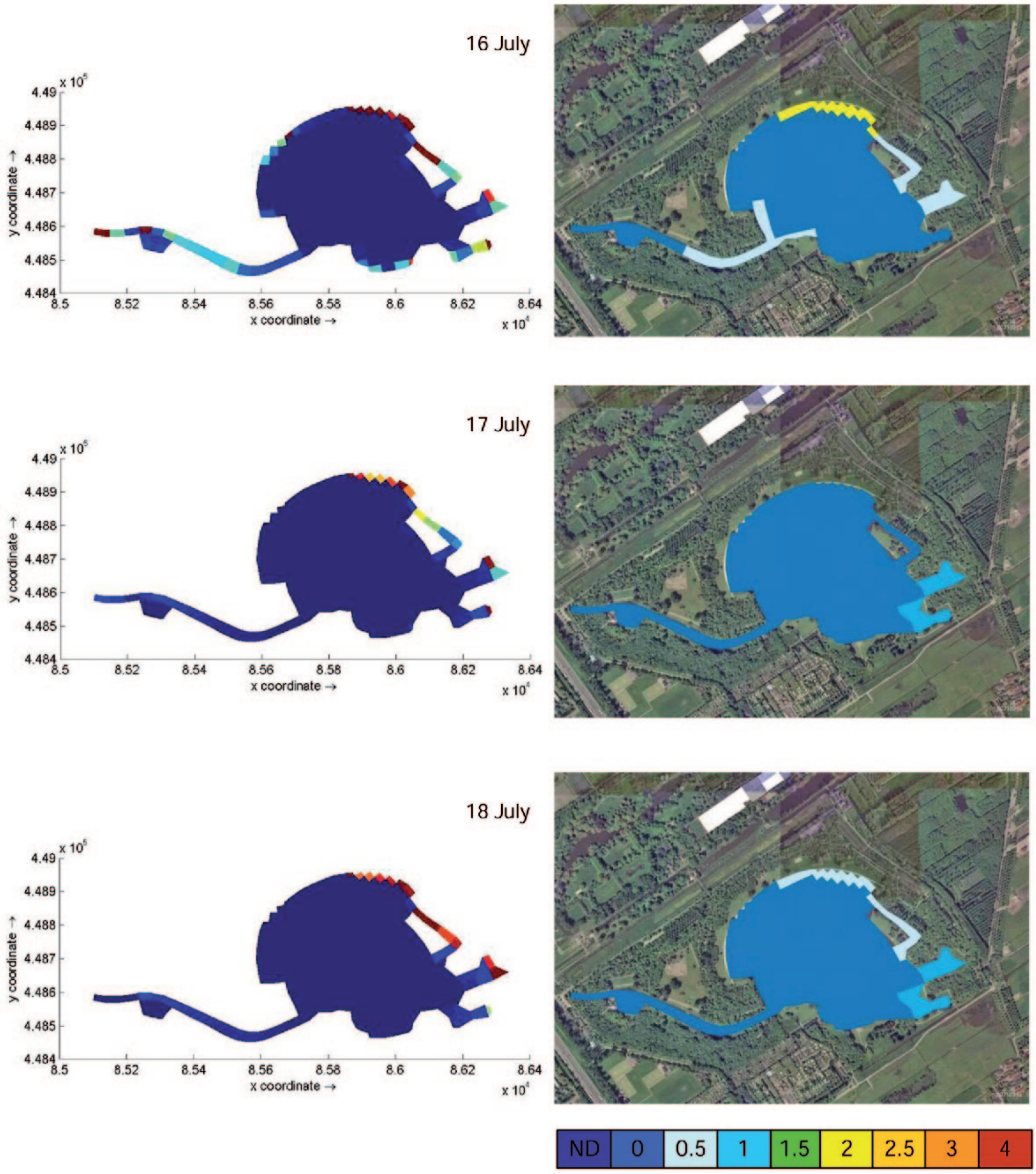


FIGURE 6.21 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN GOOIMEER-EEMMEER

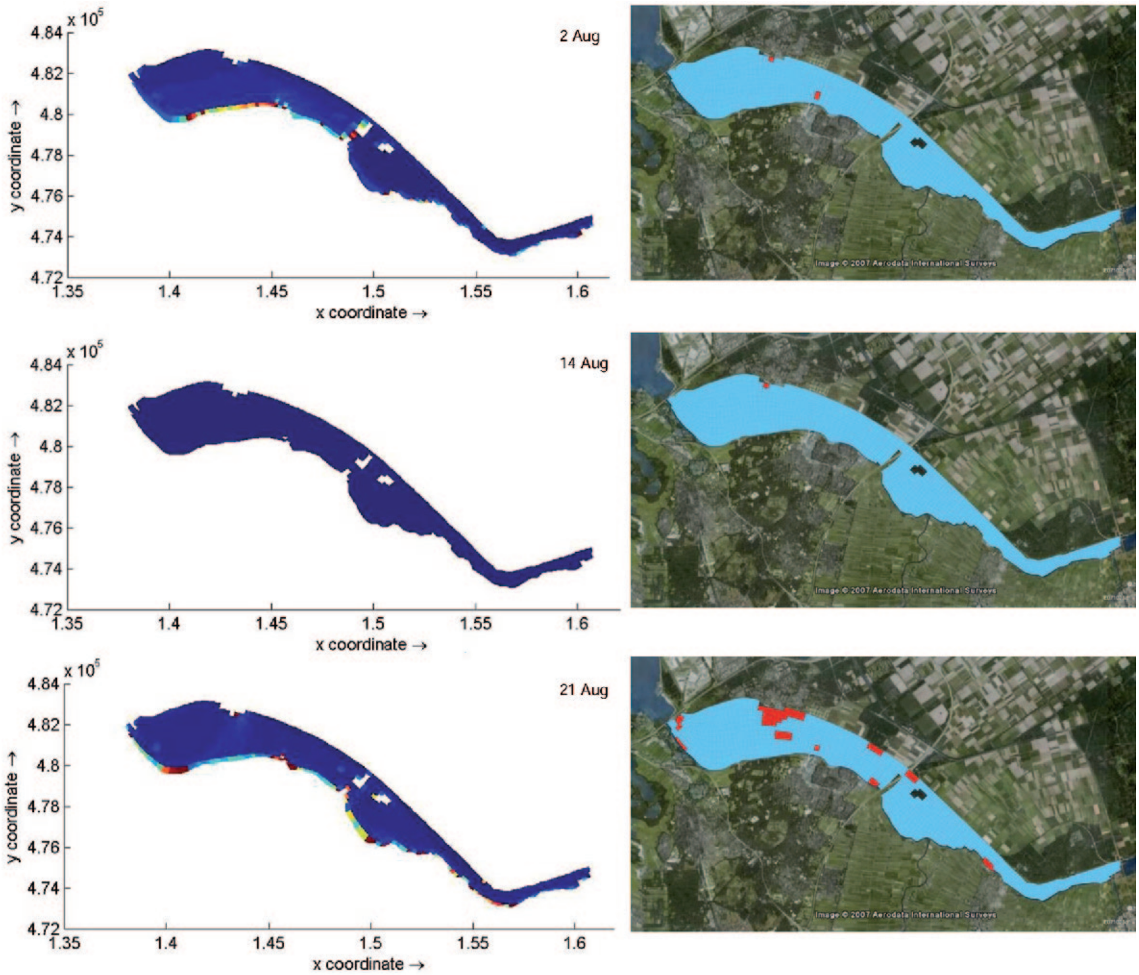


FIGURE 6.22 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN GOOIMEER-EEMMEER

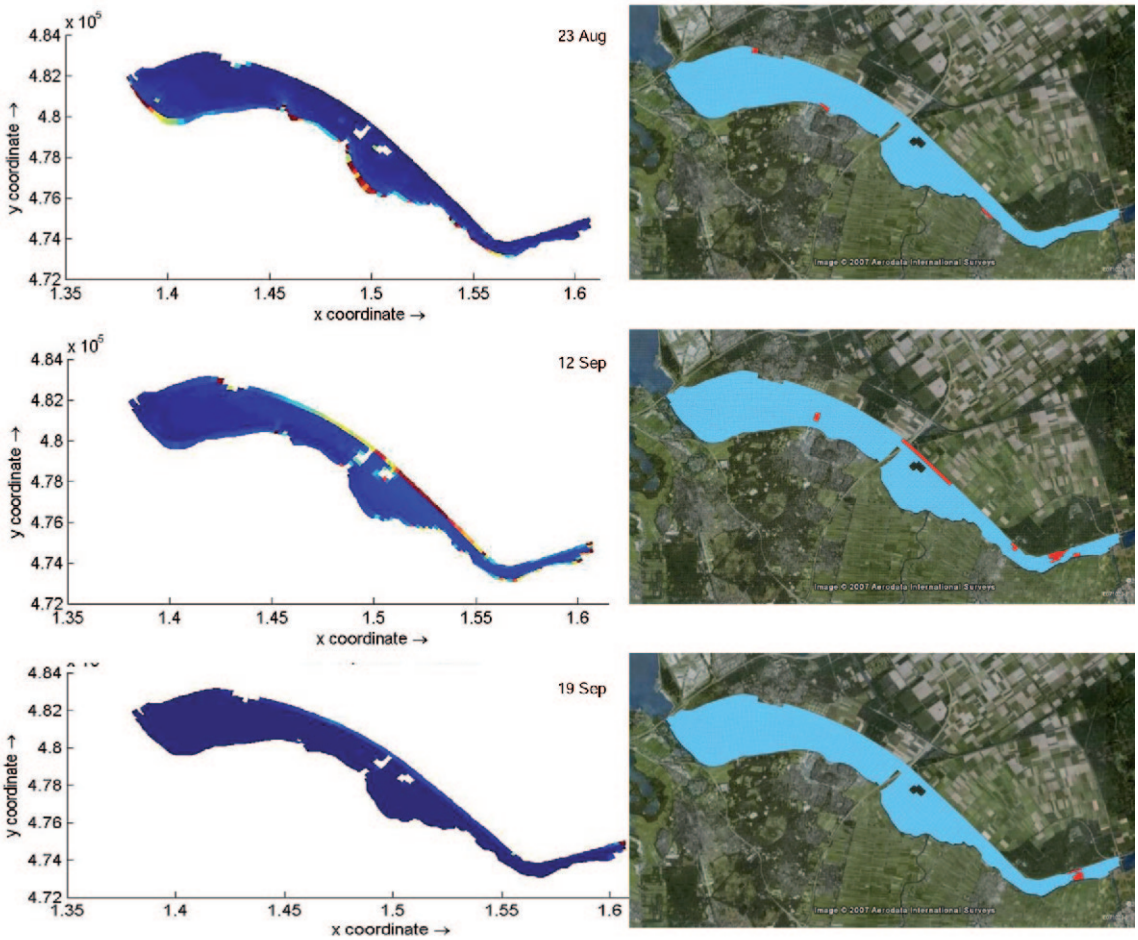


FIGURE 6.23 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN SLOTERPLAS

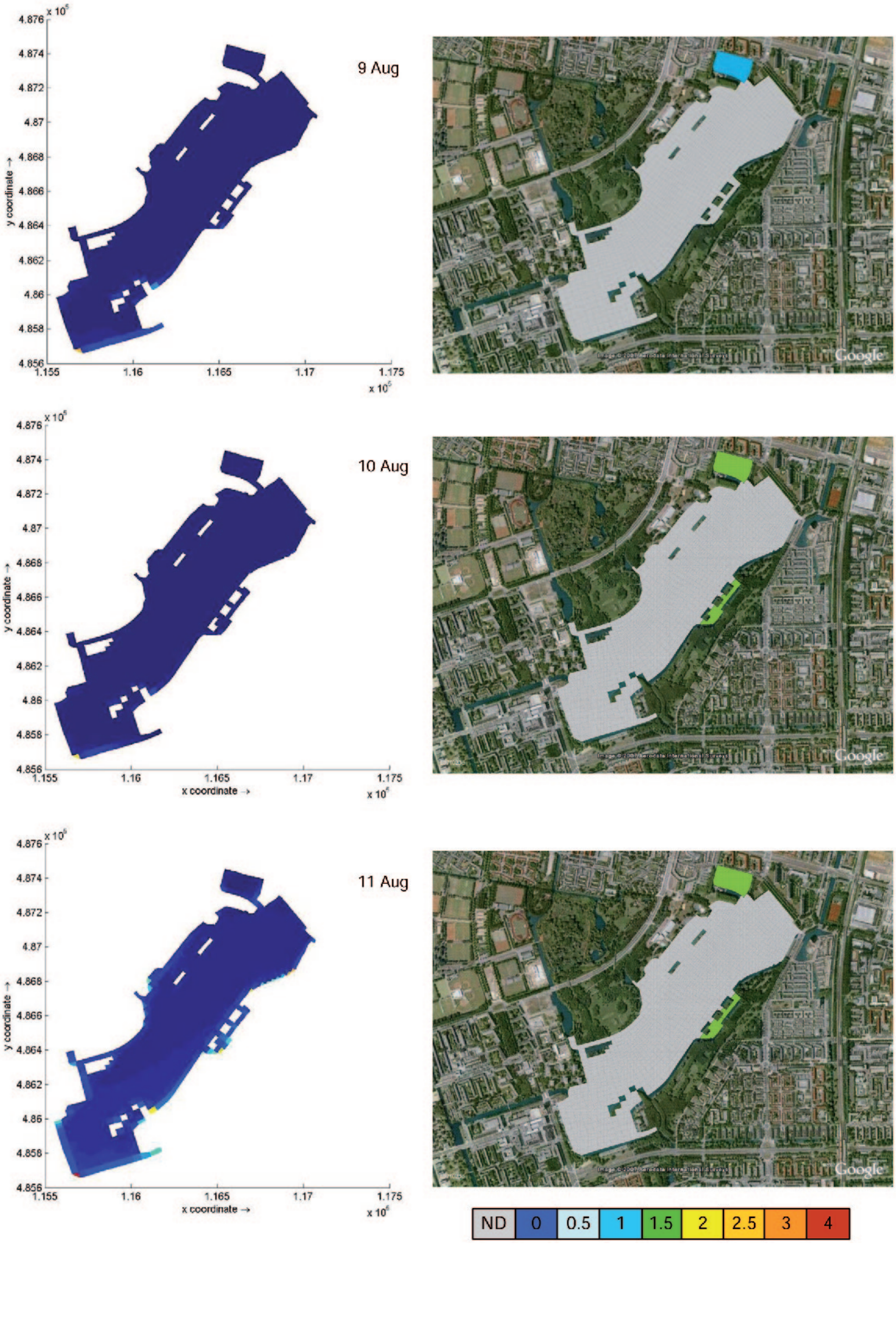


FIGURE 6.24 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN SLOTERPLAS

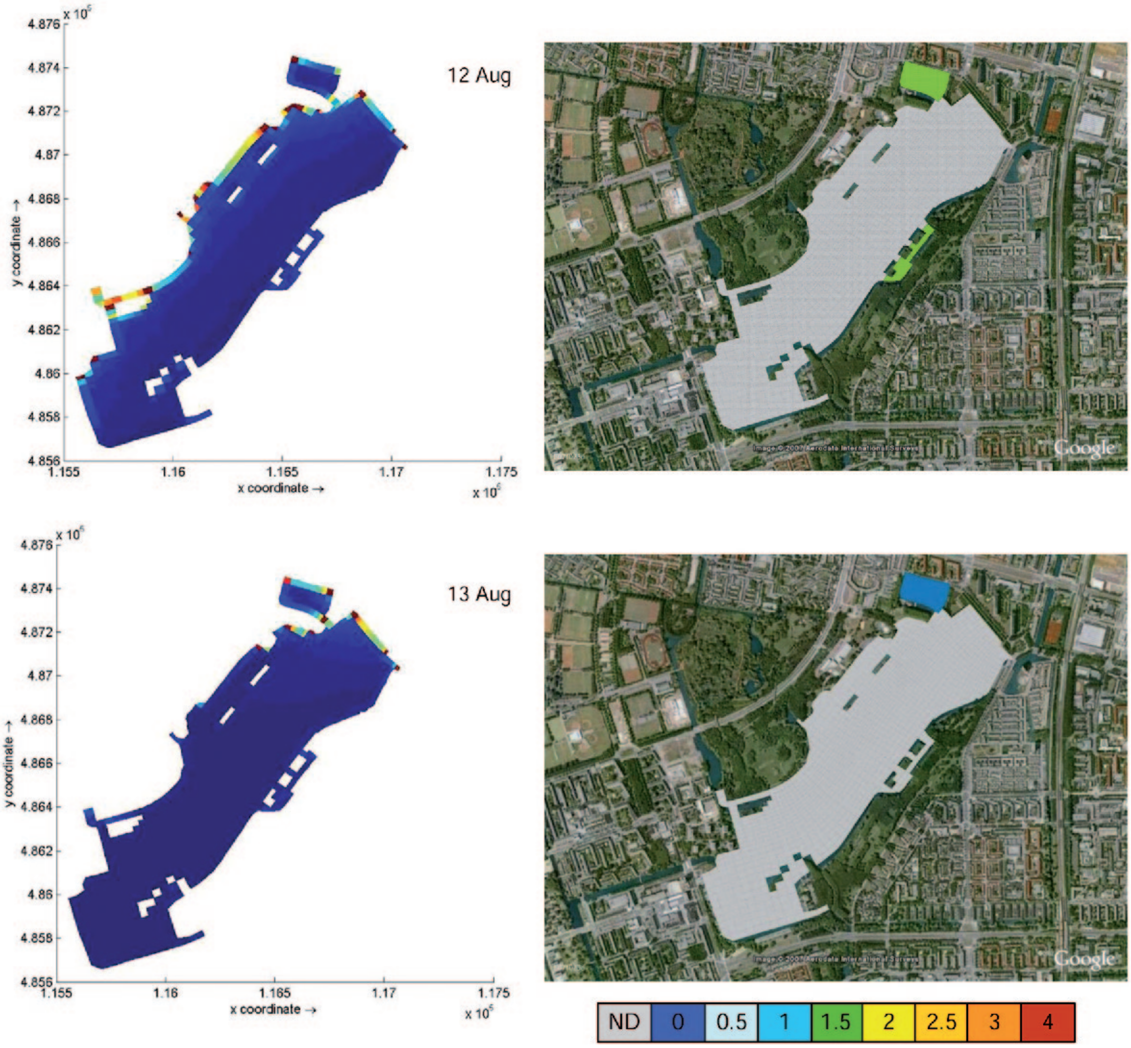


FIGURE 6.25 COMPARISONS OF MODEL SURFACE BLOOM LOCATION AND FIELD VALIDATION DATA IN WESTEINDERPLASSEN

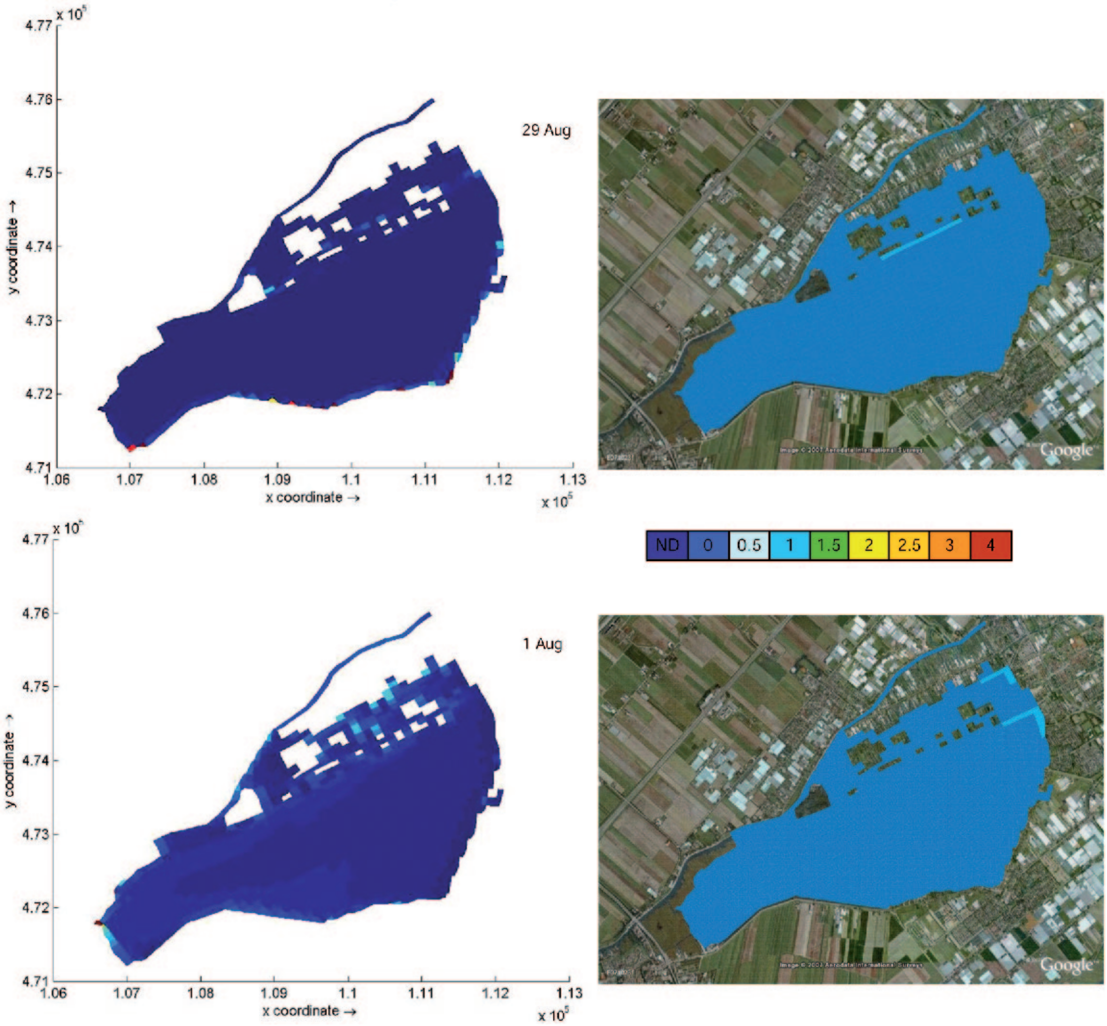
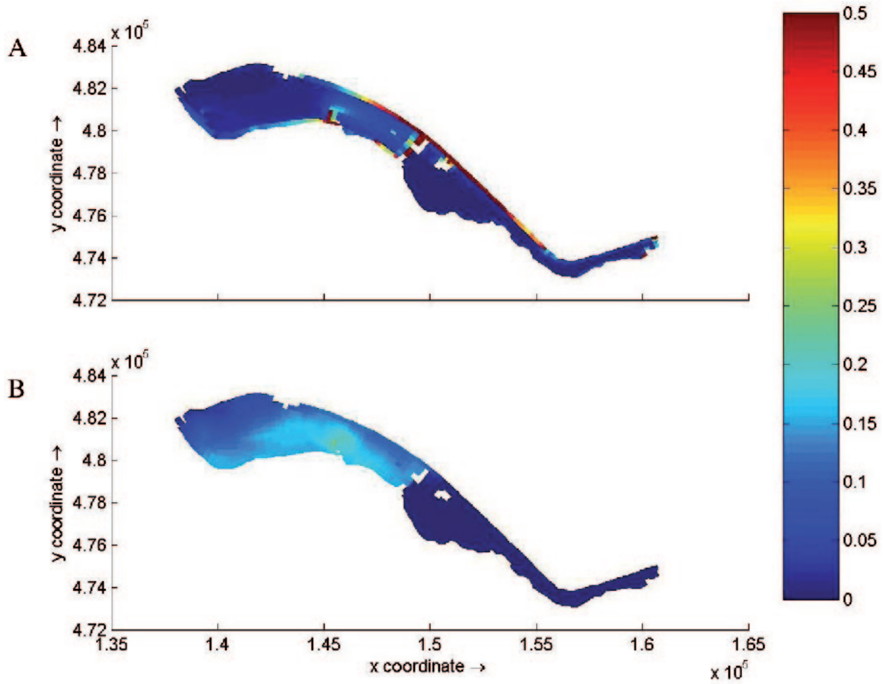


FIGURE 6.26 COMPARISONS BETWEEN MODEL OUTPUT OF SURFACE SCUM ACCUMULATION FOR USING A WIND DRAG COEFFICIENT OF (A) 1 AND (B) 0, GOOIMEER-EEMMEER, 3 AUGUST 2007



7

RESULTS WATER QUALITY SIMULATIONS WITHOUT BIOMASS MODEL

Based on results presented in Chapter 6 for the cyanobacterial biomass and species composition, it is apparent that despite many attempts at various calibrations, it is not possible to model the phytoplankton community accurately in the absence of a detailed nutrient balance. Although a periodic model reset does provide better results than simulations without the reset, inaccurate water column nutrient concentrations always led to a change in species dominance and unrealistic cyanobacterial growth rates in all four study lakes. While the model simulations of scum appearance and horizontal bloom transport indicate that these processes are working well, the overall modelling tool could be improved if the phytoplankton biomass simulations are more realistic.

In order to improve the phytoplankton biomass simulations, changes were made in the approach to the modelling, with the phytoplankton model BLOOM simplified to prevent sudden changes in species composition in response to the inaccurate water column nutrient simulations.

7.1 MODEL SETUP

All model simulations conducted in Chapter 6 were repeated with more simplified phytoplankton model as follows:

- Phytoplankton growth rates were set to zero for all species and types, so that growth would not occur;
- Phytoplankton mortality and respiration rates were set to zero, so that in the absence of growth, phytoplankton biomass would not decrease. Under this scenario the biweekly biomass measurements are highly important as further changes in biomass over the simulation period are not modelled;
- Sedimentation rates for all species were also set to zero;
- Phytoplankton biomass was reset in the model every fortnight, as in the existing model simulations.

With this modelling approach, water column nutrient concentrations are no longer important in the absence of phytoplankton growth. For the bloom forming cyanobacterial species, concentrations would change between individual grid cells dependent on activation of the scum forming process and horizontal transport processes. All other species would remain constant at the concentration specified for each model reset.

Cyanobacterial thresholds used to regulate the EcoFuzz scum appearance result based were set based on when blooms were actually observed in each lake. The inclusion of the cyanobacterial threshold in the model code is described in Section 3.3.2 and in Figure 3.4. The thresholds applied were:

- Delftse Hout 0.12 mg C L^{-1};
- Gooimeer-Eemmeer 0.4 mg C L^{-1};
- Sloterplas 0.4 mg L^{-1}, and;
- Westeinderplassen 0.4 mg C L^{-1}.

Cyanobacterial thresholds were set based on visual comparisons between scum appearance validation data and the measured cyanobacteria biomass observed when scum appearance was most common. All other processes in the complete model instrumentation were kept unchanged. The cyanobacterial threshold in Delftse Hout is much lower than for the other lakes as surface scums were observed regularly throughout the sampling period, even when measured cyanobacterial biomass was low.

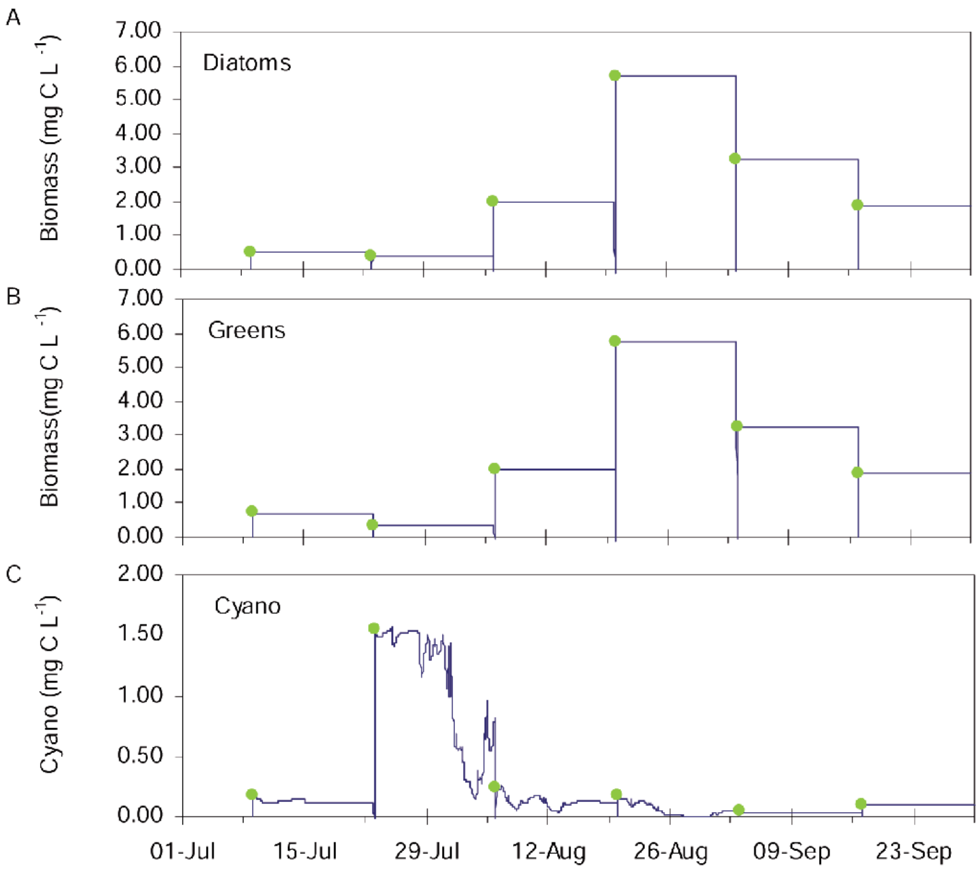
7.2 RESULTS

7.2.1 PHYTOPLANKTON BIOMASS SIMULATIONS

Results of the new model simulations conducted without the detailed phytoplankton module showed a more stable result for phytoplankton biomass and species composition. As prescribed in the model, concentrations of diatoms and chlorophytes in the model always remained constant throughout each reset simulation in all four lakes. For example in Delftse Hout (Figure 7.1), there is now no change in diatom and chlorophyte biomass during each reset period. Concentrations of cyanobacteria did change in response to the scum activation processes (Figure 7.1), due to vertical and horizontal transport, although the total biomass does not change. The patterns of results were identical for all other lakes.

Nutrient concentrations also changed in the simulations, but are no longer relevant as phytoplankton growth and mortality are not simulated in the model. In this case, nutrient concentrations are not required to regularly reset the model.

FIGURE 7.1 MODEL SIMULATIONS OF MEAN WATER COLUMN (A) DIATOM, (B) CHLOROPHYTE AND (C) CYANOBACTERIAL BIOMASS, DELFTSE HOUT, JUNE-SEPTEMBER 2007. POINTS REPRESENT FIELD MEASUREMENTS WHILE MODEL OUTPUT REPRESENTS MEAN WATER COLUMN CONCENTRATION AT A MID LAKE SITE



7.2.2 CYANOBACTERIAL BLOOM APPEARANCE

As cyanobacterial biomass remained constant throughout each simulation, the total biomass was always above or always below the cyanobacterial threshold used to regulate scum formation throughout a particular simulation period, as determined by the last available field measurements of cyanobacterial biomass. Therefore, if the EcoFuzz model results determined that cyanobacterial bloom formation conditions were favourable, surface blooms would always develop throughout a simulation period if the threshold was exceeded. The simulation results therefore show that for each fortnightly model simulation, surface blooms either developed regularly or not at all.

This can be seen particularly well for the last modelling period in the Delftse Hout, where cyanobacteria biomass for the reset period starting 3 September was below the cyanobacterial bloom formation threshold of 0.12, and therefore there was no further bloom development throughout the rest of September.

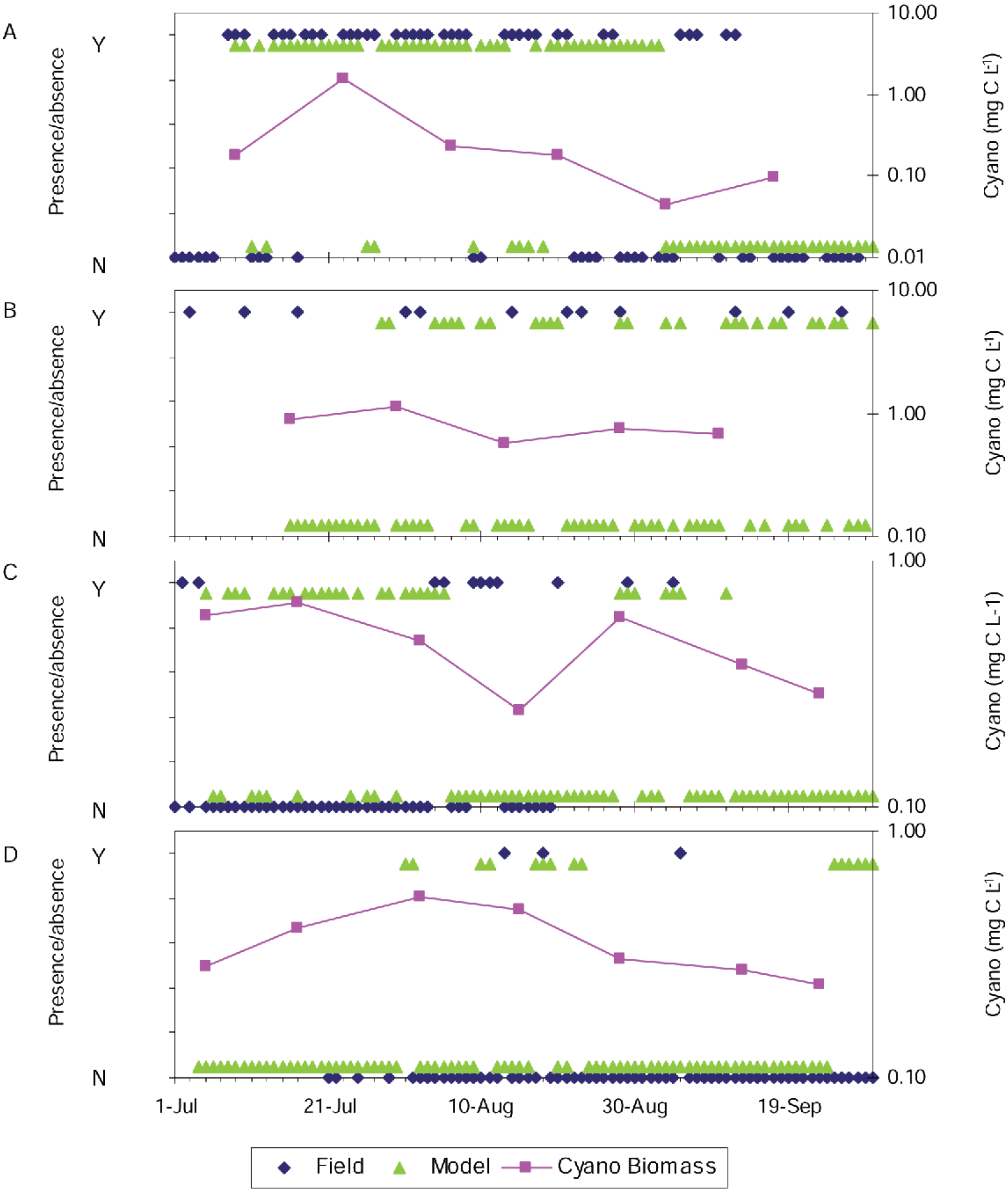
The model results for cyanobacterial bloom appearance showed a much bigger improvement compared to the field presence and absence validation data than the previous simulations conducted using the full phytoplankton module. Model simulations in the Delftse Hout of both bloom presence and bloom absence were more accurate than in the earlier simulations, due to better predictions during periods when no cyanobacterial blooms were observed (Table 7.1 Figure 7.2). Model simulations of scum presence and absence are now correct 68 % of the time overall. Model simulations in the Sloterplas were also 10 % better overall, while simulations of the Westeinderplassen were 66 % better, also due to the better representation of bloom absence (Figure 7.2).

Model results for the Gooimeer and Eemmeer did not show an improvement in the predictions, with the results being more accurate for the simulations conducted with the complete phytoplankton model (Figure 7.2).

TABLE 7.1 COMPARISONS BETWEEN OUTPUT OF MODEL SCUM APPEARANCE AND FIELD VALIDATION DATA FOR CYANOBACTERIAL BLOOM PRESENCE AND ABSENCE FOR DELFTSE HOUT (DH), GOOIMEER-EEMMEER (GE), SLOTERPLAS (SP) AND WESTEINDERPLASSEN (WP). MODEL CORRECT AND INCORRECT REPRESENTS THE TOTAL DAYS ON WHICH MODEL CORRECTIONS FOR BOTH SCUM PRESENCE AND ABSENCE WERE CORRECT. NO DATA REPRESENTS DAYS WHICH WERE SIMULATED IN THE MODEL FOR WHICH THERE WAS NO FIELD DATA AVAILABLE TO VALIDATE THE RESULTS

		Field		Model	Model	No Data
Lake	Model	Bloom present	Bloom absent	Correct	Incorrect	
DH	Bloom present	26	10			
	Bloom absent	10	18			
	Total	36	28	44	20	16
GE	Bloom present	4	0			
	Bloom absent	6	0			
	Total	10	0	4	6	67
SP	Bloom present	4	20			
	Bloom absent	6	26			
	Total	10	46	30	26	39
WP	Bloom present	1	7			
	Bloom absent	2	55			
	Total	3	62	56	9	23

FIGURE 7.2 DAILY COMPARISON BETWEEN SCUM PRESENCE (Y) AND ABSENCE (N) FOR THE AVAILABLE VALIDATION DATA (FIELD) AND MODE SIMULATIONS (MODEL), FOR (A) DELFTSE HOUT), (B) GOOIMEER-EEMMEER, (C) SLOTERPLAS AND (D) WEST-EINDERPLASSEN), JULY – SEPTEMBER 2007. MODEL OUTPUT FOR SCUM PRESENCE WAS INFERRED FROM SCUM APPEARANCE. FIELD MEASUREMENTS OF CYANOBACTERIA BIOMASS (CYANO, ON LOG SCALE) ARE ALSO SHOWN FOR EACH LAKE. MISSING DATA POINTS FOR THE FIELD VALIDATIONS ARE NOT SHOWN (SEE TABLE 6.1)



8

FORECASTING MODEL SIMULATIONS

8.1 INTRODUCTION

The ultimate aim of the algae early warning system is to forecast cyanobacterial blooms up to several days in advance, using forecasted climate data as input to the model. Meteorological forecasts can be received daily from the KNMI and following some modification, may be used to force the model. As part of the model development and testing carried out within the scope of the current project, the cyanobacterial forecasting system was tested over a period of 1 month based on the forecast climate data provided.

8.2 MODEL INPUT REQUIREMENTS

Meteorological data is used as input for all of the coupled models making up the complete cyanobacterial forecasting tool. In Delft3D-FLOW, meteorological data is required as input to the heat flux and wind sub models:

- Heat flux model:
  - Relative humidity (%)
  - Air temperature (°C)
  - Fraction cloud cover (%)
- Wind model:
  - Wind speed (m/s)
  - Wind direction (deg)

In Delwaq-BLOOM, meteorological data is used to determine phytoplankton primary production and to determine scum appearance for the EcoFuzz scum module. The complete list of meteorological data required as model input is:

- Solar radiation (j cm ^{2});
- Wind speed (m/s), and;
- Wind direction (deg).

8.3 DATA AVAILABILITY AND FORMAT

All the data required for the complete model tool is technically available from the KNMI, although the actual data supplied is dependent on the subscription chosen. For example, relative humidity, air temperature and cloud cover were part of the data provided to Hoogheemraadschap van Rijnland but not Hoogheemraadschap van Delfland.

Meteorological forecasts can be supplied daily by the KNMI in the following format:

- Day 1: hourly mean or total
- Days 2 to 5: 3-hourly mean or total
- Day 5 to 7: daily mean or total

Mean values represent for example wind speed, wind direction and air temperature while total values represent for example solar radiation (hourly, 3-hourly or daily total).

Relative humidity was only provided as part of the hourly and 3-hourly forecasts, and is not provided as part of the daily forecast (days 5 to 7).

8.4 METHODS

Forecasted meteorological data from the Schiphol climate station were downloaded most Mondays between 3 July and 25 September by Hoogheemraadschap van Rijnland. Each data set covered the coming week in the format described in Section 8.3. Forecasted data from the Rotterdam airport climate station were provided every two weeks by Hoogheemraadschap van Delfland over the same period. Due to the format of the data, each forecast contained only information for the coming 7 days and the second week was therefore not included. For the month of August, daily data sets were also provided, each containing actual hourly data for the first day, hourly forecasts for the second day, and 3-hourly forecasts for the next three days.

A period of 1 month was chosen to examine model predictions of scum appearance using the forecasted meteorological data. These were:

- Delftse Hout: 1 to 31 August 2007;
- Gooimeer-Eemmeer: 17 July to 16 August 2007;
- Sloterplas: 17 July to 16 August 2007;
- Westeinderplassen: 17 July to 16 August 2007.

Identical periods were chosen for the Gooimeer-Eemmeer, Sloterplas and Westeinderplassen as the forecast data used for all three lakes were identical (Schiphol climate station). For all parameters, linear interpolations between measurements were used to obtain hourly measurements from the 3-hourly forecasts. For days 5 to 7 of the forecast, where only one value was provided for the whole day, hourly values were estimated based on a running average of the previous 24 hours.

For wind speed, the format of the data provided to Hoogheemraadschap van Rijnland was in Beaufort scale. Each value on the Beaufort scale encompasses a wide range of wind speeds in m/sec. For example, Beaufort scale 1 represents a wind speed range of 0.3 to 1.5 m/sec, while Beaufort 4 represents a range of 5.5 to 7.9 m/sec. For this application, a median wind speed representing each Beaufort number was used to convert the wind data to m/sec.

For the Delftse Hout, the daily forecasts provided between 2 August and 2 September 2007 were used. As this data set was very comprehensive, simulations were conducted to compare differences in output for hourly and 3-hourly forecasted data, both of which were available for every day of the simulation period. Wind speed for the Delftse Hout was provided in m/sec so no further reformatting to correct the data was required other than linear interpolation to derive hourly data from the 3-hourly forecasts.

For all lakes, model simulations were conducted to examine differences in scum appearance between the different types of forecasted data provided. Given the inaccurate simulations of phytoplankton biomass observed in the model runs conducted in Chapter 6, it was decided that the best possible method to examine cyanobacterial scum appearance using different types of climate data was intended to run the model in the absence of the phytoplankton module and cyanobacterial thresholds.

8.5 RESULTS

Comparisons between the forecasted climate data and the actual climate data provided for the same day indicated that there is a time difference of 2 hours between the two data sets. This became apparent in the data set provided by Delfland, which contained also actual meteorological measurements before the forecasts commence. The reason for this difference is unknown and it was assumed that the actual data provided directly weekly from the KNMI was the correct series.

8.5.1 GOOIMEER-EEMMEER, SLOTERPLAS AND WESTEINDERPLASSEN

Figures 8.1 and 8.2 compare the actual and forecasted climate data over a one week period, based on the forecast data format provided. There is little difference between the forecasted and actual data over the first few days of the forecast, where data is provided either hourly or 3-hourly. Differences do become apparent towards the end of day 4 (3-hourly format) and on days 6 to 7, when the forecast data is provided as a daily value.

FIGURE 8.1 COMPARISON BETWEEN MEAN HOURLY (A) TEMPERATURE, (B) RELATIVE HUMIDITY AND (C), CLOUD COVER, DIRECTION DERIVED FROM ACTUAL MEASUREMENTS (ACTUAL) OR GENERATED FROM HOURLY, 3-HOURLY OR DAILY DATA PREDICTIONS (FORECAST) FOR THE SCHIPHOL CLIMATE STATION, 17 TO 24 JULY, 2007

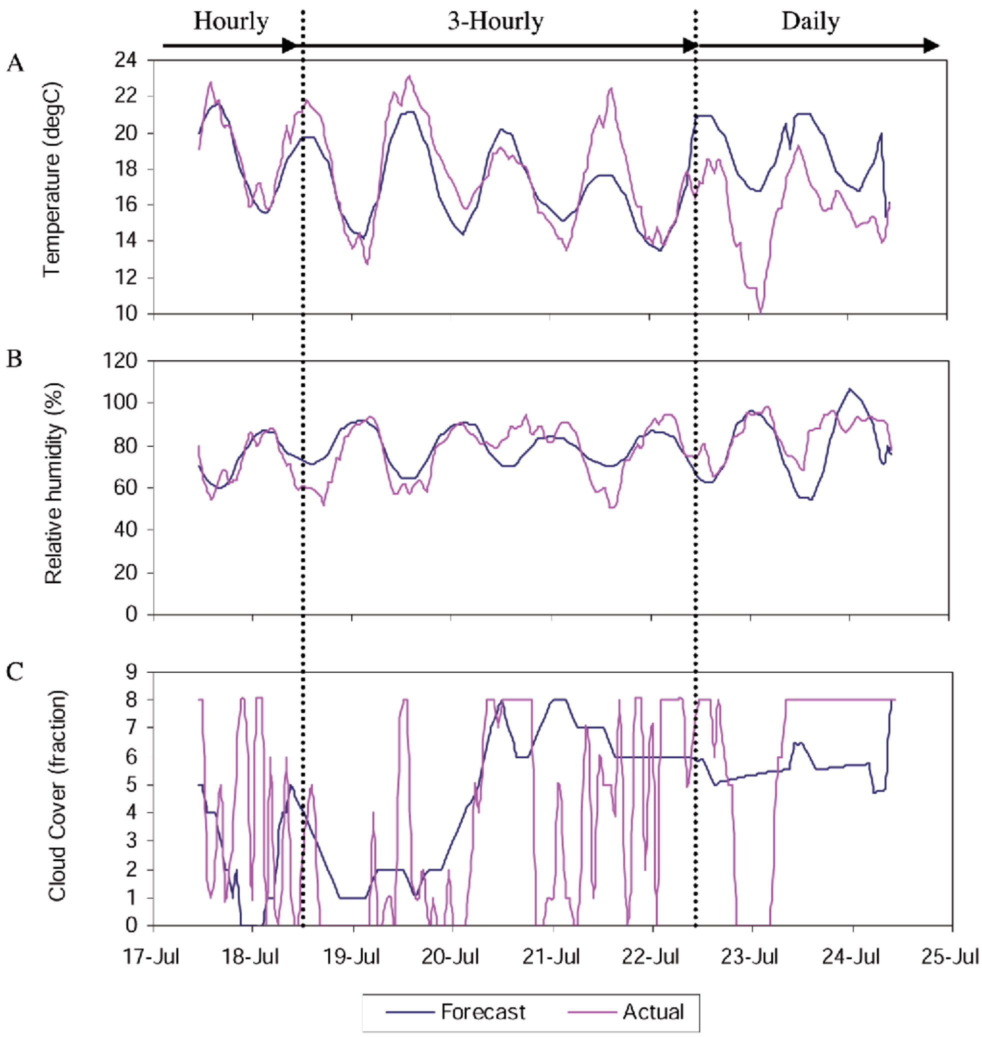
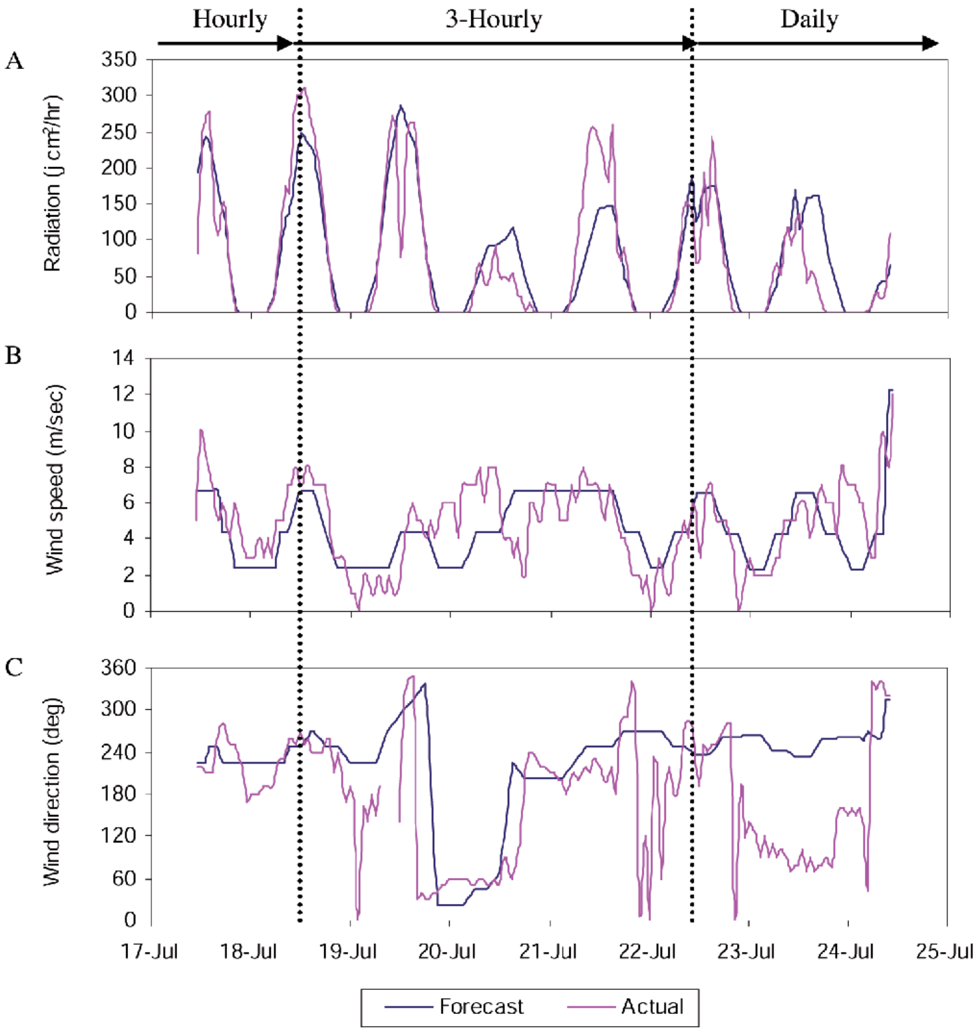


FIGURE 8.2 COMPARISON BETWEEN (A) TOTAL RADIATION, (B) MEAN HOURLY WIND SPEED AND (C), MEAN HOURLY WIND DIRECTION DERIVED FROM ACTUAL MEASUREMENTS (ACTUAL) OR GENERATED FROM HOURLY, 3-HOURLY OR DAILY DATA PREDICTIONS (FORECAST) FOR THE SCHIPHOL CLIMATE STATION, 17 TO 24 JULY, 2007. RADIATION REPRESENTS A TOTAL FOR THE PERVIOUS 6 HOURS, AS USED IN THE ECOFUZZ MODEL TO DETERMINE SCUM APPEARANCE



Given that the forecasted climate data used for the Gooimeer-Eemmeer, Sloterplas and Westeinderplassen is identical, in the absence of phytoplankton production and cyanobacterial biomass thresholds, the scum appearance results are identical for all four lakes. The model results for scum appearance over the period 17 July to 19 August 2007, using a combination of hourly, 3-hourly and daily forecast data, are shown in Figure 8.3. The daily results show that scum appearance was predicted poorly relative to the results based on the actual climate data. Scum appearance was predicted for only 6 days over the simulation period, much less than the 23 days predicted by the model using actual forecast data (Table 8.1). There appeared to be little difference in the results between the hourly, 3-hourly and daily forecasted data used as input to the model (Figure 8.3).

To examine possible differences in scum appearance due to incorrect determination of the wind speed associated with the conversion from Beaufort to m/sec, additional model simulations were conducted using the median wind speed within each Beaufort range plus or minus 20 %. The simulations conducted using the reduced wind speed showed much better results in comparison to the scum appearance results derived using actual climate data (Figure 8.3).

The results of the simulations conducted using different wind speeds suggest that the conversion of Beaufort to m/sec can lead to errors in the results, particularly when wind speeds are low (< 2 m/sec) and scum formation is most likely. The forecasted wind speed data used as input to the model should therefore be in m/sec to increase model accuracy, given that this data appears to be available anyway.

FIGURE 8.3 ECOFUZZ SIMULATIONS OF SCUM APPEARANCE USING ACTUAL AND FORECASTED METEOROLOGICAL DATA FROM SCHIPHOL AIRPORT CLIMATE STATION (GOOIMEER-EEMMEER, SLOTERPLAS AND WESTEINDERPLASSEN), 17 JULY TO 19 AUGUST 2007 USING (A) UNCORRECTED FORECAST DATA AND (B) WIND CORRECTED (WIND SPEED LESS 20 %) FORECAST DATA. THE PERIOD OF THE FORECAST DATA IS INDICATED ABOVE FIGURE A (1, 3 AND 24 HOURLY). HOURLY, 3-HOURLY AND DAILY FORECASTS WERE NOT AVAILABLE FOR EVERY DAY OF THE SIMULATION PERIOD

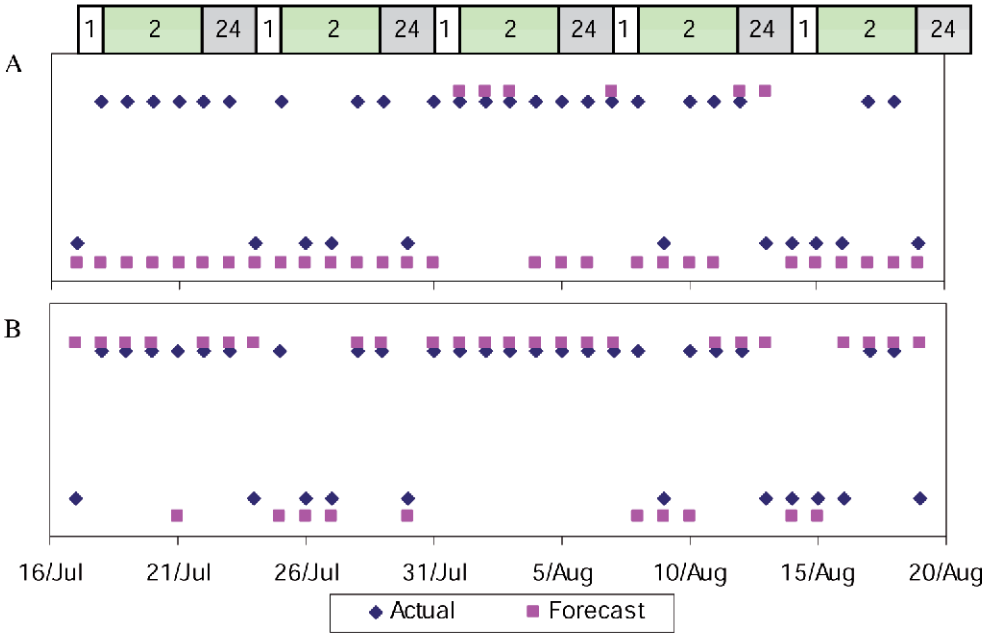


TABLE 8.1 RESULTS OF ECOFUZZ SIMULATIONS OF SCUM APPEARANCE USING ACTUAL (ACTUAL) AND FORECASTED (FORECAST) METEOROLOGICAL DATA DERIVED FROM SCHIPHOL AIRPORT CLIMATE STATION (GOOIMEER-EEMMEER, SLOTERPLAS AND WESTEINDERPLASSEN), 17 JULY TO 19 AUGUST 2007. FOR THE FORECAST DATA SIMULATIONS, THREE SCENARIOS WERE SIMULATED: NORMAL UNCHANGED DATA, WIND SPEED + 20 % AND WIND SPEED – 20%

	Actual		Forecast	
		Normal	Wind - 20 %	Wind + 20%
Scum No	11	2	10	28
Scum Yes	23	6	24	6

8.5.2 DELFTSE HOUT

Comparisons between the actual and hourly forecasted data for total radiation and wind speed show that there is little difference between the two data sets (Figure 8.4). Differences are more evident between the 3-hourly forecasts and actual data, particularly for wind speed. Differences in 3-hourly forecasted wind speed and the actual data were up to 5.4 m/sec on some days of the simulation period (2 August to 1 September, 2007), although mean differences were only 0.2 m/sec over this time. Differences appeared greatest in the late afternoon, when wind speeds are expected to be highest.

Daily model results of cyanobacterial scum appearance show that minor differences exist between the model output for using the actual and forecasted data. Scum appearance was predicted for 27 of the 32 days simulated based on the actual data, compared to predictions of 24 days based on the hourly forecasts (Table 8.2). Scum appearance was predicted for 21 days based on the 3-hourly forecast. Hourly forecasts therefore yielded better results than the 3-hourly forecast.

FIGURE 8.4 COMPARISON BETWEEN TOTAL HOURLY (A) RADIATION AND (B), WIND SPEED FOR ACTUAL, HOURLY FORECAST AND 3-HOURLY FORECAST DATA FOR THE ROTTERDAM AIRPORT CLIMATE STATION, 2-16 AUGUST 2007. RADIATION REPRESENTS A TOTAL FOR THE PERVIOUS 6 HOURS, AS USED IN THE ECOFUZZ MODEL TO DETERMINE SCUM APPEARANCE

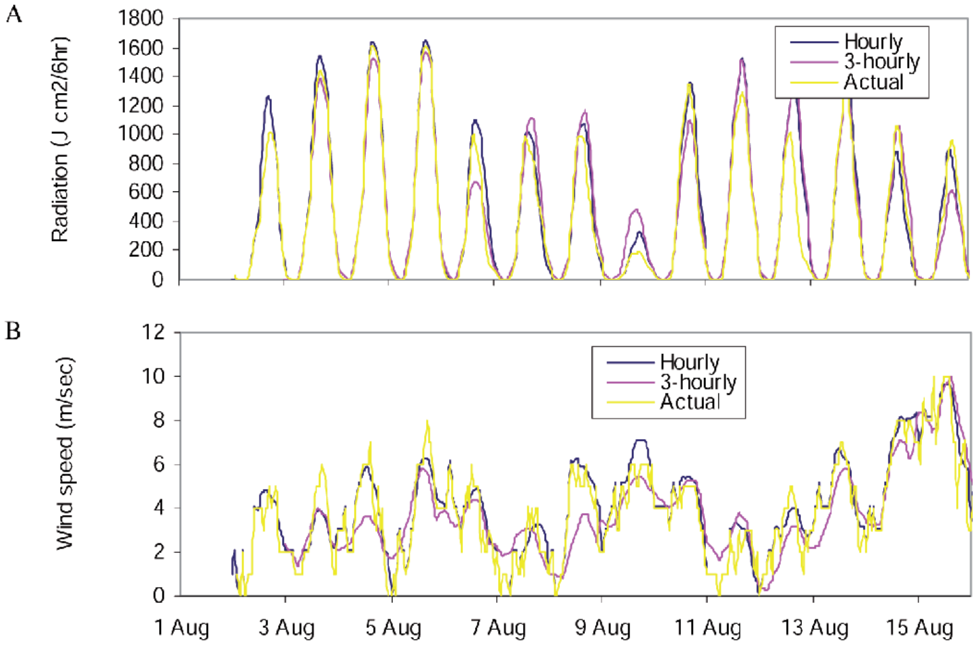


FIGURE 8.5 COMPARISON BETWEEN SCUM APPEARANCE (YES, NO) FOR SIMULATIONS MADE HOURLY AND 3-HOURLY, AND ACTUAL CLIMATE DATA FOR THE ROTTERDAM AIRPORT CLIMATE STATION, 2 AUGUST TO 2 SEPTEMBER, 2007

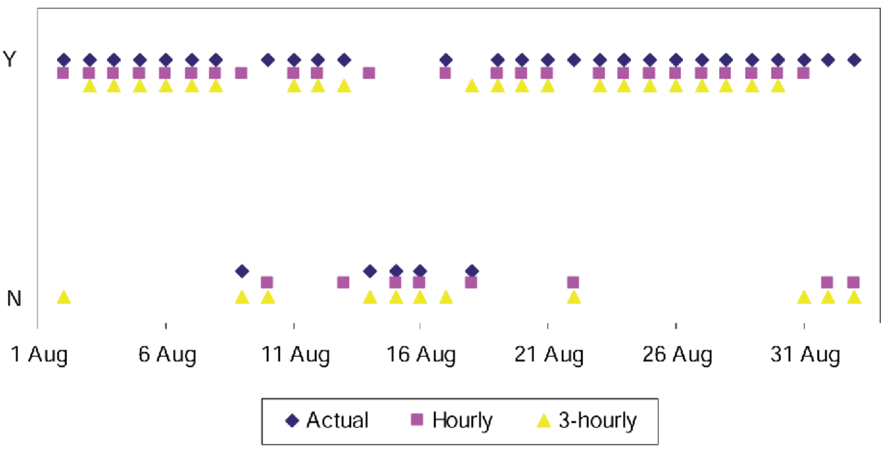


TABLE 8.2 RESULTS OF ECOFUZZ SIMULATIONS OF SCUM APPEARANCE USING ACTUAL AND HOURLY AND 3-HOURLY FORECASTED METEOROLOGICAL DATA DERIVED FOR DELFTSE HOUT, 2 AUGUST TO 2 SEPTEMBER 2007

	Actual	Hourly	3-hourly
Scum No	5	8	11
Scum Yes	27	24	21

9

DETAILED ANALYSES DELFTSE HOUT

In order to better assess model performance for predictions of scum appearance and overall scum presence and absence, the results for Delftse Hout were examined in more detail to determine how overall model performance could be improved and better calibrated. The field validation data collected for this lake was the most comprehensive of all the study lakes, and may therefore offer better insights as to why the model predicted or failed to predict scums accurately in comparison to the available field data for the Delftse Hout.

Special emphasis was placed on:

1 Sensitivity analyses of EcoFuzz stand alone membership functions to determine the most important parameters and to improve model predictions for scum appearance;
2 Review and modification of methods used to interpret the model and analyse model performance relative to the field data;
3 Reassessment of model scoring using new post-processing methods, and;
4 Further calibration of the complete model instrumentation.

9.1 ECOFUZZ APPEARANCE OUTPUT AND SENSITIVITY ANALYSES

Comparisons of model output for scum appearance simulated by the complete model instrumentation with output from EcoFuzz stand alone indicate that the days on which scum appearance were not accurately predicted relative to the field data are identical between the models. Therefore the various thresholds implemented in the complete model tool to regulate the translation from EcoFuzz to the scum appearance and disappearance processes did not have a strong influence on the final results in the present configuration. This suggests that any model improvements should focus on altering the membership functions governing scum appearance rather than the various thresholds used within the complete model instrumentation.

To examine the role of EcoFuzz in more detail, a sensitivity analyses was completed on the three membership functions used to determine scum appearance: wind speed, irradiance and time of day. Testing was completed in EcoFuzz stand alone module, as model simulations could be run for the entire 3-month period in one simulation, and previous comparisons between the complete model tool and EcoFuzz stand alone output indicated that the inaccurate forecasts of scum appearance value relative to the field data were similar between the two models. However, only scum appearance could be examined in the EcoFuzz model output, not the combined result of scum appearance and disappearance.

The classes within each of the three membership functions were varied as follows:

- Wind speed (m/sec) +0.5, -0.5, +1.0, -1.0
- Irradiance (J cm^{-1} 6 hr) +250, -250
- Time of day (hour) +1, -1, +2, -2

The results of the sensitivity analysis suggest that wind speed is the most important variable regulating scum appearance, with decreased wind speeds of 1.0 m/sec increasing the days on which scum appearance occurs by 4 relative to the original settings and model output. However, decreased wind speeds also increase the total number of false positive events by 4. Increasing wind speed led to a reduction in the false positive events, but also a decline in the number of accurate predictions for scum presence. Changes in solar radiation and the time of day had little or no effect on the scum appearance results (Table 7.2) relative to the original results.

The results of the sensitivity analyses on scum appearance alone did not improve the overall model performance, i.e. sum appearance and disappearance results relative to the field data. However, it is likely that overall model performance could be improved through alteration of also the disappearance membership function, or the appearance and disappearance functions concurrently in stand alone mode as only values of scum appearance and disappearance are given, not the final result of both. This can not be easily tested in the current model.

TABLE 9.1 RESULTS OF THE ECOFUZZ STAND ALONE SENSITIVITY ANALYSIS OF SCUM APPEAR VERSUS FIELD DATA FOR MEMBERSHIP FUNCTIONS WIND (W), TIME OF DAY (T) AND 6-HOUR ACCUMULATED SOLAR RADIATION (RAD). ORIGINAL REPRESENTS THE RESULTS BASED ON THE EXISTING MEMBERSHIP FUNCTIONS

	Original	w + 0.5	w +1.0	w -0.5	w -1.0	t +1	t +2	t -1	t -2	Rad +250	Rad -250
Field no, Model no	9	9	16	16	5	9	9	9	9	9	8
Field no, Model yes	23	23	16	16	27	23	23	23	23	23	24
Field yes, Model no	5	5	12	12	1	5	5	5	5	5	5
Field yes, Model yes	32	32	25	25	36	32	32	32	32	32	32

The results of the stand-alone model were examined with all field scums of category 1 or greater. In the Delftse Hout, a surface bloom greater than or equal to category 2 were recorded only for 12 days over the duration of the study (3 July to 30 September), and these events may more closely represent a true field scum in the field data. The model accurately predicted the appearance of scums on 11 of the 12 days using the original scum membership functions without further sensitivity analyses, although if only the category 2 field scums or greater are used in the overall model validation, the total number of false positive predictions by the model are high.

Model output from EcoFuzz stand alone was validated with the field data by examining only scum appearance output, not the combination of scum appearance and disappearance. If scum appearance values generated by the model were greater than a minimum value of 5, than a surface bloom was assumed to be present in the system on that day. This method of validating the model output makes a number of assumptions, including that:

- All surface scums generated by the model are of the same magnitude, and;
- Surface scums disappear when the conditions required for scum appearance are not met. For example if the wind speed is too high for scum formation, then it is also likely to be sufficiently high enough for scums to disappear. This assumption may not always be correct, particularly for very intense scums where much higher wind speeds may be required to disperse scums back into the water column.

Further improvements to the model to allow for better comparisons of the model output with the field data are discussed in Section 9.2.

9.2 DETAILED ANALYSES MODEL RESULTS

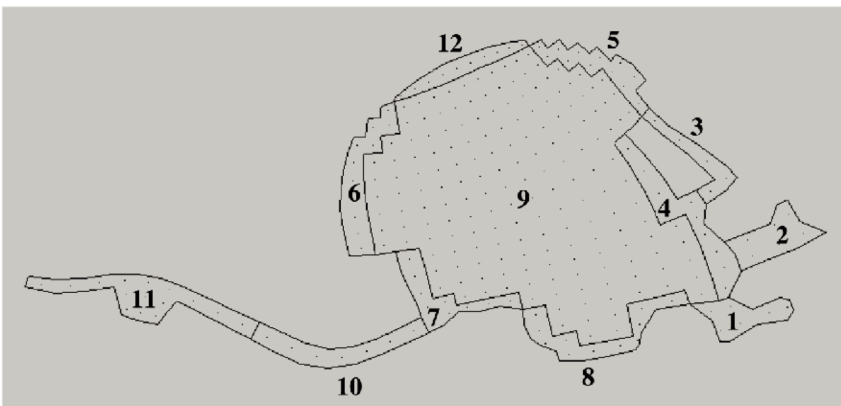
9.2.1 INTERPRETATION OF MODEL OUTPUT

To better interpret and validate the complete model instrument relative to the field validation data for the Delftse Hout, additional changes were made to the model setup to allow the simulation results to be expressed also as a concentration of scum forming cyanobacteria in the surface layer. This concentration, expressed as units of carbon per square meter (g cyano C m^{-2}), represents the final end product of both surface bloom appearance and disappearance routines simulated by the model, and can therefore be directly compared to scum presence and absence in the field data.

Results derived from new model simulations with the improved post-processing setup showed that concentrations of surface scum cyanobacteria varied greatly between individual grid cells even along the same shoreline. This made it difficult to identify how the results should be compared to the field validation data, which are expressed as a scum category per area of shoreline (see Section 5.4.1 and Figure 5.4). Based on this, it was decided to use spatial aggregation to average the model results over various pre-defined zones within the model grid, similar to the zones already used for the field validation sampling.

In the field data for Delftse Hout, 11 zones were used to map spatial trends in daily scum formation (Figure 5.4, Section 5). Before these same zones were implemented into the model setup for aggregation, the spatial results of the existing model were analysed to identify where model scum accumulation most often occurred. This analysis revealed that scums in the current model results also often accumulate on the northern shoreline of the lake, currently represented by 2 zones in the field data (Zone 5 and 6). To incorporate this in the model output, a total of 12 zones were used for aggregation: the existing 11 field zones plus an additional zone for the northern lake edge (Figure 9.1). Each shoreline zone represents at least 1 grid cell in width, corresponding to a distance of approximately 28 m. The new aggregation scheme incorporated in the model setup is only used for post processing and the actual computation is still based on the original model grid. To obtain the new results for both concentration and aggregation, the model was rerun for each simulation period in the Delftse Hout.

FIGURE 9.1 ZONES USED FOR SPATIAL AGGREGATION OF THE MODEL RESULTS IN THE DELFTSE HOUT



9.2.2 ASSESSMENT OF MODEL PERFORMANCE

To fully assess the performance of the new model simulations, model output of scum forming cyanobacteria in the surface layer were compared with the field validation data for each of the 12 assigned zones in the lake. Plots were made for each zone and model simulation period, and scored based on visual examination of the results (Figure 9.2). Scoring of the model for each zone was based on numbers of:

1 Field scum present, model scum present;
2 Field scum present, model scum absent;
3 Field scum absent, model scum absent;
4 Field scum absent, model scum present
5 Model scum present, no field data, and;
6 Model scum absent, no field data.

The sum of score (1) and (3) represent the total number correct, and the sum of (2) and (4) the total number incorrect.

As the model output represents concentration and the field data scum categories, a number of intermediate steps were taken to translate the model output to the field data as part of the validation process. The field data represents categories between 0 and 4, and in this application it was assumed that only field categories greater or equal to category 2 represent a true field surface scum. This occurred on 12 days over the model period (9 July to 30 September), although scums were present in multiple zones on the same day. As a category 2 scum was also recorded 1 day prior to the simulation start date (8 July), the model run was started earlier to allow also this day to be included in the validation. For the additional new model zone not corresponding directly to a field zone (Zone 12), the model data was compared to the maximum field validation data from the adjacent zones 5 and 6.

For the model output, which is expressed as a concentration and varies between different scum events, in the first instance it was assumed that concentrations greater than 1 g C m^{-2} equate to a true model scum. Therefore in validating the model, model scum presence scored correct if the model concentration was greater than 1 g C m^{-2} and the field validation category greater than or equal to 2. The model was scored at midday each day, which corresponds as closely as possible to the field data collection time of between 11:30 and 13:00 each day. Due to slight differences in daily timing of the field data collection, the results were compared 2 hours either side of midday each day. The biomas concentration threshold is in addition to the appearance and disappearance thresholds in the model setup.

9.2.3 ADJUSTMENT MODEL CODE

The results from earlier model simulations suggested that concentrations of surface cyanobacteria changed rapidly in response to rapid changes in scum appearance and disappearance values. This was because the model code did not translate the degree of scum formation as predicted by the EcoFuzz model to the final result, but rather, only activated the process. For example, the fuzzy logic approach used by EcoFuzz to govern both scum appearance and disappearance gives a range of values for both, with the minimum value being 5 (no scum appearance or no disappearance) and maximum value of close to 100 (maximum scum formation or disappearance). Scum appearance and disappearance is currently regulated in Delwaq through the scum appearance and disappearance thresholds which must be exceeded before these processes will be activated. Once activated, all the algae were changed from one type to another, regardless of the degree of scum appearance or disappearance, and further regulated only by the sedimentation rate and transport. This may provide for very rapid and sudden changes in scum presence and absence over short time scales.

To better translate the EcoFuzz predictions in the complete model tool, the model code was altered so that the actual value predicted by EcoFuzz is used to directly regulate the percent of cells converted from their normal type to their scum forming type. For example, if the EcoFuzz scum appearance output is 42 for a particular time step, than 42 % of the total biomass represented by a potential scum forming algal type is converted to its scum type and will form a surface scum. The same approach in reverse is now implemented for scum disappearance.

Results model score each zone

The results of the model validation carried out for each of the 12 zones and for each day of the simulation period are given in Table 9.2. The results can be examined in two ways; assessment of overall model performance by examining the total number of correct and incorrect instances, and assessment within the results to see in which areas the model performance is strong or weak.

The total results indicate that the model has an overall accuracy of 89 % relative to the field data, based as a total over all zones (Table 9.2). However, this success is largely because the model scores well when there are no field scums present, which occurs on most days (96 %) of the simulation period. The instances of incorrect predictions are predominantly due to a high number of false positive scores, when the model predicts a scum which is not observed in the field data.

Model performance for scum presence relative to the field data within individual zones is weak, with a total of only 9 of the 28 field scums predicted accurately in space and time over all zones and the complete duration of the model simulation period (Table 9.2). There were 192 instances of no data, with the model predicting a scum on 18 of these events. The total number of no data instances represents the sum of all 12 zones.

FIGURE 9.2 EXAMPLE OF PLOTS USED TO SCORE MODEL OUTPUT RELATIVE TO THE OBSERVED FIELD DATA. IN SCORING MODEL PERFORMANCE, MODEL SURFACE CYANOBACTERIA CONCENTRATION (MODEL SCUM BIOMASS IN THE SURFACE LAYER) WAS COMPARED TO THE THRESHOLD USED TO DIFFERENTIATE A TRUE MODEL SCUM (SCUM THRESHOLD) AND THE FIELD SCUM CATEGORY FOR THAT DAY (FIELD CATEGORY). FIELD DATA ABSENT REPRESENTS DAYS ON WHICH NO FIELD DATA IS AVAILABLE. NOTE THAT THE FIELD SCUM CATEGORY RANGES FROM 0 TO 4

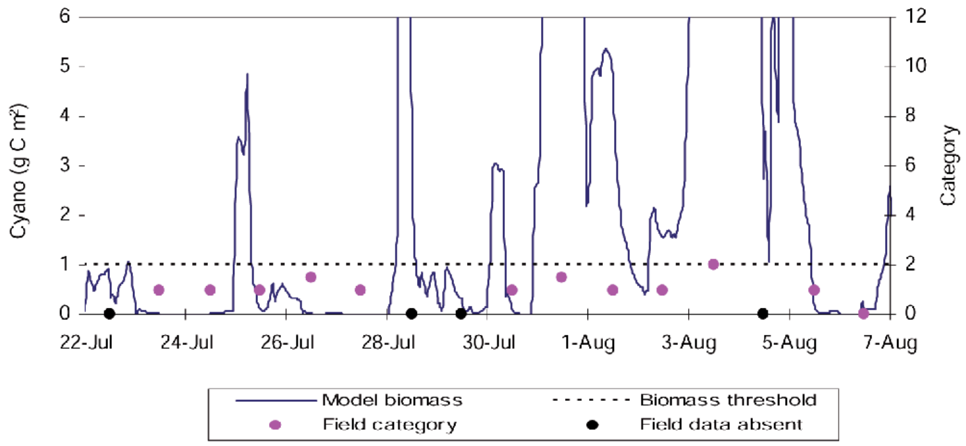


TABLE 9.2 COMPARISONS BETWEEN MODEL AND FIELD RESULTS FOR EACH SPATIAL ZONE IN THE DELFTSE HOUT. MY REPRESENTS SCUM PRESENT IN MODEL, FY SCUM PRESENT IN FIELD, MN NO SCUM PRESENT IN MODEL, FN NO SCUM PRESENT IN FIELD AND ND NO FIELD DATA. MN FY REPRESENTS SCUMS OBSERVED IN THE FIELD BUT NOT PREDICTED BY THE MODEL, AND MY FN SCUMS PREDICTED BY THE MODEL BUT NOT OBSERVED IN THE FIELD. WHILE A SCUM OF CATEGORY 2 OR GREATER WAS OBSERVED ON 13 DAYS OVER THE COMPLETE SIMULATION PERIOD, THESE OCCURRED IN MORE THAN ONE ZONE ON SOME DAYS. ZONE LOCATIONS ARE SPECIFIED IN FIGURE 9.1

Zone	MY FY	MN FY	MN FN	MY FN	MY ND	MN ND	Correct	Incorrect	No data
1	1	1	52	11	2	14	53	12	16
2	1	1	55	8	3	13	56	9	16
3	1	0	51	13	4	12	52	13	16
4	0	0	65	0	0	16	65	0	16
5	2	6	54	3	3	13	56	9	16
6	1	1	55	8	0	16	56	9	16
7	0	2	62	1	0	16	62	3	16
8	1	0	56	8	2	14	57	8	16
9	0	0	65	0	0	16	65	0	16
10	0	2	60	3	1	15	60	5	16
11	0	0	60	5	1	15	60	5	16
12	2	6	51	6	2	14	53	12	16
Total	9	19	686	66	18	174	695	85	192

9.2.4 DETAILED ANALYSES 13 FIELD SCUM EVENTS

To assess model performance in more detail for the Delftse Hout, the model results were more closely examined around the 13 days for which a category scum of 2 or greater was recorded in any zone in the field data. The emphasis of this assessment was to identify when the model accurately simulates the observed scum or not, and if the prediction is not accurate, then why not. The results of this analysis are summarised in Table 9.3. From the results it is apparent that there is no single reason for the inaccurate model predictions, but rather a combination of three factors:

1. Scum is present in model output but in the wrong location (4 occasions);
2. Scum is not present in the model output (2 occasions);
3. Scum is present in the model output but of insufficient biomass (3 occasions), and;
4. A combination of these factors (1 occasion).

Model scum predictions were spatially correct on 3 of the 13 occasions (Table 9.3). Accurate scum prediction but inaccurate location can be due to two main reasons; either the hydrodynamic simulations are not correct, or in some of the observed cases, the location of the scum is potentially incorrect due to differences in zones between the field data and model output (Zone 12, which is not represented in the field data). Zone 12 was introduced in the post processing of the model results as scums were often found to accumulate in this zone in earlier model runs.

For instances where the scum was not present in the model at all in any concentration, this was due to the EcoFuzz predictions, with either scum disappearance activated too soon, or scum appearance not activated for long enough. For instances where scum presence did occur in the model but at very low concentrations, this suggests that the EcoFuzz module is working correctly but that biomass is not sufficient to create a significant surface layer.

The model results in Table 9.2 also indicate a large number of false positive events present, and this can only be due to the EcoFuzz membership functions or the thresholds used to regulate their translation to the complete model instrument. For example for a false positive event to occur, there must already be sufficient biomass present in the model, scum appearance must be high, and scum disappearance must not be low or zero. Further calibration of these parameters is discussed in the following sections.

The cyanobacteria concentration used in the model simulations are based on field measurements collected every two weeks, and changes in biomass and species composition are therefore not modelled.

TABLE 9.3 SUMMARY OF MODEL PERFORMANCE AROUND 13 EVENTS FOR WHICH FIELD SCUMS GREATER OR EQUAL TO CATEGORY 2 WERE OBSERVED. FIELD AND MODEL SCUM LOCATIONS ARE DEFINED IN FIGURE 9.1. BOLDED VALES INDICATE A DIRECT MATCH BETWEEN THE FIELD AND MODEL SCUM LOCATION

Date	Field scum location	Model scum location	Reason difference
8-Jul	5, 7	1, 3, 8	Scum forecasted in Zone 5 earlier, but not sustained Model produces scum in wrong location Timing of scum appearance is correct
16-Jul	5	3	Scum forecasted for Zone 5 but biomass < 1 Model produces scum in wrong location Timing of scum appearance is correct
19-Jul	5	12, 6	Model scum produced in Zone 12, adjacent to field Zone 5. Model produces scum in wrong location Potentially due to difference in field and model zone definition
1-Aug	**1**	**1**, 2, 5, 6	Model scums disappearing around or before field collection time Timing and/or hydrodynamics incorrect
3-Aug	**2**, **3**	1, **2**, **3**	Model correct
13-Aug	**5**	3, **5**	Model mostly correct
14-Aug	5	3	Model scum observed in Zone 12, adjacent to Zone 5. Potentially due to difference in field and model zone definition
20-Aug	5	No scum	Small scum earlier in day in Zone 5 EcoFuzz disappearance activated before field collection time
21-Aug	5, **6**, 7, **8**	**6**, **8**, 10	odel generally correct
5-Sep	4, 5	No scum	Model small scum earlier in Zone 5, although biomass low EcoFuzz disappearance high
6-Sep	2, 10	3	Small scum observed in Zone 2. Biomass insufficient
7-Sep	10	No scum	Biomass insufficient, EcoFuzz appearance not sustained
12-Sep	5	No scum	Biomass too low

9.2.5 LAKE WIDE SPATIAL AGGREGATION OF RESULTS

The timing of the model predictions in the model simulations was mostly correct although the spatial distribution of the scum was not. Given that there are multiple reasons for the potential model inaccuracies, a further analysis was conducted to mask the effects of hydrodynamics on the model output. In this assessment, the maximum biomass of surface scum forming cyanobacteria of all the 12 zones were compared to the field data to see on which days the lake wide model predictions were correct. Again given the potential differences in field daily field data collection times, the model maximum biomass over a 2 hour period immediately before and after midday was used for the comparisons. The threshold of 1 g cyano C m^{-2} was still used to differentiate between a true and non model scum events and only field category 2 or greater scums were considered to be true field scum events. The results of this analysis are plotted monthly in Figure 9.3, and are scored in Table 9.4.

The results show that 10 of the 13 field scum events are predicted accurately by the model, although there are also 21 false positive events recorded. For 2 of the 3 inaccurate predictions, there was insufficient biomass present in the model to lead to a scum event greater than a biomass threshold of 1 g C m $^{-2}$ (Figure 9.3). Overall model accuracy (total number correct) is 63 %, again skewed by the large number of correct predictions for scum absence (Table 9.4).

To see if the high number if false positive events could be attributed to the incorrect translation of the field scum categories, the analyses were repeated using field scum category 1 or greater to define a true field scum event. In total there are 37 days on which a field scum greater than or equal to 1 are recorded, nearly 3 times higher than field category 2 or higher. The new analysis indicates that the total proposition of model correct and incorrect remains about the same (60 % and 40 %, respectively). However, the number of accurate scum events predicted decrease when using category 1 to define a true field scum (-20 %, Table 9.4).

FIGURE 9.3 COMPARISONS BETWEEN MODEL OUTPUT OF SCUM FORMING CYANOBACTERIAL BIOMASS (MODEL BIOMASS) AND FIELD SCUM CATEGORIES LESS (FIELD SCUM < 2) OR GREATER OR EQUAL TO 2 (FIELD SCUM > 2) FOR (A) JULY 2007, (B) AUGUST 2007 AND (C) SEPTEMBER 2007

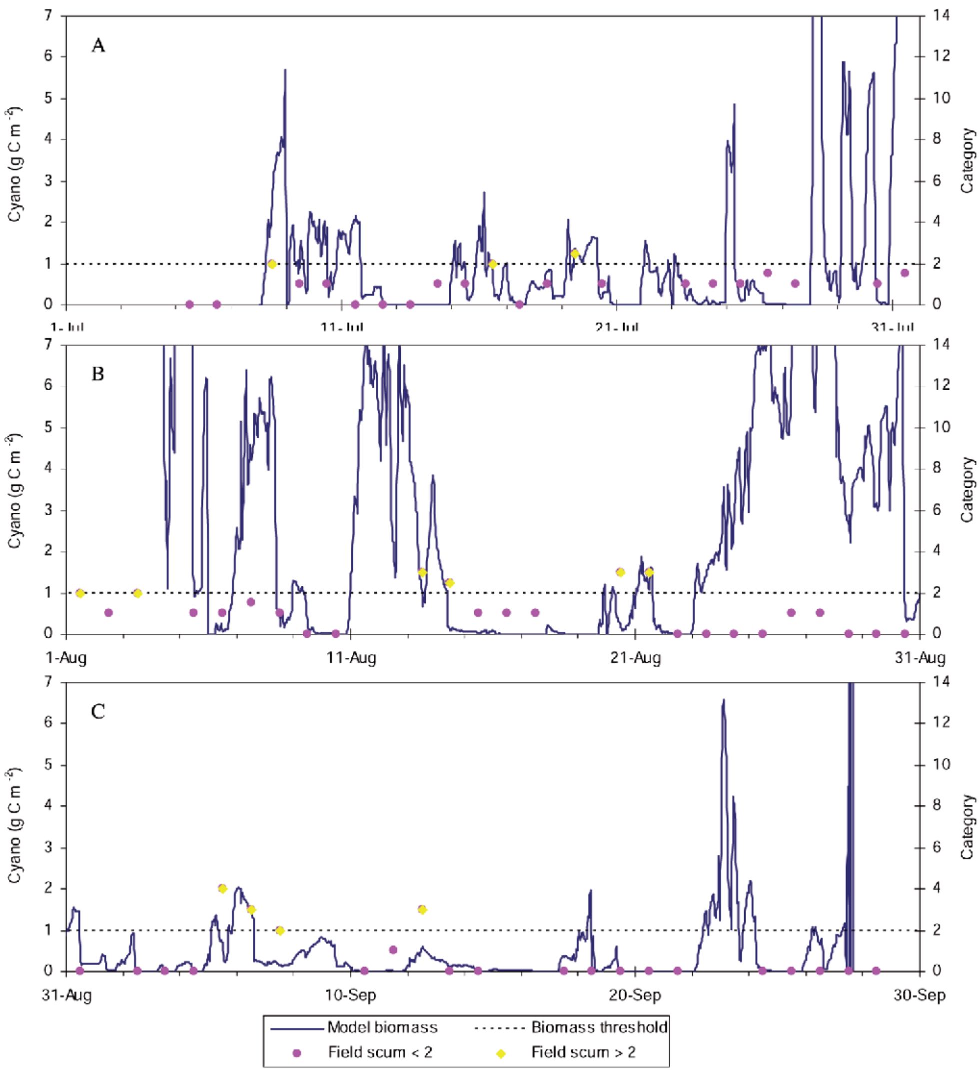


TABLE 9.4 **SUMMARY OF MODEL PERFORMANCE FOR DIFFERENT FIELD CATEGORIES, OVER THE SIMULATION PERIOD JUL.-SEP. 2007. Y REPRESENTS SCUM PRESENT, N SCUM ABSENT. CATEGORY 2 REPRESENTS SCENARIO CONSIDERING ONLY FIELD SCUMS GREATER THAN OR EQUAL TO CATEGORY 2, AND CATEGORY 1 FIELD SCUMS GREATER THAN OR EQUAL TO CATEGORY 1**

Field category	MY FY	MN FY	MN FN	MY FN	Correct	Incorrect
2	10	3	31	21	41	24
1	21	16	18	10	39	26

9.2.6 ANALYSES OF MODEL OUTPUT THRESHOLD

To assess whether a low biomass threshold (1 g C m $^{-2}$) used to define a true model scum event also leads to over prediction of scum events, a further analysis was completed to assess whether (1) field scum events greater than category 2 corresponds to higher model surface scum concentrations than those observed for categories less than 2, and (2) changes in the biomass threshold would improve the model performance.

Visual comparisons of model output with the field data show that the model concentrations are as high for the false positive events as for the actual scum events. The biomass threshold used for the model results was varied between 1 and 16 g C m $^{-2}$, and higher, and suggest that although the total number of model inaccuracies due to false positive predictions can be decreased with increasing biomass threshold, the number of accurate field predictions also decrease (Table 9.5).

TABLE 9.5 **SUMMARY OF MODEL PERFORMANCE FOR DIFFERENT BIOMASS THRESHOLDS USED TO DEFINE TRUE MODEL SCUM EVENTS, OVER THE SIMULATION PERIOD JUL.-SEP. 2007. MY FY REPRESENTS SCUM PRESENT IN MODEL AND FIELD, AND MY FN SCUM PRESENT ONLY IN MODEL (FALSE POSITIVES). INCORRECT REPRESENTS THE TOTAL INACCURATE PREDICTIONS RELATIVE TO THE FIELD DATA. ONLY FIELD CATEGORIES GREATER THAN OR EQUAL TO CATEGORY 2 ARE CONSIDERED IN THE ANALYSES. BIOMASS REPRESENTS CONCENTRATION OF SCUM FORMING CYANOBACTERIA IN THE SURFACE LAYER (G C CYANO M^{-2})**

Biomass	Incorrect	MY FY	MY FN
1	24	10	21
2	24	4	15
4	23	2	12
8	16	2	5
16	14	2	3

9.3 FURTHER CALIBRATION OF COMPLETE MODEL TOOL

9.3.1 METHODS

The analyses conducted in the previous sections were focused on how best to interpret the model results relative to the field data to analyze and improve model performance. The results of this analysis suggest that while the model has a high accuracy rate for predicting actual scum events, the false positive events forecasted by the model are too high. Further improvement of the model may be to some extent achieved through further calibration of the various thresholds used within the model itself as well as the membership functions used within EcoFuzz appearance and disappearance. The most important parameters are considered to be:

1 Scum appearance threshold;
2 Scum disappearance threshold;
3 Membership function wind speed appearance, and;
4 Membership function wind speed disappearance.

The scum appearance and disappearance thresholds regulate the amount of cyanobacteria biomass transferred between their normal and scum forming types, based on output from EcoFuzz (see Figure 3.4). For both appearance and disappearance, wind speed is important. The EcoFuzz value must exceed the threshold for this process to take place in the complete model tool. The membership functions for wind speed appearance and disappearance are used to determine the likelihood of a scum appearance and disappearance in the model. A sensitivity analysis of the all membership functions in EcoFuzz stand-alone suggested that wind speed was the most important parameter influencing scum appearance and disappearance in the model (Section 7.1).

A number of additional parameters may also influence the model results, including:

5 Wind drag coefficient, and;
6 Cyanobacteria biomass threshold

The wind drag coefficient influences horizontal transport of surface cyanobacterial scums after formation while the biomass threshold regulates scum formation in the model. Cyanobacterial biomass in the model must exceed the biomass threshold before scum formation can take place.

The initial settings of the dominant model parameters, based on multiple calibration runs in Sections 5 and 6 of this study, are listed in Table 9.6 (Base run). Additional calibration runs were completed to assess the importance of these parameters, and to try and improve the model performance by reducing the number of false positive predictions while still maintaining a high level of accurate predictions. A summary of some of the model runs completed and the changed parameters are listed in Table 9.6. The model was re-run for each simulation period in the Delftse Hout, with calibration focused on the wind speed appearance and disappearance thresholds, wind speed appearance and disappearance membership functions to decrease the false positive events.

The cyanobacterial threshold was not tested as part of the listed calibration runs as the field cyanobacterial biomass in the Delftse Hout was very low, particularly during the month September. The previous analyses indicated that model scum prediction was inaccurate in September as there was insufficient biomass in the model. While increasing the biomass threshold will reduce the number of false positive events during some periods (e.g. August), scum prediction will also decrease in others, given that the biomass is kept constant in the model between fortnightly resets.

TABLE 9.6 SUMMARY OF ADDITIONAL MODEL CALIBRATION RUNS AND THEIR INPUT PARAMETERS. EXISTING REPRESENTS THE EXISTING MEMBERSHIP FUNCTIONS IN ECOFUZZ AS DESCRIBED IN FIGURE 5.3. CHANGES IN PARAMETERS FROM THE EXISTING SIMULATION ARE MARKED IN GREY

Run	Thres app	Thres disp	Wind drag	Wind app	Wind disp
Base	40	80	0.5	existing	existing
1	40	40	0.5	existing	existing
2	0	0	0.5	existing	existing
3	80	80	0.5	existing	existing
4	40	80	0	existing	existing
5	40	80	0.5	+0.5	existing
6	40	80	0.5	existing	+0.5
7	40	80	0.5	+0.5	+0.5

9.3.2 RESULTS

The results of the various calibration runs in Table 9.6 on total model performance as well as the total number of accurate scum predictions and false positive events are summarised in Table 9.7. The results of the analyses were first analysed using a field category of 2 or greater to define a field scum. The analysis was repeated using field scum category 1 or greater to define a true field scum event, to see if a different interpretation of the field categories influenced the results.

Wind appearance and disappearance thresholds

Decreasing the scum disappearance threshold in the complete model tool (calibration run 1, Table 9.7) had the least number of total incorrect forecasts (20), due to a large decrease in the number of false positive events (from 22 to 15). Reduction of the scum threshold ensured that scums disappeared more rapidly from the system. The total number of accurate scum predicted decreased by 20 % relative to the base run.

Simulations conducted using a zero scum appearance and disappearance thresholds in the model (Scenario 2, Table 9.7) had little effect on the total number of incorrect predictions, with a slight decrease in the number of false positive events offset by a decrease in actual scum events. This is because values of wind speed disappearance produced by EcoFuzz are generally higher for scum disappearance (mean 43) compared to scum appearance (mean 18), and therefore disappearance is more often activated in the model with a threshold of zero. The use of the scum appearance and disappearance threshold to regulate and potentially improve the model calibration therefore has little effect on the simulations results.

Increasing the wind appearance threshold from 40 to 80 reduced the number of false positive events by 3 (Scenario 3, Table 9.7), with the number of accurate predictions decreasing by 1. Scum appearance during events generally always exceeded a value of 80 and therefore doubling of the threshold in the model did not have a large effect on the results overall.

Wind drag coefficient

In model run 4 (Table 9.7), a wind drag coefficient of zero led to a reduction in the total number of scum events accurately forecasted (-70 %) as formed scums were no longer transported to the lake shoreline. However, the total number of false positive events in this scenario nearly halved, although the total number incorrect forecasts only increased slightly.

EcoFuzz membership functions

The wind speed appearance membership functions were increased by 0.5 m/s in for wind speed appearance in model run 5, and wind speed appearance in model run 6. Both appearance and disappearance membership functions were increased by 0.5 m/s in model run 7 (Table 9.7).

Increasing wind appearance wind speed reduced the number of false positive events slightly, while the correct number of predictions of scum presence remained unchanged. Increasing wind speed disappearance led to a 33 % increase in the number of false positive events as forecasted scums took longer to disappear than in the existing runs. Increasing both wind speed appearance and disappearance membership functions had little effect on the overall model results.

TABLE 9.7 SUMMARY OF MODEL PERFORMANCE OVER THE SIMULATION PERIOD JUL.-SEP. 2007 FOR DIFFERENT CALIBRATION RUNS DESCRIBED IN TABLE 9.6. MY REPRESENTS SCUM PRESENT IN MODEL, FY SCUM PRESENT IN FIELD, MN NO SCUM PRESENT IN MODEL, FN NO SCUM PRESENT IN FIELD. INCORRECT REPRESENTS THE TOTAL INACCURATE PREDICTIONS RELATIVE TO THE FIELD DATA. ONLY FIELD CATEGORIES GREATER THAN OR EQUAL TO CATEGORY 2 ARE CONSIDERED IN THE ANALYSES

Field category	Run	MY FY	MN FY	MN FN	MY FN	Correct	Incorrect
Category 2	Base	10	3	31	21	41	24
	1	8	5	37	15	45	20
	2	6	7	34	18	40	25
	3	9	4	34	18	43	22
	4	3	10	41	11	44	21
	5	10	3	32	20	42	23
	6	11	2	24	28	35	30
	7	11	2	24	28	35	30
Category 1	Base	21	16	18	10	39	26
	1	17	20	22	6	39	26
	2	14	23	18	10	32	33
	3	18	19	19	9	37	28
	4	11	26	25	3	36	29
	5	20	17	18	10	38	27
	6	25	12	14	14	39	26
	7	25	12	14	14	39	26

9.3.3 SUMMARY OF CALIBRATION RESULTS

The analyses of the different calibration runs conducted suggest that striking a balance between reducing the total number of false positive events while maintaining a high degree of accurate model scum predictions is not feasible based on the current validation data available. The original parameters used in the base model and derived from earlier model runs in Sections 6 and 7 provide a good calibrated basis balancing scum prediction accuracy and the number of false positive events. Various calibration runs did show a decrease in the false positive events, but were matched by a concurrent decrease in accurate scum predictions. The calibration runs suggest that the disappearance threshold is important, with model run 2 producing a large decrease in false events and only a slight decrease in scum correct predictions.

While it is apparent that changes to the input parameters do influence the results, the model responds in an almost step like fashion with improvements on one side always leading to a decrease in performance elsewhere. Due to the limited number of actual field scum events which can be used to calibrate the model (13 events total based on category 2), further calibration is not easily achieved, and therefore is not possible to calibrate the model further for the Delftse Hout beyond a “best settings” approach which balances maximum scum presence predictions with minimal false positives.

10

CONCLUSIONS

10.1 GENERAL CONCLUSIONS

Model development

A number of major model code developments were conducted as part of the current study to better simulate cyanobacterial buoyancy, bloom formation, horizontal transportation and shoreline accumulation in one complete model instrument for use in a wide range of lake types. The final model tool combines a combination of fuzzy logic and deterministic modelling in an attempt to model cyanobacterial scums as simply and accurately as possible without the need for a complex and data intensive modelling approach.

The model developments were focused on coupling the existing EcoFuzz model, used to predict surface bloom appearance and disappearance, with a hydrodynamics model to simulate wind dominant 3D transport (Delft3D-FLOW), a water quality model to simulate water column nutrient concentrations (Delwaq), and a primary production model to determine phytoplankton biomass and species composition (BLOOM).

The existing EcoFuzz model is now fully integrated into the Delwaq process library, including the development of three new processes: (1) cyanobacterial bloom species formation, (2) cyanobacteria buoyancy and (3) location-specific scum transportation. The complete model instrumentation was trialled in four lakes of varying area, depth and complexity, with up to seven different fortnightly reset periods used to simulate each lake between July and September 2007.

Water quality simulations

The poor predictions of water column nutrient concentrations in the model simulations suggest that the fortnightly model reset period used in the absence of detailed external nutrient load simulations was insufficient in all four study lakes. Several of the study lakes showed a rapid decline in water column nutrient concentration immediately after each model reset, despite significant attempts to artificially calibrate and simplify the modelled processes and rate constants to maintain background concentrations. While simulations of TP and TN appeared to be relatively representative of the field measurements, particularly for the smaller lakes such as Delftse Hout, concentrations of dissolved nutrients, which represent the nutrient form utilised by the phytoplankton for growth, deviated greatly from field observations, especially towards the end of each simulation period.

The decision to exclude external nutrient loading from the modelling approach was based on a lack of data as well as the need to set up the model as simply as possible to allow the tool to be easily applied to other lake systems. Therefore a closed nutrient balance accounting for all dominant nutrient sources and sinks has not been simulated through this approach.

Phytoplankton biomass and species composition

The weak simulations of water column nutrients relative to the field observations also had a detrimental effect on simulations of phytoplankton biomass and species composition in all four study lakes. Model resets were often preceded by a rapid shift in species composition, with growth of cyanobacteria species often out competing diatoms and chlorophytes. In the absence of further growth, diatoms and chlorophyte biomass declined exponentially in the model simulations, due to mortality and sedimentation. Cyanobacteria growth often continued during each simulation, reaching biomass values many times higher than the starting concentration at the beginning of each reset.

Phytoplankton species composition may also be strongly determined by historical nutrient concentrations on time scales of days to weeks before each model reset. For this reason, phytoplankton production models are often initiated during winter conditions before the period of interest, at a time when growth rates are low and cyanobacterial species are generally not present or at very low concentrations.

The new model simulations conducted in Chapter 7 using a much simplified version of the phytoplankton production model not incorporating changes in species composition throughout the simulation period showed more stable simulations of phytoplankton biomass. Phytoplankton growth, mortality and sedimentation were inactivated, and the total phytoplankton biomass therefore did not change over the duration of each model reset. Cyanobacterial concentrations did change between grid cells in the model, due to the buoyancy and horizontal processes when activated by the model. In reality, cyanobacterial biomass may change rapidly over much smaller time scales than the fortnightly simulation period prescribed in this study.

Scum appearance and disappearance

The current research demonstrates that the principle of fuzzy logic initially applied to the Lake IJssel is also valid for use in much smaller lakes, with suggested minimal changes required to the membership functions. However, the model could not be fully calibrated and validated for many of the study lakes due to a general lack of daily validation data and perhaps low summer cyanobacterial biomass compared to previous years. The validation data was by far the most complete for Delftse Hout, however, total model performance was accurate for both cyanobacteria scum presence and absence 55 % of the time compared to the field data based on scum appearance output. Simulations of the Sloterplas and Westeinderplassen were not as accurate, and although both lakes are highly complex systems compared to the Delftse Hout, better validation data may certainly have improved the model calibrations.

The additional simulations conducted using the more simplified phytoplankton modelling approach greatly improved the overall performance of the model results for scum appearance relative to the field data, with simulations of scum absence being more accurate than in the first model runs. While this approach did provide more realistic simulations of cyanobacteria biomass compared to the field measurements, the results were strongly determined by cyanobacterial threshold and starting concentrations. The effect of a constant biomass above the specified threshold for a particular period was that if scum forming conditions based on water stability and buoyancy were favourable, then surface blooms would always appear during that period.

A sensitivity analyses carried out on the membership functions of scum appearance suggest that wind speed is the most important variable regulating scum appearance in the model. Decreasing the wind speed in the membership functions increased the incidences of scum appearance prediction in the model, although a large number of false positive events were also recorded. Varying membership functions for solar radiation and time of day had little or no effect on the model results for scum appearance for the sensitivity analysis carried out.

Surface bloom horizontal transportation

Surface bloom appearance and horizontal transportation could have been better validated in the study if more field validation data had been available for some of the study lakes. Only nine days of validation data were available for one of the systems while for other lakes, not all the shorelines were represented in the field survey. For the Delftse Hout, shoreline-specific validation data was collected almost daily throughout the study period for 11 spatial zones within the lake. Model output of cyanobacteria biomass was examined relative to the scum field category for each zone and model simulation day to assess model performance. Model performance for scum presence relative to the field data within individual zones is weak, with a total of only 9 of the 28 field scums predicted accurately in space and time over all zones and the complete duration of the model simulation period (Table 9.2).

Model simulations of bloom location looked promising for the Gooimeer and Eemmeer based on visual comparisons between field and model spatial plots, although small problematic locations such as the Almere harbour, which features nearly constant high cyanobacterial biomass, were not well represented by the model simulations due to the course grid size. It is very likely that better field validation data for some of the lakes would have improved model calibrations greatly, and a smaller grid size may also improve model performance in terms of grid size resolution, but not in computational time.

Applicability to an early warning system

The overall aim of the complete study, of which this report only represents a part of, is to develop an early warning system for predicting cyanobacterial surface blooms and location for a wide variety of lake types. In order to achieve this aim, the model needs to have a relatively fast computational time, be robust, and preferably have low data and management requirements, but yet produce an accurate forecast in both time and space.

The complete model instrumentation developed in this study aimed to strike a balance between the need for a simple water quality model to simulate water column nutrient concentrations and phytoplankton biomass, and a simple approach which is not reliant on large data requirements, setup time, and is not lake specific so that it can easily be applied to a wide variety of other lake systems. These aims were achieved in the current study for the model setup for simulations of water transport, scum appearance and disappearance, cyanobacterial buoyancy and horizontal transport, but not cyanobacterial biomass. The complete model instrumentation developed in this study has a computational time of up to 1 hour for a fortnightly simulation period.

Complex and simple modelling approaches applied to model the phytoplankton biomass and species composition in all four test lakes did not lead to accurate cyanobacteria predictions due to the poor predictions of water column dissolved nutrient concentrations.

Forecasted climate data simulations

The model results for scum appearance derived from simulations using forecasted climate data demonstrate that the application of the model as a forecasting tool is indeed feasible. Comparisons between hourly and 3-hourly forecast data with the actual data indicate that hourly forecasts are more accurate for use as input to the model. Three-hourly forecasts were also similar to the actual data for the first four days of the forecast.

Wind speed, a critical parameter for determining scum appearance, was provided in Beaufort scale for the Gooimeer-Eemmeer, Sloterplas and Westeinderplassen, and had to be converted to m/sec for input to the model. Each Beaufort value encompasses a wide range of wind speeds in m/sec, and the median in the range was used in this application. Model predictions of scum appearance using the wind converted data were poor, as the median wind speed in m/sec used for low Beaufort values was too high to allow scums to form. Reducing the wind speed by 20 % greatly increased model performance relative to predictions made using the actual data.

For the Delftse Hout, the forecasted wind data provided was in m/sec, and hourly and 3-hourly forecasts were available for every day of the simulation. Model predictions of scum appearance were better for the hourly forecast data than the 3-hourly data, relative to the predictions made using the actual climate data.

10.2 DETAILED ANALYSES DELFTSE HOUT

Previous assessment of model performance in this study for all four pilot lakes were focused on comparisons between scum appearance predictions by the model, and scum presence or absence as observed in the field data available. This approach was used as a means to rapidly assess model performance quantitatively, rather than focusing purely on visual comparisons of the model output. This method makes the assumption that if the conditions governing scum appearance as determined in the EcoFuzz membership functions are not met, than scum disappearance occurs and there is no scum present in the system. This may not always be correct, for example in instances when the surface scum is so dense that much higher wind speeds are required for scum dispersal than the minimum wind speed for preventing sum formation.

To further assess model performance for scum presence and absence, a detailed analysis was conducted for the Delftse Hout as this lake featured the most available field validation data. The number of model code and post-processing changes implemented allowed the results of both scum appearance and disappearance to be better compared to the field data, and decreased the rapid fluctuations observed in the model output for biomass. The spatial aggregation used to provide more detailed information on scum biomass in the surface layer for a number of predefined zones also allowed for better spatial scoring of the model results relative to the field data.

Model performance overall was high (89 % relative to the field data), although this was mostly because the model scores well when there are no field scums present, which occurred on most days. Model performance for scum presence within individual spatial zones around the lake was weak during field scum events due to a combination of incorrect hydrodynamics, incorrect EcoFuzz output and insufficient biomass in the model. The new method of scoring the model for the Delftse Hout showed that although the majority of the category 2 or higher field scums could be accurately predicated in the lake as a whole

(10 out of the 13 events), model output of the false positive events relative to the available field data was also high. Further analysis using different methods of interpreting the field or model data, for example increasing the model biomass threshold to alter what is considered a real scum event in the model output, did lead to a reduction in the number of the false positive events but also a decline in the number of correct actual scum predictions.

Additional calibration of the model focusing on a number of important input parameters, including appearance and disappearance thresholds and wind speed in the membership functions, also indicted that the false positive events could be reduced, but at the expense of a lower number of accurate scum presence predictions. The adjustment of parameters did not lead to an obvious overall improvement in the model for the combined result of high number of correct field scum predictions and limited false positive field predictions. Instead, the model responded in an almost step-like fashion towards one or another, with the total scores adjusting only slightly overall. Given that there are only 13 field scum events available for calibration overall, further calibration beyond what has been achieved in this study is not likely to be trivial.

The 2007 summer did not represent a “good” year for cyanobacterial scums due to highly unstable weather patterns and limited periods of warm, calm, low wind conditions. Cyanobacterial scums were considered to be mostly absent in many lake systems compared to previous years, and in the Delftse Hout, where the most validation data was available, scums of category 2 or higher were recorded on only 13 occasions throughout the model period. Further, of the scums that were present, only two were longer than 1 day in duration on the same location. This meant that there were a limited number of actual scum events to calibrate the model on in this study, with limited scum events lasting more than 1 day in duration. Further, the model output from EcoFuzz for appearance and disappearance was also highly variable on a day by day basis.

The phytoplankton biomass in the Delftse Hout as measured in the field sampling program show that the algal community was dominated by cyanobacteria species on only one occasion, and that dynoflagelate species dominated for the remaining periods. Further, the highest category scum events in the Delftse Hout were recorded in September 2007, when the biomass counts for cyanobacteria were lowest. There are two possible explanations for this; (1) the observed field scum events were not cyanobacterial scums but rather *Ceratium* blooms which could also potentially produce a surface, scum-like layer, or (2) during field sampling in the middle of the lake the scum was already concentrated along the shoreline. Both possibilities have major implications for the accurate validation of the model results.

Given the complexity of the model, the limited number of field scum events for calibration (13), the lack of cyanobacterial biomass, potential confusion of what the field scums represent coupled with what was a poor year for cyanobacterial scum formation, we suggest that only further model validation on a larger number of actual scum events and for a larger number of different lake types is likely to improve overall model calibration and therefore performance.

10.3 RECOMMENDATIONS FUTURE RESEARCH

The model in its present form is not yet suitable for use as an operational early warning system for predicting cyanobacterial surface scums in freshwater lakes. A number of additional research activities and data collection are recommended to improve the current status of the model. These recommendations are related to both the model code, and the availability of field data through monitoring. Several approaches can be applied to improve the data availability for calibration and validation (surface scums), as well as the input of phytoplankton biomass to the model (water column biomass):

1 More validation data on surface bloom presence or absence as well as shoreline location is required to enhance the calibration process to improve overall model performance for all four study lakes. While it is extremely difficult to motivate members of the public to continuously collect daily validation data, a number of alternative techniques could be applied;
   - Better and more detailed validation data;
   - More photos of actual events;
   - The use of webcams to monitor scum location;
   - The use of shore or buoy mounted high definition spectral cameras to infer cyanobacterial biomass and spatial distribution;
   - Regular aerial surveys during peak bloom periods.

2 More frequent water column cyanobacteria biomass measurements for input to the model:
   - More frequent (weekly?) model resets;

3 More intelligent model restarts:
   - Biomass reset scaled according to new measurements;

4 Quantification of cyanobacterial biomass without the use of modelling, for example:
   - The use of in-situ fluorescence probes to provide real-time data on cyanobacterial biomass which can be directly coupled to the model through remote sensing for further simulations of bloom appearance and horizontal transport. This could be in combination with methods 2 and 3;
   - The use of shore or buoy mounted high definition spectral cameras to infer cyanobacterial biomass, for example as is being routinely applied by Water Insight BV.:

5 Observation of scum formation dynamics and wind driven dispersal at short time scales through an intensive field sampling campaign, for example every 4 hours:
   - Combination with remote sensing.

11

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STICHTING
TOEGEPAST ONDERZOEK WATERBEHEER

stowa@stowa.nl www.stowa.nl
TEL 030 232 11 99 FAX 030 232 17 66
Arthur van Schendelstraat 816
POSTBUS 8090 3503 RB UTRECHT