the phytoplankton-nutrient model SEAWAQ
and its application to the southern bight
of the North Sea

report on investigations

R 1908

december 1985
List of figures

1 Carbon and nutrient cycles in the model
1A Forcing functions
2 Statistically homogeneous compartments of water quality parameters determined by RWS Direktie Noordzee
3 The partitioning of the Dutch coastal area as used in the model together with the locations of the WAKWON monitoring program
4-14 Annual variation of state variables computed by the model version 1. for the seven compartments. Vertical bars indicate monthly means and extremes of observed values
4 Diatoms
5 Other Phytoplankton
6 Chlorophyll-a
7 Primary Production
8 Silicate
9 Total Phosphorus
10 Ortho-Phosphorus
11 Total Nitrogen
12 Nitrogen: NO₂⁻-N + NO₃⁻-N + NH₄⁺-N
13 Detritus
14 Organic Sediment
15 A comparison between computed and measured phytocarbon biomass per square meter. Data are from Fransz and Gieskes (1984)
16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36 and 38 Annual variation of state variables computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
17, 19, 21, 23, 25, 27, 29, 31, 33, 35, 37 and 39 Annual variation of state variables computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
the phytoplankton-nutrient model SEAWAQ and its application to the southern bight of the North Sea

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R 1908

december 1985
CONTENTS

List of figures
List of symbols

<table>
<thead>
<tr>
<th>1</th>
<th>Introduction</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Description of the model SEAWAQ</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>3</td>
</tr>
<tr>
<td>2.2</td>
<td>Phytoplankton specific growth rate ( G_A )</td>
<td>4</td>
</tr>
<tr>
<td>2.2.1</td>
<td>The light limitation function</td>
<td>5</td>
</tr>
<tr>
<td>2.2.2</td>
<td>The nutrient-limitation function</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>Phytoplankton specific loss rate ( D_A )</td>
<td>8</td>
</tr>
<tr>
<td>2.3.1</td>
<td>The respiration rate</td>
<td>9</td>
</tr>
<tr>
<td>2.3.2</td>
<td>The specific mortality rate</td>
<td>9</td>
</tr>
<tr>
<td>2.3.3</td>
<td>The grazing rate</td>
<td>10</td>
</tr>
<tr>
<td>2.4</td>
<td>The transition in physiological state of the phytoplankton</td>
<td>12</td>
</tr>
<tr>
<td>2.4.1</td>
<td>The formation and activation of phytoplankton spores</td>
<td>13</td>
</tr>
<tr>
<td>2.5</td>
<td>The suspended detritus submodel</td>
<td>14</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Production of suspended detritus</td>
<td>14</td>
</tr>
<tr>
<td>2.5.2</td>
<td>The loss of suspended detritus</td>
<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>The bottom detritus submodel</td>
<td>16</td>
</tr>
<tr>
<td>2.7</td>
<td>The dissolved nutrient submodel</td>
<td>17</td>
</tr>
<tr>
<td>2.8</td>
<td>Net primary production</td>
<td>18</td>
</tr>
</tbody>
</table>

3 Application of SEAWAQ to the Southern Bight of the North Sea in front of the Dutch coast | 19 |
| 3.1 | Spatial representation of the area and water currents | 19 |
| 3.2 | The nutrients discharged into the area | 20 |
| 3.3 | The conversion procedure of WAKWON data to those representative for the model compartments | 21 |
| 3.4 | Simulations of annual variations | 22 |

4 The main deviations between primary model results and monitoring observations | 25 |
<table>
<thead>
<tr>
<th>CONTENTS (continued)</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. An extended model version of SEAWAQ</td>
<td>26</td>
</tr>
<tr>
<td>5.1 The density dependent mortality rate of phytoplankton</td>
<td>26</td>
</tr>
<tr>
<td>5.2 The nutrient exchange water-bottom</td>
<td>28</td>
</tr>
<tr>
<td>6 Sensitivity analysis</td>
<td>32</td>
</tr>
<tr>
<td>6.1 The background extinction coefficient</td>
<td>33</td>
</tr>
<tr>
<td>6.2 The density dependency in the phytoplankton mortality</td>
<td>35</td>
</tr>
<tr>
<td>6.3 Nutrient load crossing the southern border of the area</td>
<td>37</td>
</tr>
<tr>
<td>6.4 Discussion on some unsure aspects with appreciable influence</td>
<td>38</td>
</tr>
<tr>
<td>7 Recommendations for future research</td>
<td>40</td>
</tr>
</tbody>
</table>

LITERATURE
List of figures

1 Carbon and nutrient cycles in the model
1A Forcing functions
2 Statistically homogeneous compartments of water quality parameters determined by RWS Direktie Noordzee
3 The partitioning of the Dutch coastal area as used in the model together with the locations of the WAKWON monitoring program
4-14 Annual variation of state variables computed by the model version 1. for the seven compartments. Vertical bars indicate monthly means and extremes of observed values
4 Diatoms
5 Other Phytoplankton
6 Chlorophyll-a
7 Primary Production
8 Silicate
9 Total Phosphorus
10 Ortho-Phosphorus
11 Total Nitrogen
12 Nitrogen: NO₂-N + NO₃-N + NH₄-N
13 Detritus
14 Organic Sediment
15 A comparison between computed and measured phyto carbon biomass per square meter. Data are from Fransz and Gieskes (1984)
16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36 and 38 Annual variation of state variables computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
17, 19, 21, 23, 25, 27, 29, 31, 33, 35, 37 and 39 Annual variation of state variables computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
List of figures (continued)

16 and 17 Diatoms
18 and 19 Other Phytoplankton
20 and 21 Chlorophyll-a
22 and 23 Mortality Rate Factor
24 and 25 Primary Production
26 and 27 Silicate
28 and 29 Total Phosphorus
30 and 31 Ortho Phosphorus
32 and 33 Total Nitrogen
34 and 35 Nitrogen: NO$_2$-N + NO$_3$-N + NH$_4$-N
36 and 37 Detritus
38 and 39 Organic Sediment
40 Salinity distribution computed by the model ESTFLOW compared with the measured distribution
### List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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</tr>
<tr>
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<td>temperature coefficient</td>
<td>degrees⁻¹</td>
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<td>specific loss rate of diatoms</td>
<td>day⁻¹</td>
</tr>
<tr>
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<td>specific loss rate of ophy</td>
<td>day⁻¹</td>
</tr>
<tr>
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<td>depth</td>
<td>m</td>
</tr>
<tr>
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<td>maximum waterdepth</td>
<td>m</td>
</tr>
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</tr>
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<td>diatom sediment</td>
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</tr>
<tr>
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<td>diatom biomass</td>
<td>mgC.m⁻³</td>
</tr>
<tr>
<td>DIATJ</td>
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<td>mgC.m⁻³</td>
</tr>
<tr>
<td>DIATO</td>
<td>diatom biomass (old)</td>
<td>mgC.m⁻³</td>
</tr>
<tr>
<td>DIATS</td>
<td>spores of diatoms</td>
<td>mgC.m⁻³</td>
</tr>
<tr>
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<td>minimum function</td>
<td>-</td>
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</tr>
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</tr>
<tr>
<td>EXO</td>
<td>excreted fraction ophy</td>
<td>-</td>
</tr>
<tr>
<td>EXZ</td>
<td>excreted fraction zooplankton</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>relative photoperiod</td>
<td>-</td>
</tr>
<tr>
<td>FLID</td>
<td>light reduction function for DIAT</td>
<td>-</td>
</tr>
<tr>
<td>FLIO</td>
<td>light reduction function for OPHY</td>
<td>-</td>
</tr>
<tr>
<td>FTED</td>
<td>temperature reduction function for DIAT</td>
<td>-</td>
</tr>
<tr>
<td>FTEO</td>
<td>temperature reduction function for OPHY</td>
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</tr>
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</tr>
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<td>day⁻¹</td>
</tr>
<tr>
<td>GPHY</td>
<td>specific growth rate of OPHY</td>
<td>day⁻¹</td>
</tr>
<tr>
<td>GF</td>
<td>grazing function</td>
<td>mgC.m⁻³.d⁻¹</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Unit</td>
</tr>
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<td>----------------------------------------------------------------------------</td>
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</tr>
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<tr>
<td>KNO</td>
<td>monod parameter for N-limitation</td>
<td>mgN.m⁻³</td>
</tr>
<tr>
<td>KPD</td>
<td>monod parameter for P-limitation</td>
<td>mgP.m⁻³</td>
</tr>
<tr>
<td>KPO</td>
<td>monod parameter for P-limitation</td>
<td>mgP.m⁻³</td>
</tr>
<tr>
<td>KSD</td>
<td>monod parameter for SI-limitation</td>
<td>mgS.m⁻³</td>
</tr>
<tr>
<td>KZF</td>
<td>monod parameter for zooplankton grazing</td>
<td>mgC.m⁻³</td>
</tr>
<tr>
<td>N</td>
<td>dissolved nitrogen</td>
<td>mgN.m⁻³</td>
</tr>
<tr>
<td>NCRT</td>
<td>nitrogen-carbon ratio</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td>other phytoplankton biomass (young)</td>
<td>mgC.m⁻³</td>
</tr>
<tr>
<td>OPHYO</td>
<td>other phytoplankton biomass (old)</td>
<td>mgC.m⁻³</td>
</tr>
<tr>
<td>OPYS</td>
<td>spores of OPHY</td>
<td></td>
</tr>
<tr>
<td>ORSC</td>
<td>organic C-sediment</td>
<td>mgC.m⁻³</td>
</tr>
<tr>
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<td>mgN.m⁻²</td>
</tr>
<tr>
<td>ORSP</td>
<td>organic P-sediment</td>
<td>mgP.m⁻²</td>
</tr>
<tr>
<td>P</td>
<td>dissolved phosphate</td>
<td></td>
</tr>
<tr>
<td>PCRT</td>
<td>phosphate-carbon ratio</td>
<td></td>
</tr>
<tr>
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<td>J.cm⁻²d⁻¹</td>
</tr>
<tr>
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<td>rel. mineral. between bottom and susp. detr.</td>
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<td>effect of season on KO</td>
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<tr>
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</tr>
<tr>
<td>RND</td>
<td>nitrogen limitation factor for DIAT</td>
<td></td>
</tr>
<tr>
<td>RNO</td>
<td>nitrogen limitation factor for OPHY</td>
<td></td>
</tr>
<tr>
<td>RPD</td>
<td>phosphate limitation factor for DIAT</td>
<td></td>
</tr>
<tr>
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<td>phosphate limitation factor for OPHY</td>
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<td>silicate limitation factor for DIAT</td>
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</tr>
</tbody>
</table>
**List of symbols (continued)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>rate of change of DIATO</td>
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<tr>
<td>RTDND</td>
<td>rate of decrease of N-detritus</td>
<td>mgP.m⁻³.d⁻¹</td>
</tr>
<tr>
<td>RTDPD</td>
<td>rate of decrease of P-detritus</td>
<td>mgSI.m⁻³.d⁻¹</td>
</tr>
<tr>
<td>RTDSD</td>
<td>rate of decrease of diatom detritus</td>
<td>mgC.m⁻³.d⁻¹</td>
</tr>
<tr>
<td>RTF</td>
<td>rate of filtration by zoobenthos</td>
<td>mgC.m⁻³.d⁻¹</td>
</tr>
<tr>
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<td>rate of grazing by zooplankton</td>
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<td>rate of increase of N-detritus</td>
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</tr>
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<td>rate of increase of diatom detritus</td>
<td>mgSI.m⁻³.d⁻¹</td>
</tr>
<tr>
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<td>maximum assimilation rate</td>
<td>day⁻¹</td>
</tr>
<tr>
<td>RTMAO</td>
<td>maximum assimilation rate</td>
<td>day⁻¹</td>
</tr>
<tr>
<td>RTMD</td>
<td>mortality rate of DIAT</td>
<td>day⁻¹</td>
</tr>
<tr>
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<td>day⁻¹</td>
</tr>
<tr>
<td>RTMIN</td>
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</tr>
<tr>
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<td>mineralization rate of P</td>
<td>day⁻¹</td>
</tr>
<tr>
<td>RTMO</td>
<td>mortality rate of OPHY</td>
<td>day⁻¹</td>
</tr>
<tr>
<td>RTMDJ</td>
<td>mortality rate (DIATJ)</td>
<td>day⁻¹</td>
</tr>
<tr>
<td>RTMDO</td>
<td>mortality rate (DIATO)</td>
<td>day⁻¹</td>
</tr>
<tr>
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<td>mortality rate (OPHYJ)</td>
<td>day⁻¹</td>
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</tr>
<tr>
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<td>net relative growth of OPHY</td>
<td>day⁻¹</td>
</tr>
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<td>mgN.m⁻³.d⁻¹</td>
</tr>
<tr>
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<td>rate of change of OPHYO</td>
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</tr>
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</table>
List of symbols (continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
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<tr>
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</tr>
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<td>resuspension rate of bottom sediment</td>
<td>day$^{-1}$</td>
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<td>RTSUSM</td>
<td>maximum of RTSUS</td>
<td>day$^{-1}$</td>
</tr>
<tr>
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</tr>
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</tr>
<tr>
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<td>time</td>
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</tr>
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<tr>
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<tr>
<td>ZF</td>
<td>zooplankton food concentration</td>
<td>mgC.m$^{-3}$</td>
</tr>
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1 Introduction

This report is focused primarily on the presentation of the model SEAWAQ. The model SEAWAQ simulates the spatial and temporal distribution of phytoplankton and nutrients in a vertically well mixed estuary or coastal sea in response to external conditions such as nutrient loads, currents, light etc. An overview of the various components and their interrelations described in Section 2 of this report is shown in Figure 1.

SEAWAQ contains 17 state variables listed below.

4 Phytoplankton groups:
   diatoms divided in a young and old class          DIATJ
   DIATO
   other phytoplankton also divided in young and old class OPHYJ
   OPHYO

2 Spores or resting stages of:
   diatoms                                          DIATS
   other phytoplankton                              OPHYS

4 Suspended detritus pools expressed in:
   carbon                                           DETC
   phosphorus                                       DETP
   nitrogen                                         DETN
   silicate                                         DIAD

4 Bottom detritus pools expressed in:
   carbon                                           ORSC
   phosphorus                                       ORSP
   nitrogen                                         ORSN
   silicate                                         DIAS

3 Dissolved nutrients:
   phosphorus                                       P
   nitrogen                                         N
   silicate                                         S1

The forcing functions are:
Light (I), temperature (TEM), the background extinction coefficient (k_o), the grazing function of zooplankton (GF) and the grazing function of macrozoo-
benthos (FB); all place- and time-dependent. See Figure 1A. The extended model version described in Section 5 contains also a density dependent phytoplankton mortality rate (RM) as a forcing function.

The model must be considered as a research tool, with which effects of new or alternative process formulations on the system behaviour can be studied. Application of the model to field situations can enlarge insight in how that specific system is functioning and by comparing model and real system behaviour the attention can be focussed on gaps in our knowledge.

In Section 3 the application of SEAWAQ to the Southern Bight of the North Sea is described.

A more detailed description of this application and its first results are given in Waterkwaliteitsplan Noordzee deel 2 (1985).

From a comparison between model results and WAKWON monitoring data (RIJKS-WATERSTAAT, 1980) indications were obtained where the main model improvements were needed, see Section 4.

The improved model version of SEAWAQ is described in Section 5, and in Section 6, the attention is drawn to the most sensitive and uncertain aspects of the model which need further research. The recommendations for further research are summarized finally in Section 7.

The research described in this report is started within the framework of the "Waterkwaliteitsplan Noordzee" and was carried out by order of the Environmental Division of the Delta Department.

The research activities were guided by members of the Delta Department notably by: Ir. J.P.G. van de Kamer, Dr. G.Th.M. van Eck, Ing. J.H.M. van der Meulen, Ir. P.B.M. Stortelder and Drs. L.P.M.J. Wetsteyn.

The contribution of Dr. Ir. H.G. Fransz of the Netherlands Institute of Sea Research to this study is also greatly acknowledged.

The research and reporting was carried out by Ir. J.H.G. Verhagen of the Delft Hydraulics Laboratory.

Ir. S. Groot, also of DHL designed the computer simulation programme.
2 Description of the model SEAWAQ

2.1 Introduction

The basic approach to simulate phytoplankton growth is founded upon the expression

\[
\frac{dA}{dt} = (G_A - D_A) \cdot A
\]  

(1)

in which \( A \) = phytoplankton concentration in mg carbon m\(^{-3}\)

\( G_A \) = specific growth rate, day\(^{-1}\)

\( D_A \) = specific loss rate, day\(^{-1}\)

The fundamental equation is expanded to account for the effects of growth-limiting conditions, respiration, predation and settling.

To incorporate the effects of growth limiting condition the specific growth rate is written as

for diatoms:

\[
G_{DIAT} = RTMAD.(1 - EXD).DMIN(RSD, RPD, RND).FLID.FTED
\]  

(2)

and for other phytoplankton:

\[
G_{OPHY} = RTMAO.(1 - EXO).DMIN(RPO, RNO).FLIO.FTEO
\]  

(2)

in which

RTMAD, RTMAO maximum assimilation rate of DIAT, respectively OPHY at 20°C, day\(^{-1}\)

EXD, EXO excreted fraction by DIAT, OPHY

DMIN (-,-,-) minimum function

RSD silicate limitation factor for DIAT

RPD, RPO phosphate limitation factor for DIAT, OPHY

RND, RNO nitrogen limitation factor for DIAT, OPHY

FLID, FLIO light reduction function for DIAT, OPHY

FTED, FTEO temperature reduction function for DIAT, OPHY
The specific loss rate may be separated into a death rate, a respiration term, a predation term by zooplankton and a predation term by filtering bottom fauna. The present model neglects phytoplankton loss due to settling. It is assumed that living algae, whether they belong to the young or to the old group, do not settle at all. Only dead algae settle, but that material belongs to the detritus pool and will be discussed in Section 2.5.

So, the specific loss rate for diatoms is

\[ D_{\text{DIAT}} = R_{\text{TRD}} + \frac{R_{\text{TG}}}{ZF} + \frac{R_{\text{TF}}}{ZF} + R_{\text{TM}} \]  

(3)

and for OPHY

\[ D_{\text{OPHY}} = R_{\text{TRO}} + \frac{R_{\text{TG}}}{ZF} + \frac{R_{\text{TF}}}{ZF} + R_{\text{TM}} \]  

(3)

in which

- \( R_{\text{TRD}} \), \( R_{\text{TRO}} \) respiration rate of DIAT, OPHY, \( \text{day}^{-1} \)
- \( R_{\text{TG}} \) grazing rate of zooplankton, \( \text{mgC m}^{-3} \text{ day}^{-1} \)
- \( R_{\text{TF}} \) grazing rate of filtering zoobenthos, \( \text{mgC m}^{-3} \text{ day}^{-1} \)
- \( R_{\text{TM}} \) death rate of DIAT, OPHY, \( \text{day}^{-1} \)
- \( ZF \) zooplankton food concentration \( \text{mgC m}^{-3} \)

The rates given in expression (2) and (3) can be substituted in equation (1).

2.2 Phytoplankton specific growth rate \( (G_A) \)

According to equation (2) the specific growth rate of DIAT and OPHY at optimum light and nutrient conditions is equal to \( R_{\text{MAD}}(1 - \text{EXD}) \cdot F_{\text{TED}} \) and \( R_{\text{MAO}}(1 - \text{EXO}) \cdot F_{\text{TEO}} \).

The effect of temperature on algal growth is expressed as

\[ F_{\text{TED}} = \exp(C_{\text{TD}} \cdot (T \text{EM} - 20)) \]  

(4)

\[ F_{\text{TEO}} = \exp(C_{\text{TO}} \cdot (T \text{EM} - 20)) \]

in which

- \( C_{\text{TD}} \), \( C_{\text{TO}} \) characteristic temperature coefficient for DIAT, OPHY, \( \text{°C}^{-1} \)
Parameter values in general were chosen in accordance with accepted values in modelling studies compiled by the EPA-report of ZISON et al. (1978).

The maximum assimilation rate at 20 °C, RTMAD and RTMAO are of course different for various phytoplankton groups.

Part of the carbon assimilated is not used for growth but excreted by the cell as dissolved organic matter.

Literature studies show that the excreted fraction in terms of nutrients is rather variable. In carbon units however it is more or less constant and equal to about 0.1.

2.2.1 The light limitation function

The light dependency of the growth rate of phytoplankton is described as follows:

At low light intensity it is assumed that growth increases proportional to light until an optimum light level is reached. At higher light intensities growth remains constant.

Note that this formulation does not account for photo-inhibition at higher light levels. Photo-inhibition is neglected because it is believed that the exposure time of an individual algal cell in the euphotic zone, of the rather turbid and vertically well mixed coastal waters, is too short to damage the algal cell by an excess of light.

So \( F(z,t) \) is written as:

\[
F(z,t) = \begin{cases} 
\frac{I(z,t)}{I_s} & \text{for } \frac{I}{I_s} \leq 1 \\
1 & \text{for } \frac{I}{I_s} > 1
\end{cases}
\]

The light intensity \( I(z,t) \) at depth \( z \) follows from Lambert-Beer's law

\[
I(z,t) = I_o(t) e^{-k_e z}
\]

Following DI TORRO et al. (1970) the incident solar radiation as a function of time, is approximated by:
The graphical presentation of the light reduction function (scaled to \( f \)) as a function of \( I_a/I_s \) for two values of \( k_eH \) is shown in the figure below.

\[
\frac{F(z,t)}{f} = 1.0
\]

\[
\frac{I_a/I_s}{k_eH = 1}
\]

\[
\frac{I_a/I_s}{k_eH = 5}
\]

The extinction coefficient is written as the sum of three contributions.

\[
k_e = k_o * RELSED + EPSD * DIAT + EPSO * OPHY
\]  \( (6) \)

The last two contributions express the effect of the concentration of both phytoplankton groups on the extinction coefficient. So EPSD and EPSO are the specific extinction coefficients for the two phytoplankton groups with the dimension \( mg \ C^{-1} \ m^2 \).

The first term is the extinction coefficient attributable to other causes, the so-called background extinction coefficient. The background extinction coefficient will be related to the concentration of suspended particulate material in the water column. This material originates mainly from the bottom and is brought into suspension by turbulence. The intensity of turbulent velocities near the bottom will be higher with increasing wind and tide generated bottom water currents, so with decreasing water depth. Therefore, turbulence near the bottom and bottom erosion and suspended material concentrations will be higher in the more windy winter season especially in the more shallow waters near the coast.

Following FRAN SZ (1979) the effect of season and water depth is specified by the empirical factor RELSED. Fransz expressed the coefficient RELSED as a
function of season in an empirical way, with a maximum in winter and a minimum in summer. The graphical presentation of the forcing function RELSED is shown in Figure 1A.

The background extinction coefficient in winter \( k_0 \) is dependent of water depth, leading to higher values on more shallow water.

2.2.2 The nutrient-limitation function

The effect of nutrient limitation on growth is specified in equation (2) as the minimum value of the following Michaelis-Menten expressions:

For diatoms

\[
RSD = \frac{S_1}{KSD + S_1}
\]

\[
RPD = \frac{P}{KPD + P}
\]

\[
RND = \frac{N}{KN + N}
\]

and for other phytoplankton

\[
RPO = \frac{P}{KPO + P}
\]

\[
RNO = \frac{N}{KNO + N}
\]

Note that only diatoms use the nutrient silicate.

2.3 Phytoplankton specific loss rate \( D_A \)

The phytoplankton specific loss rate in equation (1) represents all losses of phytoplankton biomass. Losses include respiration, grazing by zooplankton, grazing by filtering bottom fauna and a natural death rate which includes all other causes of loss of phytoplankton biomass.
2.3.1 The respiration rate

The total phytoplankton respiration is sometimes considered to be the result of two contributions, the maintenance respiration and the growth respiration. The first contribution is only temperature dependent, the second depends also on growth. The present model version however does not make such a distinction and specifies the respiration rate being only temperature dependent as:

for DIAT: \( RTRD = RTROD \times \exp(CTD \times (TEM - 20)) \)

for OPHY: \( RTRO = RTROO \times \exp(CTO \times (TEM - 20)) \)

(8)

2.3.2 The specific mortality rate

It is well known that phytoplankton models are very sensitive to the values of mortality and settling rates. It is also well known that values reported in literature show an extremely wide range of possible values. SMAYDA (1970) for instance summarizes measured values of settling velocities of various phytoplankton species. Most of these values range between 0-50 m/day. The higher settling velocities correspond usually to those species showing a poor physiological state. SMAYDA (1970) reports that phytoplankton sinks only after reaching a biomass maximum.

If the high rate of 50 m/day is used as a constant in the phytoplankton model, applied to a vertically not well mixed situation, it is impossible to maintain phytoplankton biomass into the euphotic zone.

It is the special feature of SEAWAQ to present a formulation of mortality and settling based on the foregoing information. This has been realized as follows:

The biomass of each phytoplankton group has been divided into two classes depending on the physiological state of the algal cell. The first class consists out of young healthy phytoplankton. The second class consists of old phytoplankton in a poor physiological state. The transition from the young to the old class occurs at the moment that the young phytoplankton group hits in the course of time a light- and/or a nutrient limitation. It is assumed in the present model that living phytoplankton whether it belongs to the young or to
the old class does not settle at all. However, the difference between both
classes is in the value of the mortality rate. The mortality rate of the old
class is one order of magnitude higher than that of the young class. Death
algae are transferred to the suspended detritus pool. The suspended detritus
in the model has a specified settling rate, which is discussed in the next
paragraph.

The mortality rate is a function of metabolic activity and is therefore taken
proportional to the respiration rate (FRANsz, 1979). So specified
for diatoms:

\[
RTMDJ = RM \times RTRD
\]

and

\[
RTMDO = RM \times RTRD \times AMD
\]  \hspace{1cm} (9)

and for other phytoplankton:

\[
RTMOJ = RM \times RTRO
\]

\[
RTMOO = RM \times RTRO \times AMO
\]  \hspace{1cm} (9)

in which

- **RTMDJ, RTMDO** = the specific mortality rate of diatoms, belonging
to the young, respectively old class \( \text{day}^{-1} \)
- **RTMOJ, RTMOO** = the specific mortality rate of OPHY, belonging to the
young, respectively old class \( \text{day}^{-1} \)
- **RM** = factor relating mortality to respiration
- **AMD, AMO** = ratio of mortality rates of the old compared to the young
class of DIAT, respectively OPHY

2.3.3 The grazing rate

The grazing rate in the present model is described as a forcing function. A
distinction is made between grazing by zooplankton and grazing by filtering
bottom fauna. The forcing function is based on measured values obtained by
FRANsz and GIESKES (1984). These authors provide data of the copepod production
in the eastern part of the Southern Bight of the North Sea. The data concern
the copepod production in mg C.m\(^{-2}\).day\(^{-1}\) over a one year period in the coastal
and in the offshore region. These data have been used by FRANsz (personal
communication) to obtain an estimate of the grazing rate in mg C.m\(^{-3}\).day\(^{-1}\) of
the zooplankton. In a similar way and estimate was made of the filtering
bottom fauna as a function of time and distance from the coast.
It is reported in the literature that the grazing rate depends on the concen-
tration of phytoplankton and particulate organic matter. The dependency is
often expressed as follows:

\[
RTG = GF \times \frac{ZF}{(KZF + ZF)}
\]

(10)
in which

\begin{align*}
RTG & \quad \text{is the zooplankton grazing rate} \\
GF & \quad \text{is the grazing rate in excess of food available} \\
ZF & \quad \text{is the zooplankton food concentration} \\
KZF & \quad \text{is the Michaelis-Menten half-saturation value for} \\
& \quad \text{grazing zooplankton}
\end{align*}

mg C.m\(^{-3}\).day\(^{-1}\) mg C.m\(^{-3}\).day\(^{-1}\) mg C.m\(^{-3}\)

The forcing function needed in the model is the grazing rate in excess of
available food GF(z,t), also called the potential secondary production. FRANsz
and GIESKES (1984), made an estimate of the potential production as a function
of time and place. This estimate of GF(z,t) has been used in the present model
version.
The food of zooplankton consists of phytoplankton and also of a small fraction
of detritus. This small fraction is arbitrarily taken as 5%, so

\[
ZF = DIAT + OPHY + 0.05 \times DETR
\]

(11)

Selective grazing between phytoplankton groups has not been considered in the
model. Consequently, the loss of diatoms, for instance, by grazing of zoo-
plankton can be written as:

\[
\frac{DIAT \times GF}{KZF + ZF}
\]

(12)
The analogous specification for the grazing bottom fauna on phytoplankton is:

\[
\frac{ZF \times FB}{KZF + ZF} \quad (13)
\]

in which \(FB(z,t)\) is the potential grazing rate by filtering bottom fauna in excess of food. \(FB\) is a prescribed forcing function based on information given by PRANSZ (personal communication).

2.4 The transition in physiological state of the phytoplankton

As mentioned before the formulation of the phytoplankton development is based on the concept that a transition takes place in physiological state, denoted by a young and an old state, as soon as the specific phytoplanktongroup hits a light- and/or nutrient limitation. The event of a light- and/or nutrient limitation for diatoms occurs in the model as soon as the minimum function \(\text{MIN}(\text{FIDN}, \text{SIKSD}, \text{PKPD}, \text{RNKND})\) becomes less than zero at a specific time, while the same function has been greater than zero one time step earlier.

The four variables in the diatom minimum function are:

- \(\text{FIDN} = \text{FLID} - \text{KLD}\)
- \(\text{SIKSD} = \text{SI} - \text{KSD}\)
- \(\text{PKPD} = \text{P} - \text{KPD}\)
- \(\text{RNKND} = \text{N} - \text{KND}\)

in which \(\text{KLD}\) is a light limitation factor (comparable to RILEY's (1957) criterium for the onset of active production in spring) and \(\text{KSD}, \text{KPD}\) and \(\text{KND}\) are Michaelis-Menten parameters for \(\text{SI}\), \(\text{P}\) and \(\text{N}\)-limitation for diatoms.

The light- and/or nutrient limitation for the other phytoplanktongroup is specified in a similar manner.

As soon as the specific phytoplanktongroup hits the above specified limitation, the young class of that phytoplankton group is transferred to the old class of the same group, except a small portion which remains young. From that remaining young part of the phytoplanktongroup a new bloom can spring if the conditions for growth are favourable again.

The old class has such a high mortality that that part of the phytoplankton-group becomes extinct, even if growth conditions improve again. The small
portion of the phytoplanktongroup remaining young at a limitation is taken in
the present model version as a fixed value, namely 5 g C/m³ for diatoms and 3
g C/m³ for OPHY.
The preceding formulation is rather new. Indications that it may be based on
biological reality can be deduced from the results of batch experiments on
phytoplanktongrowth made by ADMIRAAL et al. (in press).

2.4.1 The formation and activation of phytoplankton spores

At the end of the year light becomes insufficient to sustain nett phytoplank-
ton growth. According to the model formulation as described up till now, 
nearly all the phytoplankton becomes old and dies away. Only a small fraction
remains young. Growth conditions in winter however usually remain unfavourable
during a longer period. The young phytoplankton groups lose weight by respira-
tion and mortality. The consequence would be that the biomass of the young
phytoplankton groups becomes extremely low at the time of the early spring,
and in that way affect the timely coming up of the spring bloom.
It is known, however, from literature (LUND, 1965) that when growth conditions
are unfavourable for an extended period, some algae go into a kind of physi-
ological resting stage, the so-called spores.
This observation from nature has been built into the model. The formulation is
as follows:
The growing season ("summer") is defined as the period in the interval day 90
< TIME < day 225. Spores of for example diatoms, denoted by DIATS, are formed
only outside this period (referred to as "winter") when a light limitation for
diatoms occurs. So, spore formation occurs when the light criterium FIDN is
less than zero and one time step earlier, greater than zero. At that specific
point in time the biomass of diatom spores formed is equal to the biomass of
the young diatom group present, up to a certain upper bound, and denoted by
DIATSO. The remaining, if any, young diatoms not used for spore formation, are
converted to the old diatom group. If light conditions during the winter
period are favourable for growth again, the spores pool in the model is
activated as follows.
If FIDN is greater than zero at a specific time and in the preceding time
step less than zero the diatom spores are converted to the young diatom pool.
From the latter pool the spring diatom bloom can originate.
A similar specification for the other phytoplankton group is incorporated into the model.

2.5 The suspended detritus submodel

The suspended detritus budget is calculated as a function of time. Suspended detritus can be expressed as carbon, silicate, phosphate or nitrogen. Because the mineralization rate of the mentioned constituents differs from each other, the carbon/nutrient ratio of suspended detritus does not remain constant in time. Therefore, the budget of suspended detritus has to be calculated separately for the four constituents C, Si, P and N.

2.5.1 Production of suspended detritus

The production of suspended detritus, denoted by RTICD, RTISD, RTIPD, and RTIND for C, Si, P and N respectively, consists of three contributions, namely:

1. dead phytoplankton, mainly originating from the old phytoplankton groups, denoted by JANC, JANS, JANP and JANN, respectively.

2. a certain fraction of the food taken by the zooplankton. Expressed in carbon this amount is written as RTG(1 - EXZ), in which RTG is the zooplankton grazing function described previously and (1 - EXZ) the fraction of the amount grazed which is transformed into detritus. It contains, amongst others, faeces and dead zooplankton. Expressed in Si, P and N the contribution is somewhat more complex. For instance for phosphorus the contribution is

\[ RTG \times (1 - EXZ) \times ((DIAT + OPHY) \times PCRT + 0.05 \times DETP) / ZF \]

An identical formulation applies to the nitrogen case. Observe that EXZ is assumed to be identical for C, P and N. For the silicon case, however, it is assumed that the amount grazed is totally transferred to the detritus-pool. So, the specification for Si reads:

\[ RTG \times (DIAT \times SICRT + 0.05 \times DIAD) / ZF \]
3. A contribution of bottom detritus brought into suspension by waves and currents. The effect of waves and currents on the resuspension will diminish in water with increasing depth. Also a seasonal effect on the strength of wind induced waves and currents will be present. Therefore, the resuspension rate, denoted by RTSUS, has to be formulated as season- and depth-dependent.

The resuspension rate is written as $\text{RTSUS} \times \text{ORSC/DEP}$ (g $\text{C.m}^{-3}.\text{day}^{-1}$) in which $\text{RTSUS} = \text{RTSUSM} \times \text{RELSED}$

$\text{RTSUSM}$ = the relative resuspension rate at maximum waterdepth of the considered coastal area (day$^{-1}$)

$\text{RELSED}$ = a dimensionless reduction factor specified in the same hypothetical way as FRANZ (1979) did (see also Chapter 2.2.1)

$\text{ORSC}$ = the amount of organic bottom sediment per square meter (g C $\text{m}^{-2}$)

$\text{DEP}$ = local water depth (m).

An analogous formulation as for carbon is given for the nutrient constituents N, P, Si in the suspended detritus.

2.5.2 The loss of suspended detritus

The loss of suspended detritus, denoted by RTDCD, RTDSD, RTDPD and RTDND for C, Si, P and N respectively, consists of three contributions, namely:

1. A loss due to mineralization. The mineralization rate of suspended detritus differs for the constituents C, Si, P and N. The temperature-dependent mineralization rates are based on literature values (OFFICER and RYTHER, 1980, KAMATANI, 1969).

2. A sedimentation term. This contribution is formulated as depth dependent.

The specification of the sedimentation rate of carbon detritus is:

$$(\text{VSET/DEP}) \times \text{DETC}$$

in which $\text{VSET}$ = the settling velocity of detritus (m.day$^{-1}$).
3. a loss due to grazing by zooplankton. It is assumed that a small fraction (5%) of detritus is consumed by the zooplankton (selective grazing), with the given rate RTG/ZF (day⁻¹). So the specification in terms of carbon is:

\[(\text{RTG/ZF}) \times 0.05 \times \text{DETC}\] g C m⁻³ day⁻¹

An analogous formulation is given for N-, P-, and Si-detritus.

2.6 The bottom detritus submodel

Also the bottom detritus budget is calculated separately for the four constituents C, Si, P and N in the bottom detritus pool.

The production of bottom detritus consists of two contributions, namely:
1. settled suspended detritus in carbon units equal to

\[V\text{SET} \times \text{DETC}\] g C m⁻² day⁻¹

2. a certain fraction of the food grazed by the zoobenthos. In carbon units this contribution is:

\[(\text{RTF/ZF})(1 - \text{EXF}) \times \text{DEP} \times \text{ZF}\] g C m⁻² day⁻¹

in which RTF is the zoobenthos grazing function and (1 - EXF) the fraction of the amount grazed which is transformed to bottom detritus. In the silicate case, this fraction is taken to be one.

The loss of bottom detritus consists of three contributions, namely:
1. a loss due to mineralization. The nutrient-dependent mineralization rate of bottom detritus is taken proportional to the corresponding mineralization-rate of suspended detritus The proportionality constant denoted by RATIO is small compared to one, to account for the reduction in surface/volume ratio of the detritus due to consolidation processes in the bottom layer.

2. a resuspension rate written in carbon units as:

\[\text{RTSUS} \times \text{ORSC}\]
3. a loss due to formation of refractory detritus or, in case of nitrogen, a loss due to denitrification. These losses are specified for the time being as proportional to the amount of bottom detritus above some minimum bottom detritus value.

So in carbon units

\[ \text{FIXC} \times (\text{ORSC} - \text{CORSC}) \]

in which CORSC is the minimum bottom detritus value in g C.m\(^{-2}\). The specification needs more attention in future. For instance it is known that denitrification occurs only at low or zero oxygen content. Therefore, a realistic process description needs a book-keeping of the oxygen balance in the bottom sediment.

2.7 The dissolved nutrient submodel

The loss term of dissolved nutrients is the result of nutrient-uptake by phytoplankton. The uptake rate is obtained by converting assimilation minus excretion and respiration rates in nutrient units by using the weight ratios \( \text{Si/C = SICRT} \) for diatoms and \( \text{P/C = PCRT} \) and \( \text{N/C = NCRT} \) which are taken equal for both phytoplankton groups.

So in terms of for instance phosphorus, the loss term of \( \text{P} \) is:

\[ \left( (\text{RTAD} \times (1 - \text{EXD}) - \text{RTRD}) \times \text{DIAT} + (\text{RTAO} \times (1 - \text{EXO}) - \text{RTRO}) \times \text{PHY} \right) \times \text{PCRT} \]

The production of dissolved nutrients is the result of various contributions:

1. a contribution from mineralization of suspended as well as bottom detritus,
   in for instance P-units written as:

   \[ \text{RTMIP} \times (\text{DETP} + \text{RATIO} \times \text{ORSP/DEP}) \]

2. a fraction EXZ of the amount grazed by zooplankton.
3. a fraction EXF of the amount grazed by zoobenthos.
The last both contributions in P-units are written as

\[
\text{RTG} \times \text{EXZ} + \text{RTF} \times \text{EXF} \times (\text{PCRT} \times (\text{DIAT} + \text{OPHY}) + 0.05 \times \text{DETP})/\text{ZF}
\]

The formulation in N-units is quite similar.
In the case of silicate the contribution to the dissolved nutrient pool is zero because it is assumed that all the silicate components grazed are unreduced transferred to the detritus pool.

2.8 Net primary production

The daily net primary production is defined as the assimilation rate minus the respiration rate and excretion has been calculated as an output function. Also the integral of the daily net primary production from the first of January has been calculated.

A tentative application of SEAWAQ to the Dutch coastal area has been made. This application is extensively described in a report by RIJKSWATERSTAAT AND WATERLOOPKUNDIG LABORATORIUM (1985) (Chapter 5). A shortened version in English is given by FRANZ and VERHAGEN (1984).
3 Application of SEAWAQ to the Southern Bight of the North Sea in front of the Dutch coast

3.1 Spatial representation of the area and water currents

Tentatively a simplified partitioning of the North Sea in front of the Dutch coastal area was chosen in which a very simple residual transport regime was assumed.

In the direction parallel to the coast no concentration gradients are considered. Perpendicular to the coast the area has been subdivided in seven compartments. Between these compartments there is only turbulent exchange assumed with a constant dispersion coefficient of 150 m²/s (RIJKSWATERSTAAT AND WATERLOOPKUNDIG LABORATORIUM (1985) (Chapter 2)). The length of the compartments I to VII measured along the coastline is taken as 120 km. This choice is based on the information which can be derived from Figure 2 made by RWS. Figure 2, reproduced from (RWS-NOORDZEE, concept WKP-kustwater, 1983) shows a tentative division of the coastal area into statistically homogeneous compartments of water quality parameters. As can be seen from the figure the length of the homogeneous compartments most strongly influenced by the water quality of the rivers Rhine and Meuse is about 120 km and contains the reach named Goeree up till Callandsoog. Because there exist some questions on what has been considered as "statistically homogeneous" the specific choice of the compartment length must be seen as a first estimate.

The width and depth of the compartments increase with the distance from the coast and is taken as:

<table>
<thead>
<tr>
<th>Compartment</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>6</td>
<td>10</td>
<td>14</td>
<td>19</td>
<td>24</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Depth</td>
<td>13</td>
<td>17</td>
<td>20</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

Figure 3 shows the spatial division of the area on which the model is based.

A uniform advective residual transport current was assumed parallel to the coast going northward with a season dependent velocity, equal of 6, 4.5, 3 and 4.5 cm/s respectively in the four quarters of the year. This corresponds to a retention time of respectively 23.1, 30.9, 46.3 and 30.9 days. Linear interpolation has been used to obtain the day to day variation.
3.2 The nutrients discharged into the area

The nutrients discharged by rivers, mainly Nieuwe Waterweg and Haringvliet into compartment I are given in Table I. Table I is based on an analysis of WAKWAL-data over the years 1976 - 1982 (SALOMONS, 1984).

<table>
<thead>
<tr>
<th></th>
<th>10³ metric tons/year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>198.6</td>
<td>47</td>
<td>17</td>
<td>8</td>
<td>28</td>
</tr>
<tr>
<td>NO₂ + NO₃ - N</td>
<td>296.9</td>
<td>35</td>
<td>24</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>PO₄ - P</td>
<td>27.4</td>
<td>29</td>
<td>22</td>
<td>21</td>
<td>28</td>
</tr>
</tbody>
</table>

Table I. River discharges of dissolved nutrients during the period 1976-1982

The amount of nutrients entering the area across the south border are estimated by multiplying the measured concentration at the southern most transect of the WAKWON-monitoring area, namely Appelzak, by the estimated residual transport current across that border.

The southern most transect is chosen because it is expected to have the least direct influence of the nutrient loads of the rivers Rhine and Meuse.

Table II gives the nutrient concentrations averaged quarterly over the period 1975 - 1982 at the Appelzak transect as derived from the WAKWON data base, and interpolated to get the value at the center of the model compartments.

In addition to dissolved nutrients there are also nutrients discharged tied in suspended particulate organic matter. In the modelversion reported here those contributions in the nutrient load have been neglected. The main reason for it is that the relevant data are only partly available. On the other hand the effect of the neglection has been estimated by running two different model-versions, one in which the dissolved nutrient load has been multiplied by a factor to account for the particulate nutrient load, and the other in which the estimated particulate nutrient load has been transferred to the bottom compartments. Although the results of those model-versions differ somewhat from the version presented here, it did not affect the main conclusions given in this report.
<table>
<thead>
<tr>
<th>Quarter</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Si</strong></td>
<td>1</td>
<td>910</td>
<td>647</td>
<td>476</td>
<td>258</td>
<td>139</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>214</td>
<td>107</td>
<td>68</td>
<td>40</td>
<td>28.9</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>161</td>
<td>136</td>
<td>101</td>
<td>52</td>
<td>28.5</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>464</td>
<td>354</td>
<td>273</td>
<td>168</td>
<td>114.2</td>
<td>110</td>
</tr>
<tr>
<td><strong>NO₂ + NO₃ - N</strong></td>
<td>1</td>
<td>1121</td>
<td>794</td>
<td>560</td>
<td>303</td>
<td>156</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>551</td>
<td>316</td>
<td>217</td>
<td>102</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>299</td>
<td>178</td>
<td>117</td>
<td>46</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>542</td>
<td>366</td>
<td>248</td>
<td>124</td>
<td>65</td>
<td>58</td>
</tr>
</tbody>
</table>

| **PO₄ - P** | 1 | 88 | 64 | 48 | 31 | 21 | 18.5 | 18.5 |
|            | 2 | 47 | 28 | 20 | 11 | 5.7| 5.4  | 5.4  |
|            | 3 | 66 | 46 | 36 | 19 | 7.9| 5.9  | 5.9  |
|            | 4 | 94 | 63 | 47 | 27 | 15.6| 13.4 | 13.4 |

Table II. 1975-1982 dissolved nutrient concentrations in mg/m³ at Appelzak south border

3.3 The conversion procedure of WAKWON data to those representative for the model compartments

The subdivision of the North Sea area on which the model is based is not the same as used in the WAKWON monitoring program. Therefore, the results of the WAKWON monitoring program were processed to make a comparison between measured and calculated results possible.

The processing of WAKWON data has been as follows. The transects Goeree, Ter Heyde, Noordwijk, Egmond and Callandsoog are situated inside the area considered in the model. The observations made at these transects at a given distance of n km from the coast every 2 to 3 weeks are averaged over these transects and over each month. Denote this observation by \( Y_n \).

Denote the observations at the center of the model compartments by \( Y_1 \) up till \( Y_{VII} \).
By interpolation the following conversion is obtained:

\[ \begin{align*}
Y_I &= (2Y_1 + Y_2 + 2Y_4 + Y_{10})/6 \\
Y_{II} &= (2Y_4 + 5Y_{10} + 3Y_{20})/10 \\
Y_{III} &= (2Y_{10} + 7Y_{20} + 5Y_{30})/14 \\
Y_{IV} &= (Y_{30} + Y_{50})/2 \\
Y_{VI} &= Y_{70}
\end{align*} \]

The weighing factors in the interpolation formula's follow from the various compartment widths. Scaling on the basis of volume ratio's instead of width ratio's would be better. However, the differences in weighing factors between both methods appeared rather small.

In this way we get for every compartment one observation per month.

The observation period 1975 - 1983 extends over seven years, so we have seven monthly mean observations per compartment. The maximum, minimum and mean value of these seven observations per compartment per month are depicted in the various figures in this report in which model results are compared with measured data.

3.4 Simulations of annual variations

Starting from mean observed initial values of state variables at January 1, the rates defined in the model were numerically integrated to simulate the annual cycle and distribution of phytoplankton and nutrients.

To compare the results with monitoring observations the following conversions were made:

\[ \text{chlorophyll a} = \frac{\text{DIAT}}{25} + \frac{\text{OPHY}}{30} \]

See Figure 6.
Measured $\text{NO}_3 + \text{NO}_2 + \text{NH}_4 - N$ is compared to the calculated dissolved N-concentrations. See Figure 12.

Measured total N is compared with the sum of calculated phytoplankton-N, dissolved-N and detritus-N. See Figure 11.

Measured total-P is compared with the sum of calculated phytoplankton-P, dissolved-P and detritus-P. See Figure 9.

Figures 4 to 14 show the results of the primary model version, which is coded 1.0.

The presentation is in such a way that the annual variation in a state variable is depicted for each of the seven compartments, the next on top of the preceding ones.

In these figures a number of interesting points can be observed.

The biomass of diatoms (Figure 4) is only 1/2 or 1/3 the biomass of other phytoplankton (Figure 5).

As found already by GIESKES and KRAAY (1975) the timing of the spring bloom starts about one month later in spring in the turbid near coast compartments than it does in the off-shore compartments. The onset of active production is reached after the radiation averaged over the waterdepth exceeds a certain critical value. This conclusion of the investigation of GIESKES and KRAAY (1975) has been incorporated in the model and the effect is clearly demonstrated in the Figures 4, 5, 6 and 7.

Also the end of the productive season is dictated by the decreasing solar radiation and turbidity and is about one month later in compartment VII than it is in compartment I.

Figures 6 and 7 show chlorophyll and net primary production respectively. Both computed results seem to be an overestimation of the reality in the near-shore compartments especially in the second half of the year. See also Figure 15.

The oscillations in the computed primary production curves (Figure 7) are the consequence of nutrient limitations. It should be reminded that the model is based on the concept that as soon as phytoplankton growth hits a nutrient limitation, most of the living phytoplankton becomes old and dies away. At the same time a young phytoplankton group starts to grow again. This concept causes the mentioned oscillations.

Figure 13 shows the computed suspended detritus curve. It can be observed that
the ratio detritus versus phytocarbon is more or less constant during the growing season and equals about 40%.

From Figure 14 it can be concluded that the amount of organic sediment at the bottom has a maximum in compartment II. Nearer to the coast, less organic sediment is present due to the stronger erosion losses in shallow water, while in the offshore region less organic sediment is produced by settling detritus particles.
4. The main deviations between primary model results and monitoring observations

The tentative application of SEAWAQ to the Dutch coastal area has been extensively described in "Waterkwaliteitsplan Noordzee". Deel 2. R2000-2b, 1985. A shortened English version is given by FRANSZ and VERHAGEN (1985). Instead of repeating the description of the results it seems more appropriate to draw the attention to the main deviations between those primary model results and monitoring observation.

Those deviations are:
Chlorophyll in the near-shore compartments was overestimated, particularly during spring and fall. Presumably in connection with this result, nutrients in the near-shore compartments were underestimated particularly ortho-phosphorus in the second half of the year. See Figures 8 and 10.
Possible explanations were given in FRANSZ and VERHAGEN (1985). They mention that the carbon-chlorophyll ratio is in fact season dependent and results have to be compared with measured phyto carbon data. Figure 15 shows a comparison between calculated and measured phyto carbon. The phyto carbon data are from FRANSZ and GIESKES (1984).
From this comparison the conclusion remains that phytoplankton carbon and primary production in the near-shore compartments were still overestimated particularly during summer and fall. FRANSZ and VERHAGEN (1985) suggest that grazing may be underestimated because only copepod grazing was involved. Other grazing with immediate release of nutrients, e.g. by smaller heterotrophs (LANDRY and HASSET, 1982) may keep the algal biomass from August till October at a lower level than expected.
In the next chapter an attempt is presented to reduce phytoplankton growth in the model especially in the second half of the year in the near-shore compartments by an additional hypothetical density dependant mortality factor which has been attributed to a grazing effect of micro-heterotrophs.
5 An extended model version of SEAWAQ

Up till now phytoplankton mortality in the model is taken only dependent on temperature and on physiological state of the algae. In the extended model version the relative mortality rate is assumed to increase with the phytoplankton biomass, so a density dependent mortality is introduced. The biological background of the density dependent mortality rate is presently lacking. In this report it is assumed that a relation exists between mortality rate and the density of micro-heterotrophic organisms. However, it remains to be seen if this assumption holds true. The only message of the extended model version is to show that a density dependent mortality rate improves the model results considerably. It is the task of a sequel to this work to formulate biologically realistic hypotheses which can explain the required density dependent phytoplankton mortality rate.

5.1 The density dependent mortality rate of phytoplankton

It is assumed that the relative mortality rate of phytoplankton increases with the biomass of micro-heterotrophs per unit area. The latter biomass in its turn will be positively correlated to the phytoplankton biomass. In other words: in the coastal region a higher density of micro-heterotrophic organisms, and therefore a higher relative mortality rate of algae will be found than off-shore.

In the original model version the mortality rate of for instance diatoms has been written as (see equation (9)):

\[ \text{RTMDJ} \times \text{DIATJ} + \text{RTMDO} \times \text{DIATO} \]

in which

\[ \text{RTMDJ} = \text{RM} \times \text{RTRO} \]
\[ \text{RTMDO} = \text{RTMDJ} \times \text{AMD} \]

in which RTRO specifies the temperature effect

\((\text{RTRO} = 0.05 \exp(0.07(T - 20)))\) and RM, AMD are proportionality factors taken as one, respectively ten.
In the extended model version the proportionality factor RM should be a function of the biomass of micro-heterotrophs. The mean value of RM in the offshore region should be equal to the value in the original model version. So RM, mean, off-shore = 1.

Further, RM should increase with the phytoplankton biomass, or with the more or less equal value of the zooplankton food ZF. It seems most probable to incorporate a time delay between a change in ZF and the subsequent change in RM. Based on the information given by Fransz (personal communication) that the biomass of micro-heterotrophs increases probably strongly after the spring bloom and remains high during summer, the time delay in question must have an order of magnitude of a few months.

So the specification can be

\[
\frac{dRM}{dt} = \alpha ZF - \beta RM
\]

(14)

in which \( \beta = (0.03 - 0.01) \text{ day}^{-1} \) and the constant \( \alpha \) as to be chosen in such a way that the mean value of RM is about one in the offshore region (where ZF in the growing season is about 100).

The results of simulations appear to be very sensitive to the specific assumption made about the dependency of RM from ZF and time \( t \). Instead of a linear relation between the increase in RM and the zooplankton food ZF a less than linear relationship could as well as be supposed. For instance:

\[
\frac{dRM}{dt} = \alpha ZF^{0.8} - \beta RM
\]

(15)

The exponent 0.8 is chosen because it fits the data as can be seen reasonably.

Part of the losses of phytoplankton due to the presence of microheterotrophs goes immediately to the nutrient pools, just as in the case of zooplankton grazing.

It is assumed that the part of the losses which returns directly to the nutrient pools is somewhat higher for phosphorus than it is for the other constituents.

The specification is that the proportion of the mortality loss of phytoplankton-
ton, mineralized immediately, is 50% for P and 35% for Si, N and C. The remaining part goes into the suspended detritus pool.

Results of the extended model version for different assumptions concerning the effect of microheterotrophs are discussed in the chapter on sensitivity analysis. Those results are compared with data of the WAKWON monitoring programme.

5.2 The nutrient exchange water-bottom

Another opportunity to test the model results is to compare the calculated nutrient fluxes out of the sediments with measured values. RUTGERS VAN DER LOEFF (1980) estimated the flux of dissolved nutrients out of the sediment by multiplying the concentration gradient obtained from measured pore water profiles at the sediment surface with an estimate of the apparent diffusion coefficient in the upper layer of sediments obtained by BILLEN (1978). His Table IV converted from nmol.m⁻².s⁻¹ to mg.m⁻².day⁻¹ is shown here.

<table>
<thead>
<tr>
<th>nutrient</th>
<th>from pore water data</th>
<th>from budget studies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coastal zone</td>
<td>off-shore zone</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>65.8</td>
<td>11.98</td>
</tr>
<tr>
<td>NO₂⁻ + NO₃⁻</td>
<td>-4.6</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>-22.9</td>
</tr>
<tr>
<td>NH₄⁺ + NO₂⁻ + NO₃⁻</td>
<td>summer</td>
<td>61.2</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>42.9</td>
</tr>
<tr>
<td>PO₄³⁻</td>
<td>10.2</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>summer</td>
<td>66.5</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>38.5</td>
</tr>
</tbody>
</table>

Table III. Nutrient flux out of sediment in mg.m⁻².day⁻¹ obtained from pore water data.
The last two columns show the fluxes obtained from budget studies by THYSSEN, VAN BENNEKOM and HELDER (1974). The amount of nutrients per unit area as calculated in the extended model version is shown in the following table.

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
<th>Silicate</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>13500</td>
<td>1800</td>
<td>10300</td>
</tr>
<tr>
<td>II</td>
<td>3730</td>
<td>620</td>
<td>2900</td>
</tr>
<tr>
<td>III</td>
<td>3000</td>
<td>530</td>
<td>2410</td>
</tr>
<tr>
<td>IV</td>
<td>2320</td>
<td>440</td>
<td>2030</td>
</tr>
<tr>
<td>V</td>
<td>1850</td>
<td>330</td>
<td>1740</td>
</tr>
<tr>
<td>VI</td>
<td>1250</td>
<td>240</td>
<td>1500</td>
</tr>
<tr>
<td>VII</td>
<td>1060</td>
<td>190</td>
<td>1300</td>
</tr>
</tbody>
</table>

Table IV. Yearly mean amount of nutrients in the sediments in mg.m\(^{-2}\) as calculated by the model

The table shows the calculated yearly averaged value of P, N and Si in the sediments expressed in mg.m\(^{-2}\). The flux of nutrients out of the sediment is specified in the case of for instance Si as

\[ \text{RATIO} \times \text{RTMIS} \times \text{DIAS} \]

Analogous expressions are given for P and N. The ratio between the mineralization rate of bottom detritus compared to the suspended detritus is taken as \( \text{RATIO} = 0.2 \).

The value is smaller than one to account for the density barrier between bottom and water. Taking the mineralization rate at 11°C as representative for the yearly averaged rate we get:

\[ \text{RTMIS}_{11°C} = 0.03 \quad \text{RTMIN}_{11°C} = 0.03 \quad \text{RTMIP}_{11°C} = 0.024 \, (\text{day}^{-1}) \]
Based on this information the yearly averaged nutrient flux out of the sediments as calculated in the model becomes:

<table>
<thead>
<tr>
<th>Comp.</th>
<th>N from pore water data</th>
<th>N from pore water data</th>
<th>P from pore water data</th>
<th>P from pore water data</th>
<th>Si from pore water data</th>
<th>Si from pore water data</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>81.0</td>
<td>52.0</td>
<td>8.64</td>
<td>10.2*</td>
<td>61.8</td>
<td>52.5</td>
</tr>
<tr>
<td>II</td>
<td>22.4</td>
<td></td>
<td>2.98</td>
<td></td>
<td>17.7</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>18.0</td>
<td></td>
<td>2.54</td>
<td></td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>13.9</td>
<td></td>
<td>2.11</td>
<td></td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>11.1</td>
<td>14.7</td>
<td>1.58</td>
<td>7.0*</td>
<td>10.4</td>
<td>24.7</td>
</tr>
<tr>
<td>VI</td>
<td>7.5</td>
<td></td>
<td>1.15</td>
<td></td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>VII</td>
<td>6.4</td>
<td></td>
<td>0.91</td>
<td></td>
<td>7.8</td>
<td></td>
</tr>
</tbody>
</table>

* According to Rutgers van der Loeff probably an overestimation.

Table V. Yearly mean nutrient flux out of sediment in mg.m\(^{-2}\).day\(^{-1}\) as calculated in the model.

The model results from Table V can be compared with the measured data given in Table III.

The locations of the sampling stations used in the sediment-water exchange study of RUTGERS VAN DER LOEFF (1980) were divided into two groups. One group of sampling stations were representative for the coastal region defined as a zone to within 4 kilometres of the beach; the other group of stations were representative for the off-shore region, a zone between 4 and 90 kilometres off the beach.

Therefore, the coastal region of RUTGERS VAN DER LOEFF (1980) could be compared with compartment I in this study and the off-shore region of RUTGERS VAN DER LOEFF (1980) may be compared with compartment II up till and including V, on average about 50 km off the beach corresponding to the boundary between compartment IV and V.

Table V shows the yearly averaged nutrient flux values obtained by RUTGERS VAN
DER Loeff (1980) in Table III on comparable distance off the coast. It is encouraging that the model results show the same order of magnitude as the measured data. Therefore, it may be concluded that the model calculated the right order of magnitude of the yearly averaged nutrient fluxes out of the sediments into the water column.
6 Sensitivity analysis

The question of the sensitivity of the model output to a change in parameter values is posed frequently by those who are using model results. In this report a few remarks will be made on the important but difficult subject of - How good is a model? -.

To my opinion two things are important in this respect. First the question of the sensitivity of a given model output to a change in parameter values. Second the question of the sensitivity of the model behaviour to a change in the assumptions and approximations which are made during the process of mimicking the physical system. One of the assumptions concerns the number of state variables considered, or the choice of the model complexity. Because a simple model is often more robust than a complex model with many state variables, the question is sometimes posed "How many state variables are needed to mimic the physical system behaviour between some prescribed limits of reliability of specified output results?"

The possibilities to give an answer to the last question are, however, rather limited.

The most practical way will be to compare two or, if possible, more models, with essentially different structures, for the same data set and also for other situations without parameter adjustment in order to get an indication about the reliability of the model behaviour under various conditions. In the context of the present study the start of such an investigation is not feasible.

All what has been done during the present study is to modify the model a number of times by trial and error procedures. During such a procedure an impression is obtained of those aspects in the model, processes or parameter values, on which the model output is most sensitive.

The attention has been focussed on those aspects during the trial and error procedure and a number of different assumptions and approximations has been made.

The model appeared to be most sensitive to the following insufficiently known aspects:

1. The background extinction coefficient as a function of time and distance off the coast.
2. The density dependency in the phytoplankton mortality.
3. The influence of the boundary conditions prescribing nutrient loads at the southern transect.

Quantitatively less important but still of an appreciable influence are

4. The season-dependency in the nutrient exchange water-bottom, as a function of location.

5. The question about the nutrient loads of the rivers. Is part of the river-born load transported directly to the sea bottom in the coastal compartment?

Those aspects mentioned here will be discussed.

6.1 The background extinction coefficient

The extinction coefficient $k_e$ in natural waters is usually expressed as the sum of three contributions, see e.g. DI TORRO (1978).

$$k_e = \alpha N + \beta D + \gamma C$$

in which

$N$ is the concentration of non-volatile suspended solids

$D$ is the concentration of suspended detritus

$C$ is the algal concentration.

Using literature values of $\alpha$, $\beta$ and $\gamma$ and measured values of the concentrations $N$, $D$ and $C$ in the Dutch coastal waters, it can be shown that the first mentioned contribution in the extinction coefficient is of paramount importance in the coastal region. The concentration of suspended solids in the coastal area depends on waves and currents and on the composition of the local bottom. The variability in suspended solid concentration in the coastal region is very high mainly due to the variability in wind conditions. The effect of resuspension of bottom detritus on the concentration of suspended detritus will be season- and depth-dependent. Resuspension is higher in winter than in summer and the effect increases in more shallow water.

Instead of using the concentration data of suspended solids and of organic matter it seemed more appropriate to use data of the Secchi depth. An inverse relationship between Secchi depth $SD$ and extinction coefficient is assumed
\[ k_e = \frac{\alpha}{SD} \]

The coefficient \( \alpha \) is taken as 1.9 in the off-shore region and somewhat smaller, namely 1.5 for the coastal areas (HOLMES, 1970). It is a pity that the WAKWON Secchi-disk data seem to be cut off above the value of 3 metres. Therefore, those data could only be used in the turbid waters of the near shore region. In the off-shore region the SD data are taken from the ANNALES BIOLOGIQUES, Vol. XXIV 1967, 1968 and Vol. XXVI (1969, 1970).

The season dependency in the Secchi-depth readings is estimated from these data. The estimation is specified as follows:

A dimensionless relative Secchi-depth RELSD is introduced being one in winter in deep water and larger than one in summer and in more shallow water.

The ratio between summer and winter value in SD in the near shore compartment is about 4 according to WAKWON-data and decreases gradually in seaward direction to about 2.

So RELSD is specified as:

\[
RELSD = 1 + \frac{RAD - RADMIN}{RADMAX - RADMIN} \left( \frac{DEPMA}{DEP} \right)^{1.5}
\]

The expression differs from the one proposed by FRANSZ (1979) and denoted by RELSED in the original version of SEAWAQ. In the revised version RELSED is replaced by RELSD and the extinction coefficient is written as

\[ k_e = k_o/RELSD + EPSD \times DIAT + EPSO \times OPHY \]

The background extinction coefficient \( k_o \) is obtained from the Secchi desk readings in winter using the foregoing empirical expressions. Table VI gives the resulting \( k_o \) as a function of the compartment numbers.
<table>
<thead>
<tr>
<th>compartment</th>
<th>$k_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3.0</td>
</tr>
<tr>
<td>II</td>
<td>2.1</td>
</tr>
<tr>
<td>III</td>
<td>1.4</td>
</tr>
<tr>
<td>IV</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table VI.

As said already the model appeared to be very sensitive to changes in the value of the background extinction coefficient. In fact the growth rate of phytoplankton per unit sea-surface is more or less inversely proportional to $k_e$. From the foregoing it will be clear that the material on which the estimate of $k_e$ is based is too poor to be reliable.

The first recommendation for future field research will be, to measure the extinction coefficient as a function of time and location in the area under study. If $k_e$ is closely correlated to wind condition it will be necessary to carry out a high frequent monitoring programme to find the quantitative relationship with the external wind condition and the local parameters, as water-depth and bottom composition.

6.2 The density dependency in the phytoplankton mortality

As described in Section 5.1 the effect of density dependency in the phytoplankton mortality is introduced in the revised model. The influence is incorporated into the time dependent proportionality factor $RM$ in the phytoplankton death rate. In Section 5.1 two different formulations are given for $RM$, specified in equations (14) and (15). The difference is in the rate at which $RM$ increases with phytoplankton biomass or with $ZF$. In the first specification the increase in $RM$ is linear with $ZF$, in the second proportional to $ZF^{0.8}$.

To show the sensitivity of the model on the precise specification of $RM$ the model results for both cases are shown. The Figures 16, 18, 20, ..., 38, show results of the modified model version which is coded 2.0, in which the mortality rate factor $RM$ is based on (15), see also Figure 22.
The Figures 17, 19, 21,....39 show results of the modified model version, coded 2.1, in which RM is based on equation (14); see also Figure 23.

As can be seen from the results the aim of the model extension namely to reduce phytoplankton growth especially in the second half of the year in the near-shore compartments is reached. The specification (15) fits the data better than (14). The suppression of the phytoplankton biomass and production is in version 2.0 less prominent than in version 2.1. See Figures 16 to 21 and 24 and 25. The Figures 26, 27 and 30, 31, 34, 35 show the nutrients during the summer months in the near-shore compartments are considerably higher and in agreement with the observations, than they were in the original model version 1.0. The higher algal mortality rate in the near-shore compartments during summer and fall indeed reduces production notwithstanding the excess amount of nutrients available. Further it can be concluded that the model is sensitive to in fact a minor change in the phytoplankton loss rate. Therefore, the second recommendation for further research is to direct the attention to the various mechanisms causing the loss rate of phytoplankton especially in the near-shore region of the Dutch coastal area during summer and fall. The contribution of the various mechanisms to the loss rate has to be quantified as a function of time and location.

In this specific model version the attention has been drawn to a possible influence of the presence of micro-heterotrophs. Also other causes of phytoplankton losses as, for instance, illness of populations, infections or effects of toxic substances have to be considered. Processes as excretion loss and respiration are incorporated in the present model but may well need revision in the near-shore coastal area. In this respect it must be mentioned that JOIRIS et al. (1982) explained the observed discrepancy between oxygen production and consumption in the Belgium coastal waters by an increased phytoplankton respiration, up to 80% of the gross primary production. The respiration rate values used in this study are normal rates found in literature which are usually below 40% of the gross primary production. Finally it is recommended to study only those phytoplankton loss processes which are quantitatively much more active during the warm period of the year in the coastal area than off-shore.
6.3 Nutrient load crossing the southern border of the area

In the present model version the nutrient load entering the area across the south border is specified by multiplying the measured nutrient concentration at the Appelzak transect times the estimated residual flow. The reliability of this method depends largely on the reliability of the estimated residual flow crossing the southern border.

In this model version the residual flow is introduced as a uniform current parallel to the coast to the north with velocities dependent on the season. This simple representation of the flow pattern can be slightly improved by using the calculated results of the ESTFLOW water movement model. The results of the ESTFLOW model, however, show essentially the same unrealistic residual transport pattern in the southern part of the Dutch coastal area as does the simple uniform advective transport hypothesis. Figure 40 shows the pattern of the salinity distribution in the Dutch coastal waters as calculated by ESTFLOW. A comparison with the measured salinity distribution shows that in reality an important southward transport current must exist which is not reproduced well by the ESTFLOW model. Measured and calculated salinity distributions of course are dependent on the strength and direction of the wind. The measured pattern of the salinity distribution shows, however, in general much larger quantities of brackish water in the southern direction than calculated. In the ESTFLOW model the dispersion coefficient along the coast could be increased to fit the data. An unrealistic order of magnitude in the dispersion coefficient, however, is needed to fit the data.

Therefore, it must be concluded that a rather considerable part of the water of the river Rhine is transported across the Appelzak transect in southward direction. The concentration of nutrients at this transect is, therefore, influenced by the river nutrient load. The present model version, even if the ESTFLOW currents were used, therefore, overestimates the nutrient load entering the area across the southern border. The amount of the overestimation can be a rather considerable part of the river born nutrient load.

This leads to an overestimation of the primary production and phytoplankton biomass in the Dutch coastal area produced by the model.

The third recommendation, therefore, is that more attention should be paid to a more realistic representation of the direction and magnitude of the residual currents in the coastal waters in front of the southern part of The Nether-
lands. This recommendation gains even more importance if it would appear, as some people suggest, that the peculiar behaviour of the residual flow in that area is caused by the action of the tidal flow in the estuaries. In that case there will be an effect of the Delta-works on the residual currents and therefore on the distribution of quality parameters in Dutch coastal waters.

6.4 Discussion on some unsure aspects with appreciable influence

The season-dependency in the nutrient exchange water-bottom as a function of location. In the present model version the season dependency in the nutrient exchange water-bottom is formulated as an increasing function of temperature. Only mineralization is considered giving an upward flux of nutrients from the sediments to the water column.

The downward flux of dissolved nutrients by sorption which depends on the concentration of the nutrient in the overlaying water and on the accumulation capacity of the sediment is not considered. In fact especially for P it is known that accumulation is important from September to April (KELDERMAN, 1983).

Also the simulation results show in general an increase of dissolved nutrients in the water column in the winter months. The increase in the model is due to the riverborn nutrient load for uptake of nutrients by phytoplankton is nearly absent in winter. The measured data of dissolved nutrients show in general no increase at all during the winter months.

There are two possibilities to explain this result:
a) A strong accumulation of nutrients to the bottom sediments takes place during winter months.
b) The riverborn dissolved nutrients discharged in the winter months absorb, by one reason or another, directly to the bottom sediments in the direct vicinity of the river mouth in the North Sea.

Insufficient is known about the two mentioned possibilities. To account a little bit for the second possibility all simulation results which are shown are calculated with the assumption that a constant fraction of the riverborn dissolved nutrients is transferred directly to the bottom sediment in compartment I. The constant, i.e. season independent, fraction is taken as 0.1 for Si, 0.1 for P and 0.1 for N.
As is to be expected the simulation results show still too large an increase in dissolved nutrients in the months January - February.

The measured data can be explained only, if a large fraction of the river-born dissolved nutrient load goes directly to the bottom during the months January - February and if an important accumulation occurs of dissolved nutrients from the water to the bottom during those months.
7. Recommendations for future research

The recommendation for future research are mentioned in the foregoing section and are listed below.

1. Field research to detect the relation between extinction coefficient, weather conditions, local water depth and bottom composition in the coastal area.

2. Research directed to various mechanisms causing the loss of phytoplankton especially in the near shore region of the Dutch coastal area during summer and fall.

3. Research directed to get an improved estimation of the residual transport in the southern part of the Dutch and Belgian coastal area.
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Figure 1  Carbon and nutrient cycles in the model SEAWAQ
Figure 1A FORCING FUNCTIONS
Figure 2 Statistically homogeneous compartments of water quality parameters determined bij RWS Directie Noordzee.
Figure 3 The partitioning of the Dutch coastal area as used in the model together with locations of the WAKWON monitoring program
Figure 4: Annual variation of Diatoms computed by the model version 1.0 for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 5  Annual variation of Other Phytoplankton computed by the model version 1. For the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 6  Annual variation of Chlorophyll-a computed by the model version 1.0 for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 7  Annual variation of Primary Production computed by the model version 1. for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 8  Annual variation of Silicate computed by the model version 1.0, for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 9 Annual variation of Total Phosphorus computed by the model version 1.0 for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
ORTHO-PHOSPHORUS (MG/M3)


Results of version 1.0

Figure 10 Annual variation of Ortho-Phosphorus computed by the model version 1. for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 11: Annual variation of Total Nitrogen computed by the model version 1 for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 12 Annual variation of Nitrogen: NO$_2$-N + NO$_3$-N + NH$_4$-N computed by the model version 1.0 for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 13 Annual variation of Detritus computed by the model version 1.0 for the seven compartments. The vertical bars indicate monthly means and extremes of observed values.
Figure 15 A comparison between computed and measured phytocarbon biomas per square meter. Data are from Fransz and Gieskes 1984.
Figure 16  Annual variation of Diatoms computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 17  Annual variation of Diatoms computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 18  Annual variation of Other Phytoplankton computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 19  Annual variation of Other Phytoplankton computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 20  Annual variation of Chlorophyll-a computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 21 Annual variation of Chlorophyll-a computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14).
MORTALITY RATE FACTOR ( - )

Figure 22  Annual variation of Mortality Rate Factor computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 23 Annual variation of Mortality Rate Factor computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 24  Annual variation of Primary Production computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 25  Annual variation of Primary Production computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 26  Annual variation of Silicate computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
SILICATE (MG/M3)

compartment

VII

VI

V

IV

III

II

I

0 31 60 90 120 150 180 210 240 270 300 330 365

Time (days)

1000 500 0

Vertical bars: Minimum and maximum yearly mean from measurements 1975-1983

Line: Computation.

Results of version 2.1

Figure 27 Annual variation of Silicate computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 28. Annual variation of Total Phosphorus computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15).
Figure 29  Annual variation of Total Phosphorus computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 30 Annual variation of Ortho-Phosphorus computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 32  Annual variation of Total Nitrogen computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 33 Annual variation of Total Nitrogen computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
NITROGEN: NO₂-N + NO₃-N + NH₄-N (MG/M3)

compartment

VII

VI

V

IV

III

II

I

Time (days)

0 31 60 90 120 151 181 212 243 274 304 334 365

Line: Computations. Vertical bars: minimum and maximum yearly mean from measurements 1975-1983

Results of version 2.0

Figure 34 Annual variation of Nitrogen: NO₂-N NO₃-N + NH₄-N computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 35 Annual variation of Nitrogen: NO$_2$-N + NO$_3$-N + NH$_4$-N computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 36  Annual variation of Detritus computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
Figure 37  Annual variation of Detritus computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 38  Annual variation of Organic Sediment computed by the model version 2.0 in which the mortality rate factor RM is based on equation (15)
ORGANIC SEDIMENT (GC/M2)

Figure 39  Annual variation of Organic Sediment computed by the model version 2.1 in which the mortality rate factor RM is based on equation (14)
Figure 40 Comparison between calculated and measured salinity distribution. The computed distribution is the result of the model DELWAQ, when based on watercurrents as calculated by the model ESTFLOW (winter situation)