MODELLING WATER TRANSPORT AND PHOSPHORUS EUTROPHICATION IN AN INTERCONNECTED LAKE SYSTEM

A scenario study

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STELLINGEN

1. Voor het terugdringen van de eutrofiëring in het zuid-west Friese boezemsysteem zijn grote reducties nodig van fosfaatconcentraties in water aangevoerd vanuit het IJsselmeer, vanuit de omliggende polders en vanaf de hogere gronden ten oosten van het gebied. Het nemen van maatregelen als bijvoorbeeld baggeren en verdergaande emissiereductie bij rioolwaterzuiveringsinstallaties is dan ook slechts zinvol na reductie van de bovengenoemde belasting (dit proefschrift).

2. Uit het vergelijken van de resultaten van bemonsteringsprogramma's van een tweetal instellingen, betreffende de totaal-fosfaatconcentraties in het Tjeukemeer en het Slotermeer gedurende de jaren 1985, 1986 en 1987, blijkt dat er verschillen kunnen optreden, die leiden tot een niet overeenstemmend beeld van fosfaatnivo's. Het bij het modelleren nastreven van een zo goed mogelijke "fit" op de fosfaatgegevens van één van de instellingen dient derhalve als zinloos te worden beschouwd (dit proefschrift).

3. Het verdient aanbeveling bij het beheer van polders in de toekomst de aandacht te richten op integraal kwantitatief en kwalitatief beheer en op het opstellen van dynamische fosfaatbalansen, die ten dele gebaseerd zijn op onderzoek naar processen als uitspoeling, afspoeling, resuspensie, accumulatie en "doorslag" van fosfaat (dit proefschrift).

4. Het verdient aanbeveling om het gezamenlijk effect van processen als nalevering, bezinking en resuspensie van fosfaat te omschrijven als netto uitwisseling of netto verlies. De door Prairie gebruikte termen als sedimentatie of netto sedimentatie kunnen leiden tot begripsverwarring.
   Prairie, Y.T., 1989. Statistical models for the estimation of net phosphorus sedimentation in lakes. Aquatic sciences 51/3: 192-210.

5. Verontreiniging is overal en het milieu selecteert nog steeds (vrij naar Beijerinck en Baas Becking).

6. Uit het vrijwel nalaten van het nemen van maatregelen tegen de toename van het broeikaseffect door de Amerikaanse overheid kan geconcludeerd worden dat de spreuk "The sky is the limit" nog niet tot het federale overheidsapparaat daar is doorgedrongen.

7. Gezien de veelal slechte projectie van en de handgeschreven of te klein getypte tekst op zogenaamde overheadsheets, zou het presenteren ervan op wetenschappelijke congressen en symposia verboden moeten worden.

8. Daar de mondelinge presentatie van wetenschappelijke gegevens vaak niet boeiend is, verdient het aanbeveling een cursus dramatische vorming in het wetenschappelijke onderwijs verplicht te stellen.

9. In advertenties en sollicitatiegesprekken ten behoeve van het aantrekken van universitaire medewerkers wordt ten onrechte veelal niet of nauwelijks gelet op de didactische kwaliteiten van de kandidaat. Indien van de kandidaat een aanzienlijke onderwijsbijdrage wordt verwacht, verdient het aanbeveling deze kwaliteiten te toetsen in bijvoorbeeld een proefcollege.

10. De roman "De morgen loeit weer aan" (Uitgeverij De Bezige Bij, 1988) van de schrijver Tip Marugg, genomineerd voor de AKO-literatuurprijs in 1988, kan als één van de naoorlogse hoogtepunten in de Nederlandse literatuur beschouwd worden. Het niet toekennen van de prijs aan deze schrijver zegt derhalve veel over de jury en weinig over de kwaliteiten van het boek.

11. Gezien het hoge percentage echtscheidingen en de soms daaruit voortkomende traumatische gevolgen, verdient het aanbeveling in het huwelijksboekje met kleine letters te vermelden: "Het huwelijk kan schadelijk zijn voor de volksgezondheid".

12. Bèta-wetenschappers zonder maatschappelijke en culturele belangstelling doen zichzelf en de samenleving ernstig tekort.

13. Bûter, brea en griene tjiis, wa't dat net sizze kin is gjin oprjochte Fries.

14. Horeca est.

Stellingen behorende bij het proefschrift:
Modelling water transport and phosphorus eutrophication in an interconnected lake system
A scenario study
Harry van Huet, 26 april, 1991.

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Abstract

ABSTRACT

The water in the south-western Frisian lake district is highly eutrophicated. Summer chlorophyll-*a* concentrations often exceed 150 $\mu g.l^{-1}$, while total phosphorus (TP) concentrations are mostly above 0.2 $mg.l^{-1}$. Therefore, a research project was started in 1984 to study the origin and dynamics of phosphorus (P) in the area. The nutrient P was chosen because reducing TP concentrations was believed to result in favourable conditions for restoration of the aquatic ecosystem. The objective of the study was to model the TP dynamics and to use the model for the simulation of management reduction scenarios. In order to achieve this objective, three problems had to be solved. Firstly, information about the water transport, especially in the boundary canals, was poor. This problem was solved by the application of a wind driven water transport model using water levels in the boundary canals. Secondly, the lack of large-scale information about the TP loads from the surrounding polders was solved by an intensive monitoring program. Thirdly, knowledge about the distribution of TP in sediments and about TP exchange processes between water and sediments had to be assessed. The simulations with the dynamic TP mass balance model resulted in TP balances during three periods, showing that there were two main sources in the area: from the surrounding polders and from Lake IJssel. Moreover, management simulation scenarios showed that 75% TP concentration reductions in the external loads would be necessary to achieve the 0.15 $mg.l^{-1}$ TP concentration standard and incidentally the 0.07 $mg.l^{-1}$ target concentration.

Samenvatting

HET MODELLEREN VAN WATERTRANSPORT EN FOSFOREUTROFIËRING IN EEN KANALEN-MERENSYSTEEM Een scenario-studie

Dit proefschrift gaat in op het eutrofiëringsprobleem in het merengebied van zuid-west Friesland. Eutrofiëring kan gedefinieerd worden als de biologische reactie van aquatische ecosystemen op het verrijken met nutriënten. De gevolgen van eutrofiëring kunnen zijn ongewenste algenbloei, het afnemen van het doorzicht, zuurstoftekorten en vissterfte. Eutrofiëring in oppervlaktewateren betekent vaak een verandering in de samenstelling van de waterflora en -fauna. Bepaalde soorten gaan overheersen, zoals in Nederland o.a. blauwwieren en brasem.

Ook in de Friese meren is de waterkwaliteit als gevolg van het eutrofiëringsproces verslechterd. Onder andere om inzicht te verkrijgen in dit proces werd in 1984 gestart met onderzoek, het zogenaamde FosFri-project, een samenwerkingsproject van het Limnologisch Instituut te Oosterzee, de Universiteit Twente en de Provincie Friesland. Het project werd gefinancierd door de laatstgenoemde instelling en het ministerie VROM. Verwacht werd dat in het zuid-westelijk gedeelte van de Friese boezem eventueel te nemen maatregelen het snelst effect zouden hebben. Vandaar de concentratie van het onderzoek op dit gebied. Het onderzoek richtte zich op abiotische en biotische processen. De resultaten beschreven in dit proefschrift vormen een onderdeel van het abiotisch gedeelte. Het belangrijkste doel van dit deel was te komen tot een inventarisatie van de fosforstromen in het gebied en tot het modelmatig doorrekenen van beheersscenario's. Het veldprogramma daartoe werd uitgevoerd gedurende de jaren 1984-1987. Het project werd eind 1989 afgerond.

In dit proefschrift kunnen een viertal gedeelten onderscheiden worden. Voor een schematische weergave, zie tabel 1.

Tabel 1. Indeling van het proefschrift. De cijfers verwijzen naar de betreffende hoofdstukken.

Inleiding	Monitoring programma	Modellen	Beheersopties
1 (2,3,4,5,6,7)	2,3,4,6	5,6,7	7,8

In hoofdstuk 1 worden kort enkele eerder genomen maatregelen belicht die in Friesland genomen zijn in het kader van de eutrofiëringsbestrijding. In dit hoofdstuk wordt ook uitgelegd waarom het onderzoek zich heeft gericht op het nutriënt fosfor en waarom voornamelijk totaal-fosfaat concentraties (TP) gemeten zijn. Ook wordt in dit hoofdstuk het doel van het gehele project nader omschreven: namelijk te komen tot inzicht in de oorzaken van de toenemende eutrofiëring in het Friese boezemwater en vervolgens tot een goed onderbouwde beleidsadvisering ter beperking van de eutrofiëring. Opgemerkt zij daarbij dat het laatste deel van deze omschrijving in de loop van het onderzoek meer en meer gelezen werd als het doorrekenen van beheersscenario's.

In dit hoofdstuk worden ook de grote lijnen van de modelmatige benadering van het abiotisch onderzoek toegelicht. Die benadering betekende dat een drietal problemen opgelost moest worden. Er waren namelijk geen gegevens bekend over: a) processen en P-gehaltes in sediment; b) tijdvariabele TP vrachten vanuit de polders; c) debieten in de randkanalen van het open systeem. Dat betekende dat een keuze gemaakt moest worden voor enkele niet eerder toegepaste oplossingsmethoden.

In hoofdstuk 2 is een onderscheid gemaakt tussen een zomer- en een wintersituatie in het gebied, zo kenmerkend voor het bestudeerde ecosysteem. Ten gevolge van de klimatologische processen ontstaat er in het algemeen in de zomer een neerslagtekort en in de winter een neerslagoverschot. Dientengevolge wordt 's zomers chloride-rijk IJsselmeerwater ingelaten in het kanalen-merengebied (en vindt vervolgens inlaat plaats in de polders) en wordt 's winters humus-rijk water uit de polders gepompt op de boezem (en wordt boezemwater op het IJsselmeer gepompt of stroomt door vrij verval af op de Waddenzee).

Hoofdstuk 2 bevat tevens een overzicht van de resultaten van de metingen gedurende de eerste drie onderzoeksjaren. Drie onderwerpen kunnen worden onderscheiden: het meten van waterkwaliteitsvariabelen als TP en chloride (Cl^-), het meten van de horizontale en vertikale verspreiding van TP in sedimenten en het meten van TP-concentraties in polderwater en het kwantificeren van TP-vrachten uit de polders.

Het doel van de metingen is de gegevens te gebruiken voor de modellen en voor het verkrijgen van inzicht in de oorsprong van het water en fosfaat in het onderzoeksgebied.

Gedurende de onderzoeksjaren variëren de gemiddelde TP-concentraties in het Tjeukemeer, de Groote Brekken en het Slotermeer van 0.23 tot 0.29 $mg.l^{-1}$. De concentraties gedurende het zomerhalfjaar liggen ver boven de Nederlandse norm (1985-1989) van 0.15 $mg.l^{-1}$. De hoogste jaargemiddelde Cl^--concentratie is 153 $mg.l^{-1}$, in 1986 in de Groote Brekken, ten gevolge van een inlaat van IJsselmeerwater. De laagste jaargemiddelde Cl^--concentratie is 59 $mg.l^{-1}$, in 1987 in het Tjeukemeer, ten gevolge van een natte zomer gepaard gaande met een geringe inlaat van IJsselmeerwater en een grote watertoevoer uit de polders.

Gedurende 1984-1987 zijn 10 keer sedimenten op 34 locaties in het onderzoeksgebied bemonsterd en de TP-gehaltes bepaald (hoofdstuk 3). Niet eerder is op dermate grote schaal een onderzoek verricht naar de TP-gehaltes in de sedimenten van de Friese boezemwateren. Het gemiddelde gehalte varieert van 0.01 tot 7.78 $mg.g^{-1}$ drooggewicht. Er zijn drie groepen meetstations onderscheiden: in meren, mondingen van kanalen en in de kanalen zelf. Het hoogste TP-gehalte is gemeten in de sedimenten van de stations in de mondingen (0.86 $mg.g^{-1}$ drooggewicht). De gehaltes in kanaal- en meersedimenten zijn respectievelijk 0.55 en 0.42 $mg.g^{-1}$ drooggewicht. De laagste gehaltes zijn in zanderige sedimenten gemeten, de hoogste in modderige en er tussenin in veenachtige sedimenten. In het algemeen nam het TP-gehalte af met de diepte. Vermoed wordt dat de watersnelheid en dientengevolge sedimentatie invloed heeft op het TP-gehalte van meersedimenten.

De TP-concentraties in uitgeslagen polderwater én in het water in poldersloten, alsmede TP-vrachten vanuit de polders naar het boezemsysteem zijn beschreven in hoofdstuk 4. Een gedetailleerd onderzoek is verricht in de Echtener Veenpolder. De bruto TP-(jaar)vrachten vanuit deze polder variëren van 1.3 tot 1.83 kg P. ha^{-1} poldergebied. Van 11 andere polders variëren de bruto vrachten van 1.01 tot 4.13 kg P. ha^{-1}. Met name de wintervrachten zijn relatief hoog. Deze bruto vrachten worden op de boezem geloosd. Ook dit onderzoek werd op deze schaal niet eerder uitgevoerd in Friesland.

Het onderzoek in de Echtener Veenpolder leverde nog enkele andere nieuwe aspecten op. Ook de netto vrachten (bruto vrachten minus de inkomende vrachten) zijn namelijk gekwantificeerd. Deze variëren van 0.63 tot 1.48 kg P. ha^{-1}. Hieruit, en uit twee andere detail-onderzoekingen, kan een bijdrage van processen in de polder worden geconcludeerd. Deze processen zijn waarschijnlijk voornamelijk uitspoeling en afspoeling. Een bijdrage van de polder zelf wordt bevestigd doordat gedurende de onderzoeksjaren de gemiddelde TP-concentratie in uitgeslagen water van de Echtener Veenpolder hoger is dan ingelaten boezemwater (respectievelijk 0.37 en 0.28 $mg.l^{-1}$). Het Tjeukemeer kan omschreven worden als een typisch poldermeer: het ontvangt in het onderzoeksgebied relatief zeer veel polderwater.

De resultaten van de veldmetingen zijn gebruikt voor twee modellen: ten eerste voor een hydrodynamisch model en ten tweede voor een (Cl^- en TP) massa-balans model. Het opstellen en doorrekenen van het water transport model was met name om praktische redenen noodzakelijk. Het zuid-westelijke merengebied is een deel van de Friese boezem. Het is dus een open systeem. Datasets van de watersnelheden/debieten in de randkanalen zijn niet voorhanden en het meten van deze grootheden zou zeer arbeidsintensief en duur zijn. Toch zijn deze debieten nodig als invoergegevens voor het massa-balans model. Het doorrekenen van het hydrodynamische model is bedoeld om de gewenste debieten te kwantificeren (hoofdstuk 5). Aan dit transportmodel zijn de (gemeten) uurgemiddelde waterhoogtes in de randkanalen en uurgemiddelde windsnelheden en -richtingen opgelegd. Het model is gecalibreerd met behulp van waterhoogtes op drie locaties in het systeem. Een gevoeligheids- en onzekerheidsanalyse toont aan dat de modelgevoeligheid laag is voor modificaties in de waarde van de windexponent en tamelijk hoog voor de modificaties in de waarde van de bodemruwheidscoëfficiënt. Aldus toont deze analyse het nut aan van gedetailleerde invoerdata en wordt het gebruik van een gedetailleerd model gerechtvaardigd. De gevoeligheid voor ruis op de opgelegde waterhoogtes is gematigd, hetgeen als indicatie mag worden beschouwd dat meetfouten niet al te zeer leiden tot grove fouten in de berekende debieten. Simulaties met dag- en weekgemiddelde wind- en waterhoogtedata leiden tot ongewenst verlies van detail. Met het model zijn drie periodes doorgerekend, met een totale lengte van 25 maanden.

Met het chloride massa-balans model (hoofdstuk 6) zijn de drie periodes doorgerekend om de nauwkeurigheid van de met het transportmodel berekende debieten te verifiëren. Uit het vergelijken van berekende en gemeten Cl^--concentraties kan geconcludeerd worden dat de voor dit doel berekende debieten voldoende nauwkeurig zijn.

Aldus zijn deze debieten ook gebruikt als invoergegevens voor het TP massa-balans model, dat door middel van een term voor de schijnbare bezinkingssnelheid, waarin alle interne processen die het P-gehalte beïnvloeden zijn samengevat, verschilt van het Cl^--model. In een analyse is nagegaan of het weglaten van een dispersieterm in de modellen gerechtvaardigd is. Met beide modellen zijn concentraties in drie meren berekend: Tjeukemeer, Groote Brekken en Slotermeer. Verwacht wordt dat het vierde grote meer in het gebied, de Koevorder, nagenoeg de zelfde reakties vertoont als de Groote Brekken. De resultaten van het TP model tonen aan dat de gemeten en berekende concentraties tamelijk goed overeenkomen. Een verdere analyse toont aan dat de gevoeligheid voor modificaties in de schijnbare bezinkingssnelheid het laagst is in de simulaties voor de Groote Brekken en het grootst in die voor het Slotermeer. Dit is te verklaren uit de invloed van de verblijftijd van water in deze meren.

Met behulp van het TP model konden balansen van de drie meren worden opgesteld. Uit deze balansen blijkt dat de grootte van de externe belasting afneemt in de volgorde Tjeukemeer, Groote Brekken en Slotermeer. Twee externe posten overheersen de balansen, namelijk aanvoer van (polder)water uit het gebied ten oosten van het Tjeukemeer en aanvoer van water uit het IJsselmeer. Uiteindelijk is het TP model gebruikt om beheersscenario's door te rekenen (hoofdstuk 7). De eerste, niet in het proefschrift opgenomen, simulaties toonden aan dat grote TP-reducties in IJsselmeerwater en in polderwater nodig waren. Daarom is in hoofdstuk 7 slechts gerekend met 75% reducties. Overige redukties (bijvoorbeeld in effluent van de twee waterzuiveringsinstallaties) leidden slechts tot zeer marginale effecten. Bij de simulaties is gelet op de TP norm van 0.15 $mg.l^{-1}$ en een streefwaarde van 0.15 en 0.07 $mg.l^{-1}$. Het blijkt dat slechts een combinatie van de 75%-reducties in IJsselmeerwater én in polderwater leidt tot TP-concentraties onder de 0.15 $mg.l^{-1}$ in het Tjeukemeer en in de Groote Brekken, terwijl de 0.07 $mg.l^{-1}$ streefwaarde in deze meren slechts incidenteel wordt bereikt. Het effect in het Slotermeer is geringer, hetgeen de relatief geïsoleerde ligging van dit meer opnieuw bevestigt. In een analyse is geschat wat per meer de effecten zouden kunnen zijn van een afname per eenheid belasting op de concentratie. Waarschijnlijk zullen de werkelijk te bereiken effecten aanvankelijk nog wat minder groot zijn ten gevolge van een tijdelijke toename van de interne belasting na de te nemen maatregelen. De korte-termijn resultaten van het eenvoudige TP-model komen goed overeen met een soortgelijk lange-termijn model, dat gebruikt is bij onderzoek van de Universiteit Twente.

Hoofdstuk 8 bevat een terugblik op de benadering die gebruikt is. Met name is enige aandacht besteed aan de methode en aan verder onderzoek dat voor de modellering van belang kan zijn. In dit hoofdstuk wordt aannemelijk gemaakt dat meer gedetailleerde en aanvullende gegevens, bijvoorbeeld een betere benadering van de fluctuaties in de belastingen uit de polders en gegevens omtrent nalevering van P door het sediment, de met het TP-model voorspelde trends niet wezenlijk zullen beïnvloeden.

Tevens bevat hoofdstuk 8 een nadere beschouwing van processen in de polders (uitspoeling, afspoeling, opslag) en suggesties voor verder onderzoek, dat met name inzicht kan geven in de grootte van de bijdrage van deze processen en de manier waarop in de praktijk de bruto vrachten gereduceerd zouden kunnen worden.

Summary

SUMMARY

This thesis deals with the phosphorus (P) eutrophication problem in the south-western lake district of Friesland. Eutrophication can be defined as the biological reaction of aquatic ecosystems to nutrient enrichment. It can result in algal blooms, decrease in transparency, oxygen deficiency, fish kills and, generally, a shift in phytoplankton, zooplankton and fish species.

The water quality in the sw lake district has deteriorated due to eutrophication. However, the chances for restoration in this part of the Frisian surface water network (the so-called 'boezem') seemed relatively good. This was the main reason to start research in this area. The research objective, for the project as a whole (the so-called FosFri-project), was the simulation of scenarios for management and policy. This thesis refers to the abiotic part of the project. A monitoring program in the canal-lake system and in the surrounding polders was carried out (from 1984 to 1987), while a modelling program was started at the Limnological Institute, Tjeukemeer Laboratory, Oosterzee (up to 1989). These investigations aimed at the P dynamics in the area and at modelling P reduction scenarios. Four parts can be distinguished in this thesis, see Table 1.

Table 1. Organization of the thesis. The figures correspond with the chapters.

Introduction	Monitoring program	Models	Management options
1 (2,3,4,5,6,7)	2,3,4,6	5,6,7	7,8

The general introduction (Chapter 1) concerns a brief survey of the already existing eutrophication research programs in the Province of Friesland. Also, in this chapter it is explained why this thesis focuses mainly on total phosphorus (TP). Furthermore, Chapter 1 contains a further definition of the study objective, which is to gain an insight into the causes of the increase of eutrophication in the Frisian surface waters and to advise the water quality decision makers in the Province of Friesland on reducing eutrophication. Also, in Chapter 1 the approach of the abiotic research is emphasized. The modelling approach led to three main problems to be solved, because no information was available about: a) sedimentary TP contents and processes; b) time variable TP loads from surrounding polders; and c) discharges in the boundary canals of the open water network system. This led to some new methods in solving the problems.

In Chapter 2 a distinction is made between summer and winter conditions. Generally, in summer a precipitation-deficit occurs and chloride-rich water from IJsselmeer is let in into the system. In winter, when rainfall exceeds precipitation, humic-rich water from the surrounding polders is pumped into the system. Consequently, the hydrochemistry of the area is strongly influenced by the man-made water regime.

Also in Chapter 2, an overview of the preliminary results of the 1984-1986 monitoring program is given, while a water transport model is introduced. The monitoring program focuses on three main subjects. Firstly, water quality parameters, mainly TP and chloride (Cl^-). Secondly horizontal and vertical distribution of TP in sediments and, thirdly, external P loading from surrounding polders. The objective of the measurements is to use the data for the models and for obtaining insight into the trophic level of the aquatic ecosystem, and into the origin of phosphorus.

During the years 1984-1987, the mean TP concentrations in the lakes Tjeukemeer, Groote Brekken and Slotermeer range from 0.23-0.29 $mg.l^{-1}$. Summer concentrations are far above the water quality standard 1985-1989, laid down by the Water Action Program of the Dutch Government (0.15 $mg.l^{-1}$). The highest annual mean Cl^- concentration is 153 $mg.l^{-1}$, measured during 1986 in Groote Brekken, a result of inflow of IJsselmeer water. The lowest mean concentration is 59 $mg.l^{-1}$, measured during 1987 in Tjeukemeer, a result of large quantities of polder water pumped into this lake and of a minimal inflow of water from IJsselmeer.

The sedimentary TP investigations (Chapter 3) cover 34 stations, which are sampled 10 times during 1984-1987. Investigations on this scale concerning sedimentary TP contents are absolutely new in the Frisian surface waters. These TP contents vary from 0.01 - 7.78 $mg.g^{-1}$ dry weight (DW). Three groups of stations are distinguished: stations in lakes, stations located at inflow/outflow sites and in canals. The mean TP content is highest in inflow/outflow sediments (0.86 $mg.g^{-1}$ DW), moderate in canal sediments (0.55 $mg.g^{-1}$ DW) and lowest in lake sediments (0.42 $mg.g^{-1}$ DW). The TP contents in sandy sediments are lowest, highest in muddy sediments and moderate in peaty sediments. Generally, TP contents decrease with depth. It appears that canals with relatively low water velocities have higher sedimentary TP contents than canals with higher water velocities, probably due to differences in sedimentation.

The contribution of TP-loads from polders to the eutrophication in the canal-lake system is described in Chapter 4. The Echtener Veenpolder, located south of Tjeukemeer and the largest polder in the area, is investigated intensively. The Echtener Veenpolder gross annual TP-loads range from 1.3 to 1.83 kg $P.ha^{-1}$ polder area. Also, annual gross loads of 11 other polders are quantified, these loads range from 1.01 to 4.13 kg $P.ha^{-1}$. Especially winter loads from polders were high. These gross loads are discharged to Tjeukemeer. Information about loads from polders on this scale is new in the Province of Friesland.

The investigations in the Echtener Veenpolder resulted in some more new aspects of the polder influence. Net loads (gross loads minus incoming loads) from the Echtener Veenpolder range from 0.63 to 1.48 kg.P ha^{-1}, indicating that there is a TP contribution from processes inside the polder, which are probably mainly leaching and surface runoff. This polder contribution is confirmed by two other polder experiments, and by the fact that the mean TP concentration in water from the Echtener Veenpolder is higher than in Tjeukemeer water that is let in (0.37 and 0.28 $mg.l^{-1}$, respectively). Tjeukemeer can be described as a typical polder lake, because it receives relatively much polder water.

The results of the polder investigations are used as input for models that describe the water transport and the TP and Cl^- dynamics in the area. For modelling the TP dynamics discharges in the boundary canals of the sw lake district are needed. However, continuously measuring discharges is laborious and expensive. Therefore, a detailed wind-driven hydrodynamic model is applied (Chapter 5), in order to quantify the boundary discharges. The forcing functions of this model are the hourly mean water levels in the boundary canals and the hourly mean wind velocities and wind directions. Model tuning is done by comparing observed and measured water levels of three water stations inside the system. The model sensitivity is low for modifications of the wind exponent value and rather high for the bottom roughness coefficient, while the sensitivity for noise at the imposed water levels is moderate, indicating that registration errors do not lead to big errors in the calculated discharges. Simulations with daily or weekly mean values of wind and water level data result in undesirable loss of detail, indicating that detailed input data as well as the detailed model is useful. Three periods are simulated, together covering 25 months.

Simulations during the three periods with a Cl^- model, in which Cl^- is regarded as a conservative mass, show a good similarity between measured and calculated Cl^- concentrations (Chapter 6). Subsequently, it is concluded that the quantified discharges in the boundary canals are sufficiently accurate for the purpose of model input.

These discharges are also used as input data for the dynamic TP mass balance model. This model is similar to that of chloride; the only difference is a net loss term, that covers all internal processes that might influence the P contents. An analysis showed that dispersion terms in the models can be neglected. Both models focus on three lakes: Tjeukemeer, Groote Brekken and Slotermeer. It is expected that the results for the fourth main lake in the area, Koevorder, agree well with the Groote Brekken results. The TP model results show a fairly good similarity between measured and simulated concentrations. The sensitivity for modifications in the apparent settling rate is lowest in simulations of Groote Brekken and highest in simulations of Slotermeer, due to the influence of the water residence times in these lakes.

P balances are the result of the dynamic model. These balances show that the external loads to Tjeukemeer are highest, moderate to Groote Brekken and lowest to Slotermeer, while two loads dominate: from polders and from IJsselmeer. The model is used to simulate P reduction scenarios (Chapter 7). Apparently, only large TP reductions were likely to have effects. Therefore, only 75%-reduction scenarios are simulated. The calculations focus on TP reductions in water from IJsselmeer and from polders. A TP standard and a target level are defined, respectively 0.15 and 0.07 $mg.l^{-1}$. The simulations show that only a combination of reduction in both external loads will lead to achieving the 0.15 $mg.l^{-1}$ standard in Tjeukemeer and Groote Brekken, while incidentally the 0.07 $mg.l^{-1}$ target level is reached. Slotermeer responds only to a small extent to these measures. Probably, the short term effects will be partly counteracted by a temporary increase of internal loading. In an analysis for each lake the effect of a theoretical load reduction to the TP concentration is examined. The short-term simulation results predicted by the simple mass balance model agree well with long-term predictions of a less detailed hydrodynamic model, which is used at Twente University.

In Chapter 8, a final review is given of the approach and the methods. It is made plausible that the trends, as simulated by use of the TP mass balance model, would not have been influenced greatly if additional information had been available. For example, detailed information about the fluctuations in polder loads and about P release data.

Chapter 8 also briefly reports the processes in the polders, such as runoff, leaching and accumulation. Also suggestions are given for further research, which could be of value for a better insight into the extent of the contribution of these processes and the way in which gross loads might be reduced.

Chapter 1

General introduction

GENERAL INTRODUCTION

Eutrophication and restoration

The term eutrophication can be defined as the biological reaction of aquatic ecosystems to nutrient enrichment (Marsden, 1989). Eutrophication abatement often concentrates on reduction of phosphorus (P) sources. P is widely accepted as the critical nutrient in determining the degree of lake eutrophy. The measurement of biologically available P, which would be the most useful determinant, is problematic, while total phosphorus (TP) is easily measured (Marsden, 1989). Therefore, for practical reasons, most strategies to control phosphorus inputs into lakes are based on TP data.

In general, the objective of lake restoration in The Netherlands is a reduction of the phytoplankton standing crop, a shift from blue-green algae towards green algae, higher transparency values, and finally, a new stable equilibrium between several communities, including zooplankton and fish species.

In the 1970's the strategy to reduce P levels in The Netherlands' surface waters focused mainly on reducing P in detergents and dephosphorization of waste water. However, in the 1980's it became clear that a more integrated approach was necessary. For example, diffuse sources and internal loading had to be considered too. Therefore in many regions integrated studies started.

Eutrophication research in Friesland

Two institutions in Friesland have monitoring programs in Tjeukemeer and in the other Frisian surface waters. Since the end of the 1960's the limnology of Tjeukemeer, the largest lake in the south-western Frisian surface water network, has been the main study subject of the Limnological Institute at Oosterzee. Moreover, during 1976-1983 investigations took place in Slotermeer, the second largest lake in the area, by the Department of Public Works and Environment of the Province of Friesland (Province of Friesland, 1984). Consequently, much is known about, TP and orthophosphate (PO_4^{3-}) levels, algal species, growth and bioassays. The results of these programs indicate that the water in the canal-lake system is highly eutrophic.

Since 1979, the water of the two waste water treatment plants in the sw Frisian lake district, at Lemmer and Sloten, has been dephosphorized, resulting in approximately a 90% TP reduction in the effluent. However, this measure did not lead to a reduction of TP levels in the lakes, indicating that further measures were necessary. In order to further investigate the origin and dynamics of P in this area, an integrated approach was needed.

In 1984 the so-called *FosFri-project* started. Three institutions cooperated in this project: the Limnological Institute, the Department of Public Works and Environment of the Province of Friesland, and Twente University. The study done by the Limnological Institute, described in this thesis, focused on the sw part of the Frisian lake district and on the abiotic part of the project. Firstly, this area was chosen because it was expected that a stand-still situation or a decrease of TP concentrations could sooner be achieved in this part of the Frisian water network (CUWVO, 1983). Secondly, an intensive field program could easily be realised as the Limnological Institute at Oosterzee is situated in the study area. The study ended in 1989.

The aim of the study

The main objectives of the whole project were described as follows (De Haan and Claassen, 1983). Firstly, the study aimed at gaining an insight into the causes of the increase of eutrophication in the Frisian surface waters. A second objective was to advise the water quality decision makers in the Province of Friesland on diminishing eutrophication.

The choice that was made for the abiotic part was studying only TP dynamics in the area and not other parameters, such as PO_4^{3-} and chlorophyll-a. The reason for this choice was that in The Netherlands' surface waters a significant correlation was found between TP concentrations and chlorophyll-a. Moreover, there are indications that undesirable blue-greens will no longer dominate if the TP concentrations can be reduced to less than 0.07 $mg.l^{-1}$ (Lijklema *et al.*, 1988). Another reason, although less important, was that some basic information about the other parameters was available from the monitoring programs of the coordinating institutes.

The first main study objective implied that a TP mass balance study would be of great value. The second objective meant that a dynamic mass balance model could be an important tool for simulating management scenarios. Consequently, two operational study objectives can be defined as follows:

- Development/assessment of a dynamic TP mass balance model. This meant that new (field) investigations had to be made.
- By use of this model: simulations of TP reduction scenarios for management purposes. This should lead to a first step and necessary premise for any further control (biological control, sediment P immobilization, etc).

Organization of the research

The definition of the research objectives meant that a detailed mass balance model study became necessary. However, this study had not been done before in the area. Furthermore, modelling was not very easy because of the following reasons. Firstly, there was lack of knowledge about the role of the sediments in the area. Secondly, there are time variable TP loads from surrounding polders. Thirdly, the sw Frisian lake district has open boundaries with the rest of the water network.

The lack of sedimentary TP information meant that a field and laboratory program had to be started on topics such as distribution, release, sedimentation, and resuspension of phosphorus. This thesis describes the TP distribution, both horizontally and vertically, in relation with area site, sediment type and water transport.

Because of the time variable polder loads, an intensive monitoring program started in one large peaty polder south of Tjeukemeer, the Echtener Veenpolder. The purpose was to frequently measure discharges and TP concentrations in discharged polder water in order to quantify gross end net polder loads. This subject was not studied before in the Frisian polders. Moreover, a less detailed study started in eleven other polders in order to compare gross TP loads.

The problem of open boundaries meant that no discharges in these boundary canals were available. These discharges were needed as input data for the TP mass balance model. The problem was solved by the application of a water transport model, using hourly mean values of water levels in the boundary stations and wind data as forcing functions. By use of this model the boundary discharges could be quantified. This is a new approach in a canal-lake system in The Netherlands. In order to verify the model reliability, for example the model sensitivity for noise on the input data (water levels) had to be examined.

All these research objects lead to an intensive and frequent monitoring program in the lakes, interconnecting canals and polders. Also, water level data sets, wind data sets and data of input discharges from IJsselmeer had to be collected in order to support model calibration, tuning and verification, resulting in a highly integrated approach of the eutrophication problem. Fig. 1 shows a schematic overview of the monitoring and data collection program, of the models and the model outputs (see also *Survey of chapters*).

Survey of chapters

All chapters in this thesis contain an *Introduction* and/or an *Area description*, which focus on the themes of each separate chapter. However, some general overlap could not be avoided.

In Chapter 2 a survey is given of the preliminary results of the study, which can be of value to get more insight into the problem definition. The main research items are introduced in this chapter, viz., the sampling program, the external loading from polders and from IJsselmeer, the sedimentary

P-distribution and the assessment of models.

The sedimentary TP distribution is described in Chapter 3, while the polder TP investigations are described in Chapter 4. If possible, a distinction was made between summer and winter loads. Furthermore, it was tried to obtain an impression of the TP contribution of processes inside the Echtener Veenpolder.

In Chapter 5 the wind-driven hydrodynamic model is described. Also, in this chapter a brief survey is given of water velocity measurements. In sub-sections model tuning, parameter sensitivity analysis and model reliability and uncertainty are discussed. This chapter ends with the complete water balances during 25 months, divided into three periods, and water residence times in three lakes.

Chapter 6 deals with the results of the water quality monitoring program and the results of the TP model are described. Special attention is paid to the assessment of a similar chloride model (in order to test the accuracy of the estimated discharges), to the representativeness of TP concentrations and to the model calibration. The TP model is used for calculating TP mass balances for each lake for three periods and for simulating TP reduction scenarios, which is the subject of Chapter 7. Two scenarios are emphasized. The effects on the TP-levels in three lakes during the three periods are described. Finally, the approach, suggestions for further research, polder management options and chances for restoration, are briefly discussed in Chapter 8.

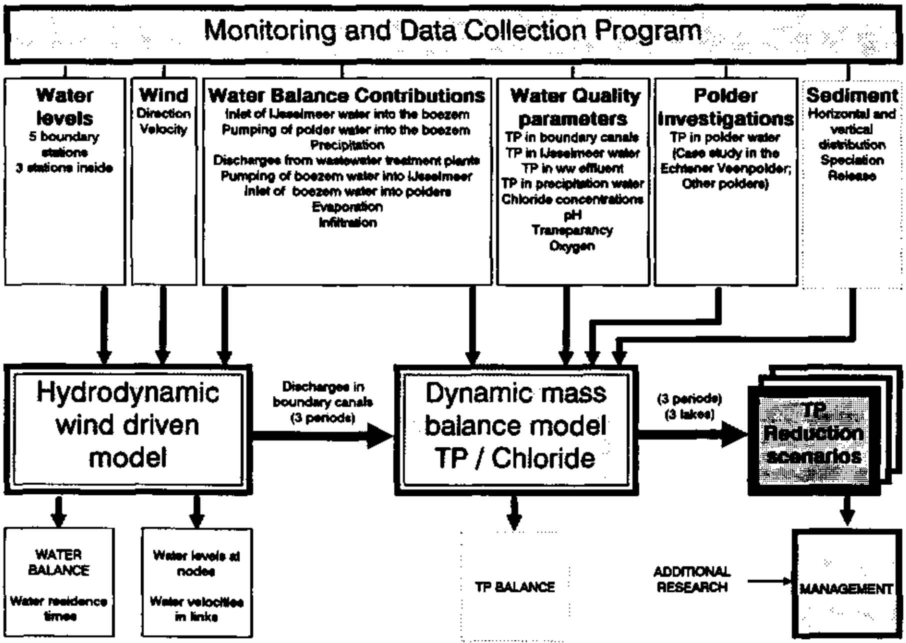

Fig. 1. Schematic overview of the monitoring and data collection program, the models and model results.

Chapter 2

Phosphorus eutrophication research in the lake district of south western Friesland, The Netherlands. Preliminary results of abiotic studies

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PHOSPHORUS EUTROPHICATION RESEARCH IN THE LAKE DISTRICT OF SOUTH WESTERN FRIESLAND, THE NETHERLANDS. PRELIMINARY RESULTS OF ABIOTIC STUDIES

Key words: eutrophication, phosphorus, hydrology, polder lake, modelling, loading, sediments

ABSTRACT

The water quality of the lakes in south western Friesland is influenced by a rather complex hydrology. The purpose of the abiotic part of the eutrophication project, started in 1984 and focused on phosphorus, is to model hydrology and phosphorus dynamics, in order to compare scenarios for policy and management.

A brief survey is given of the preliminary results of the abiotic studies: hydrology, water quality, external loading from surrounding polders, sedimentary phosphorus and internal loading. The two largest lakes, Tjeukemeer and Slotermeer, are compared regarding these processes.

INTRODUCTION

The shallow (1-2 m) lakes - Tjeukemeer, Slotermeer, Brandemeer, Groote Brekken and Koevorder Meer- in the south western part of the province of Friesland are highly eutrophicated. Summer chlorophyll *a* concentrations are often above 150 $\mu g.l^{-1}$ while total P and total N concentrations are mostly above 0.2 $mg.l^{-1}$ and 2.0 $mg.l^{-1}$, respectively (De Haan and Moed, 1984). The lakes area (40 km^2) is part of the 'boezem', a system of interconnected lakes and canals (Fig. 1) with a total water surface area of 140 km^2. The boezem is used hydrologically for regulating the water table of Friesland, for flushing the boezem network or for water supply of the province of Groningen.

Generally during April-October there is inlet of water from IJsselmeer with chloride concentrations up to 300 $mg.l^{-1}$ and simultaneously inflow takes place into the surrounding polders. During October-April humic-rich water from the surrounding polders is pumped into the boezem system while the boezem water can be pumped into IJsselmeer or flows into the Waddenzee. This man-made regime is reflected in, for example, the chloride concentrations in Tjeukemeer: generally high concentrations in the summer period and low in the winter period. The humic-rich water in

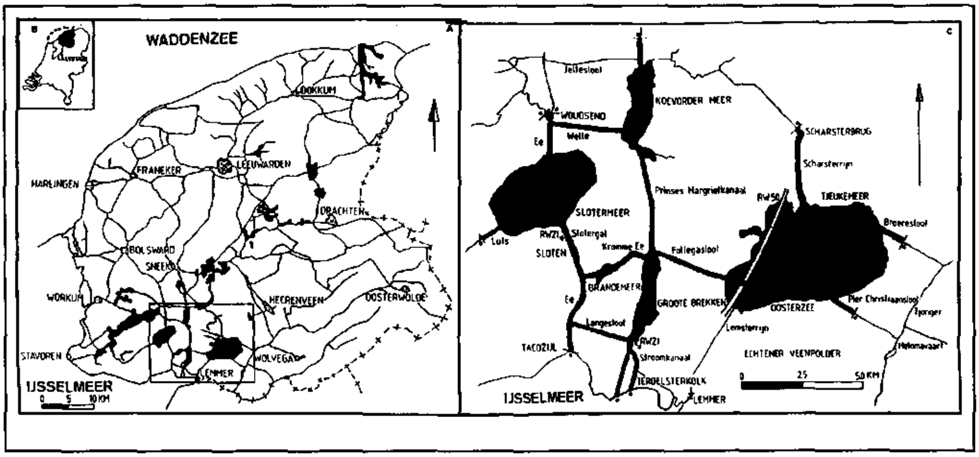

Fig. 1. (A) The Friesian 'boezem', a system of interconnected lakes. (B) Its position in The Netherlands. (C) The south western lake district. ●- : System boundaries; RWZI: Dephosphorisation Units. (from Van Huet *et al.*, 1987).

winter in this lake leads to high optical density values in winter (De Haan and Moed, 1984). There is hardly any upward or downward seepage in the study area, although local seepage may occur. The waste water of mainly housing in the agricultural area is dephosphorized at Lemmer and Sloten (capacities 20 000 and 16 500 inhabitant-equivalents, respectively). However, mainly at some places in the polders, sewage water may directly or indirectly reach the polder ditches. Also in polders manure may directly reach the ditches. For more details about the limnology, hydrology, nutrient concentrations, and algal periodicity, see Beattie *et al.* (1978), Leenen (1982), Moed and Hoogveld (1982), De Haan and Moed (1984), Claassen (1986) and Van Huet *et al.* (1987).

Thus although much research has been done on the trophic relationships especially in Tjeukemeer, up till the 80's hardly any investigations were made in modelling and detailed research of hydrology, external loading, sedimentary P and internal loading. In 1984 a eutrophication project started to study these processes, while the south western part of the boezem system was chosen as a study area because of relatively reasonable chances for restoration. The study of biotic and abiotic processes are the two main activities of research. Finally the integrated results of these studies should lead to scenario simulations for policy and management.

RESULTS AND DISCUSSION

Measuring and modelling hydrology

In meteorologically normal years in summer near Lemmer there is an average inflow of IJsselmeer water of 260×10^6 m^3, while 120×10^6 m^3 of water is pumped out of the polders into the boezem system. In 1985, however, with much rainfall these values were 60×10^6 m^3 and 210×10^6 m^3, respectively. Especially Tjeukemeer received much polder water in this year; as much as 91% of the yearly inflow originated from surrounding polders, being 50% in normal years (Van Huet *et al.*, 1987).

Figure 2 shows the water quantities let in near Lemmer, Tacozijl and Stavoren and the quantities pumped into IJsselmeer near Lemmer and Stavoren during 1984-1986. It can be concluded that during these years there is mainly inflow near Lemmer and mainly pumping near Stavoren. In 1985 inflow of water was low. In 1986 water near Tacozijl was let in, influencing chloride concentrations in Slotermeer (see also Fig. 3A).

It appeared that generally water residence times in Tjeukemeer are about half of those in Slotermeer: 1-2 weeks to 3 months and 2 weeks to 6 months, respectively. Water velocity measurements were done during three characteristic situations: when water of IJsselmeer was let in near Lemmer, when water was pumped into IJsselmeer near Lemmer and Stavoren, and when a fairly hard north eastern wind was blowing. In the case of water inflow at Lemmer, 25-40% of the water was transported through the Follegasloot in direction Tjeukemeer, and 10-15% in direction Slotermeer. In the case of pumping boezem water into IJsselmeer near Lemmer and Stavoren, the Lemmer station pumped out hardly any water that originated from Slotermeer, while 30% originated from Tjeukemeer. Wind appeared to have a great influence on the water transport (Van Huet *et al.*, 1987).

Leenen (1982) used a chloride model to calculate the inflow and outflow of Tjeukemeer in 1971, resulting in a regression line between inflow to the lake and inflow near Lemmer and Stavoren. He concluded that an assumption of instantaneous mixing in the lake, often used in mathematical models, is only a mathematical tool and not realistic.

Brinkman *et al.* (1987) reported upon a water quantity and quality model for the whole boezem network. No wind data were used. The simulation results of these authors for nitrogen were quite satisfactory. Results for phosphorus were not as good, probably because data of internal loading were poor. Scenario calculations showed that flushing the whole boezem system with water of IJsselmeer seemed to have a positive effect by a shift from a dominance of blue-green algae towards one of green algae, due to the shorter residence times. Flushing, however, will lead to higher chloride concentrations in summer. The authors concluded that this macro model could be a valuable tool for an integral water quality management.

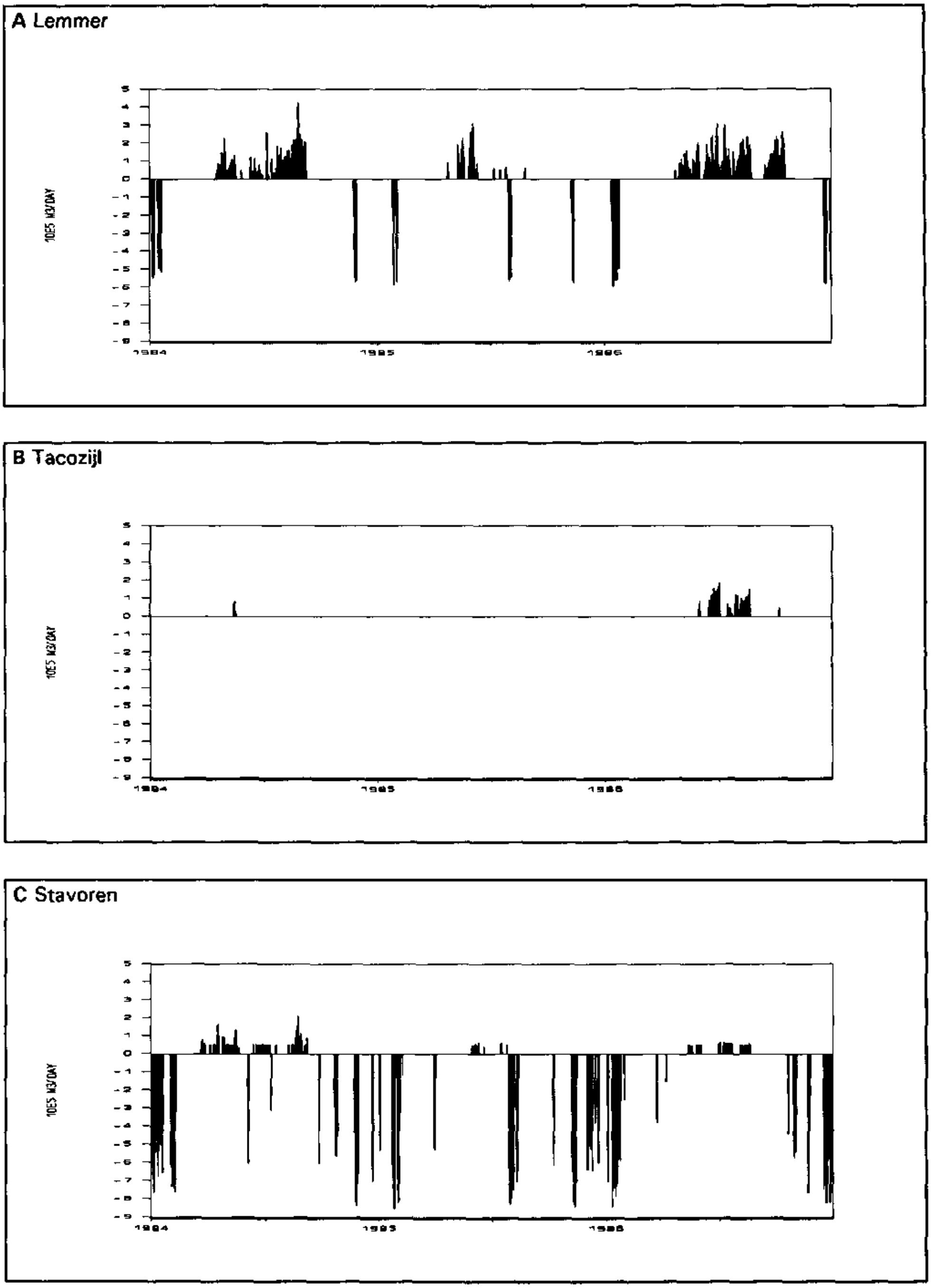

Fig. 2. Water quantities in 10^6 $m^3.d^{-1}$ let in (+) or pumped into IJsselmeer (-) during 1984-1986. (A) Lemmer. (B) Tacozijl. (C) Stavoren.

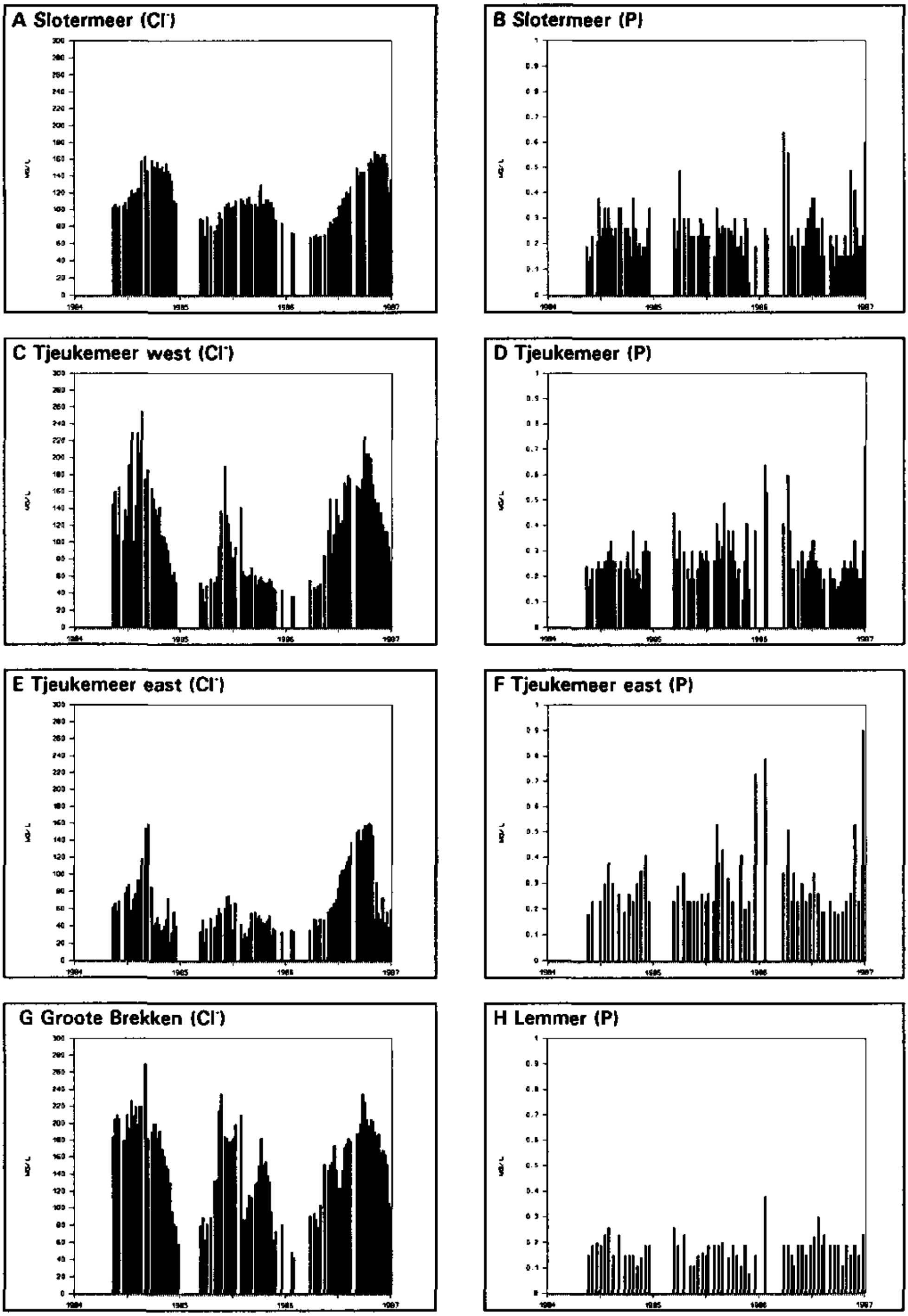

Fig. 3. Cl^- (A,C,E,G) and TP (B,D,F,H) concentrations in $mg.l^{-1}$ during 1984-1986.

Although in general water velocities are low (0-10 cm.s^{-1}), an attempt was made to model hydrology of the south western system using a more detailed network. A node-link mathematical Chezy-model with wind terms (Orlob, 1972; Lijklema and Van Straten, 1977) was used. For the Frisian situation data on water levels at the system boundaries, the partial water balance and wind are needed. The simulation results describe the complete water balance of the system, water velocities (and thus discharges) in all canals and water levels at all nodes. Research is in progress, and results of simulation periods and sensitivity analysis will be reported elsewhere.

Water quality and external loading from polders

The differences in hydrology of Tjeukemeer and Slotermeer are reflected in the Cl^- and total-P concentrations of the lake water. In Fig. 3 these concentrations are given for 1984-1986. The chloride sequence for Slotermeer (Fig. 3A) shows fewer fluctuations than that for Tjeukemeer (Figs. 3C,E). Chloride concentrations in Groote Brekken are highest because this lake is situated close to the inflow location (Fig. 3G).

Total-P concentrations in summer are mostly above 0.15 mg.l^{-1} (Figs. 3B,D), which is the basic water quality standard of this component for the period April-September laid down by the Water Action Programme 1985-1989 of the Dutch Government. The winter total-P concentrations for Tjeukemeer are higher than for Slotermeer (Figs. 3B,D). In winter when polder water was flowing into the east of Tjeukemeer, average total-P concentrations were 0.28 mg.l^{-1} for 1984/1985 and 0.33 mg.l^{-1} for 1985/1986 and 1986/1987 (Fig. 3F). Near the inlet location at Lemmer, while water of IJsselmeer was flowing into the boezem system, the average total-P concentration during 1984-1985 was 0.18 mg.l^{-1} (Fig. 3H). Thus total P concentrations in polder water are higher than in water of IJsselmeer. As Tjeukemeer is receiving more water of surrounding polders than Slotermeer (see also next paragraph), P loading in winter is highest in this lake.

Apart from the above Cl^- fluctuations, the water regime is reflected in the water colour of Tjeukemeer: greenish in summer because of algal growth and brownish in winter because of humic polder water.

During 1984-1986 transparency values of 20-60 cm were measured. The values are a result of algal growth, humic compounds from polder water and/or resuspension by wind. In the same period oxygen concentrations of 5-14 mg.l^{-1} were measured, while the pH ranged from 8.5 to 10.5.

Since 1984 the Echtener Veenpolder, a polder south of Tjeukemeer, was intensively studied (see Fig. 4). Daily discharges were registered and at several locations, especially near the pumping station in the north, water was sampled and analysed for total-P weekly. Less frequently discharges of 14 other polders were registered and water analysed for total-P concentrations.

Figure 5A shows total-P concentrations during September-December 1984 in a canal 30 metres south of the pumping station of the Echtener Veenpolder. The concentrations are increasing in time,

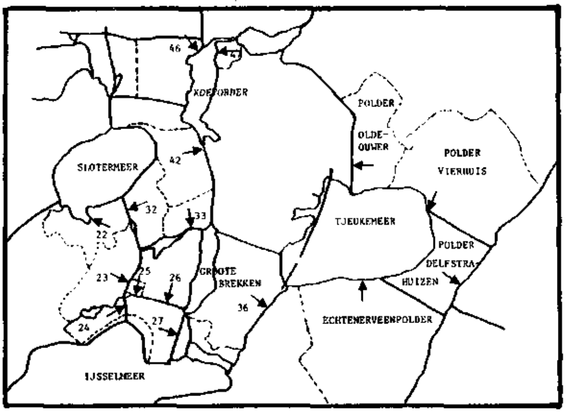

Fig. 4. The south western lake district and 15 of its surrounding sampled polders. The arrows mark the locations of the pumping stations of the polders.

which might be due to increasing rainfall causing run-off and/or increased P release from sediments. The regression lines (least squares method) show the concentrations at times when water was pumped into the boezem (interrupted line) and when the pumping station was not in operation (uninterrupted line). Probably pumping caused resuspension resulting in higher total-P concentrations. The total-P load in the boezem from this polder during this period was 2150 kg P. The average standing stock of Tjeukemeer is about 8000 kg.

Figure 5B shows the average total-P concentrations in the same polder canal from south to north during the same period (autumn 1984) and during spring 1986. The canal transports water of the whole polder to the pumping station. Concentrations are increasing because from south to north the Echtener Veenpolder is receiving more and more water from agriculture and housing. The water in the south of the polder could be characterized as boezem water because in the south there is inflow of boezem water for flushing. Thus there is a P contribution from the polder.

Figure 6A shows the quantities of water of 14 other polders (see Fig. 4), which are pumped into the boezem system during April-December 1985, and Fig. 6b shows the quantities per hectare. Two important conclusions can be drawn: first Tjeukemeer received much more polder water than for instance Slotermeer (Fig. 6A) and second except for polders 23 and 25 the relative quantities did not greatly differ (Fig. 6B). Apart from this Tjeukemeer is receiving polder water from the small river *Tjonger. Thus the eastern part of the studied area is receiving more polder water than the western* part. In 1985 the average total-P concentration of water of the Echtener Veenpolder which was pumped into Tjeukemeer was > 0.4 $mg.l^{-1}$.

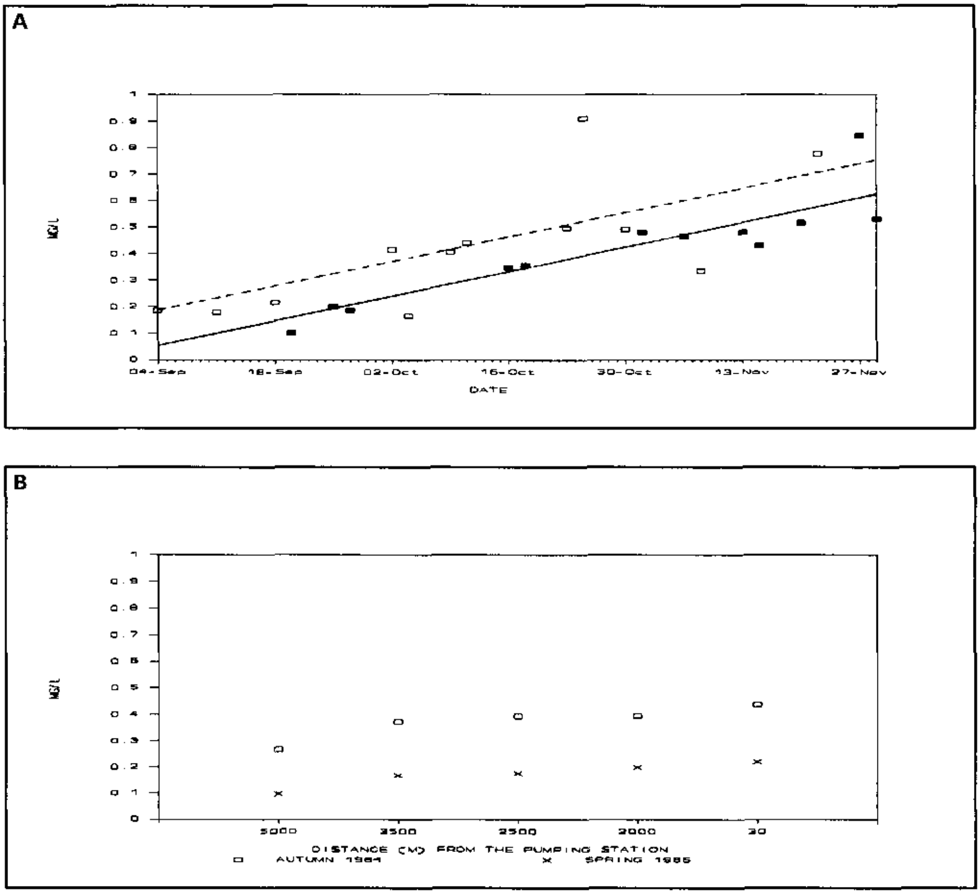

Fig. 5. (A) Total-P concentrations (mg.l^{-1}) in a polder canal in the north of the Echtener Veenpolder about 30 meters south of the pumping station. ■: Pumping station not in operation; □: Pumping station in operation. (B) Average total-P concentrations (mg.l^{-1}) at 5 locations from south to north (distances in metres) in the same canal. □: Autumn 1984; ×: Spring 1986.

Sedimentary P and internal loading

Sampling of sediments, for studying horizontal and vertical distribution of phosphorus and for measuring and modelling internal loading, took place during 1984-1986 at 35 locations. The total-P concentrations in sediments varied between 0.1 and 4.0 mg P g^{-1} of dry weight, which was in agreement with other shallow eutrophicated Dutch lakes. There was a significant correlation with Kjeldahl nitrogen concentrations. Sediments of Tjeukemeer were mostly peaty, while sediments of Slotermeer were mostly sandy. Yet the P contents of these sediments did not differ much and were relatively low. Peaty sediments of Brandemeer showed relatively high P contents just as did muddy

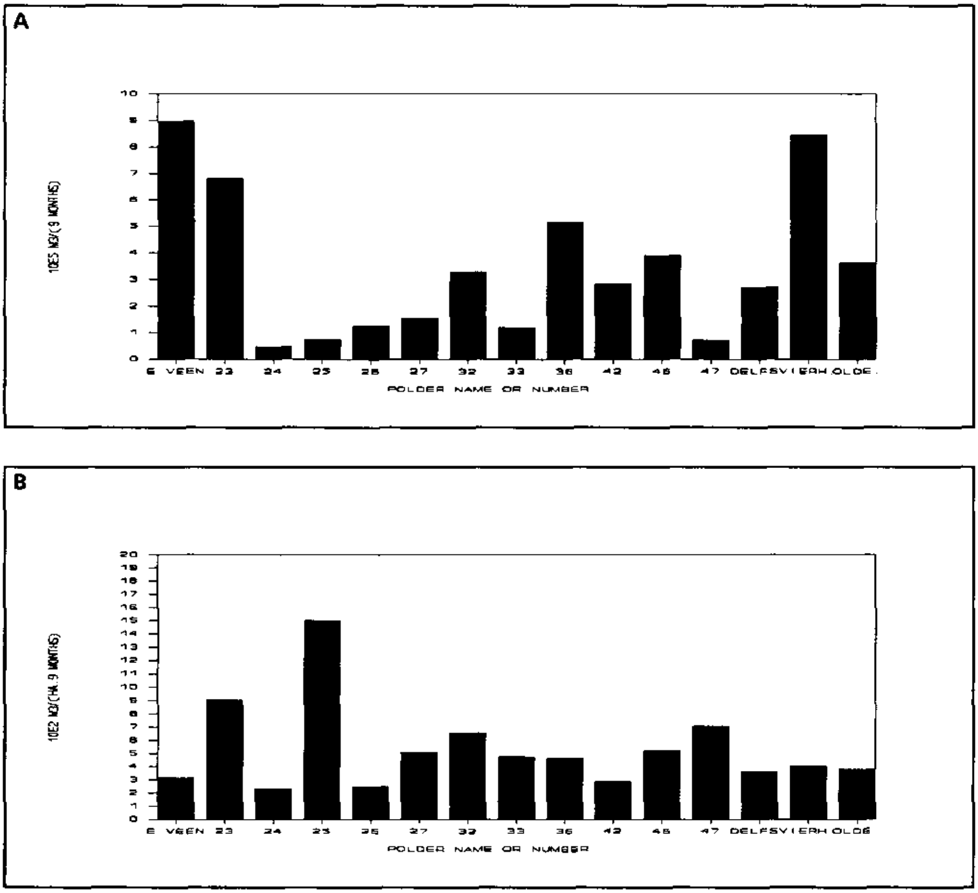

Fig 6. (A) Water quantities of 15 polders during April-December 1985 pumped into the boezem system. (B) The same expressed per hectare.

sediments near or in shipping channels and sediments of inflow/outflow locations of the lakes. Probably at places where water velocities are relatively low a sedimentation of fine particles can take place, and these sediments have high P contents. Figure 7 shows average total-P contents of all stations for 7 sampling dates. P contents decrease with increasing sediment depth. At present it is not clear if there are also yearly fluctuations.

Extraction experiments according to the extraction scheme of Hieltjes and Lijklema (1980) showed that most P was iron- and aluminium-bound, except for sediments of Slotermeer in which mainly loosely bound P was measured. Release experiments with winter samples showed an increased flux after 1 week under laboratory conditions. Probably mineralisation due to activation of the microbial flora was an important process. In general P fluxes were less than 1 mg $P.m^2.d^{-1}$. As more detailed research is in progress no further results of release experiments are given here.

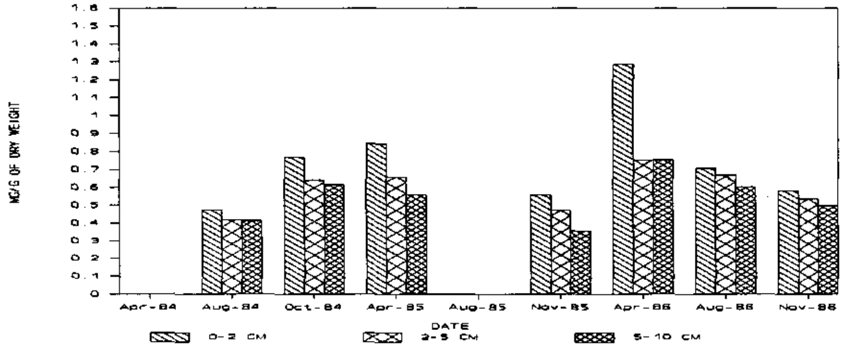

Fig. 7. Average total-P contents in sediments of all sampling stations in mg g^{-1} of dry weight.

SUMMARY AND CONCLUDING REMARKS

Although there are so far no complete water and phosphorus balances and thus no modelling results for policy and management, yet some important conclusions can be drawn:

1) The water of the study area is eutrophic. Total-P concentrations in summer are mostly above 0.15 mg.l^{-1}, which is the basic water quality standard of the Dutch Government.

2) Hydrology plays an important role in the studied area. Especially the water quality of Tjeukemeer is influenced by the summer and winter hydrology. Slotermeer appeared to be a relatively isolated lake.

3) Hydrology in the summer period can be roughly studied by monitoring Cl^- concentrations at several locations.

4) In 1985 it was estimated that about 90% of the inflowing water into Tjeukemeer originated from polders.

5) Generally the total-P concentrations of polder water are higher than those of IJsselmeer water.

6) Total-P contents in sediments varied from 0.1 to 4.0 mg.g^{-1} of dry weight. Most P was Fe- and Al-bound. There was a slight tendency for decreasing P content with increasing sediment depth.

7) Phosphorus release experiments with winter sediments showed that P release was less than 1 mg P.m^2.d^{-1}. Probably the process was influenced by mineralisation.

Chapter 3

Horizontal and vertical distribution of phosphorus in sediments of interconnected eutrophic polder lakes in sw Friesland, The Netherlands

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Submitted to Archiv für Hydrobiologie

HORIZONTAL AND VERTICAL DISTRIBUTION AND SPECIATION OF PHOSPHORUS IN SEDIMENTS OF INTERCONNECTED AND EUTROPHIC POLDER LAKES IN SW FRIESLAND, THE NETHERLANDS

Key words: sediments, phosphorus, nitrogen, dry weight, loss on ignition, distribution, speciation, polder lakes, eutrophication

ABSTRACT

To study horizontal and vertical distribution and speciation of phosphorus (P) in sediments of interconnected, eutrophic lakes in sw Friesland, 34 stations were sampled ten times during 1984-1987. Besides total phosphorus (TP), the sediments were analyzed for dry weight (DW), organic matter by loss on ignition (LOI), and Kjeldahl nitrogen (KjN). The hydrochemistry of the area is strongly influenced by the man-made water regime.

Although TP varied greatly (0.01-7.78 mg.g^{-1} of DW), the morphometry of the area affects the horizontal TP distribution. This impact could be attributed to sediment nature and water velocities. Sediments at inflow/outflow locations exhibited higher mean TP contents (0.86 mg.g^{-1} of DW) than sediments from the central lake areas (0.42 mg.g^{-1} of DW). The TP contents increased from sandy to peaty sediments and were highest in muddy sediments. Generally, TP contents decreased with depth. There was a slight seasonal TP variation.

A significant interrelation of all variables studied was found for all sediments. The unexpected low correlation between LOI and TP is probably due to the occurrence of P-poor substances next to P-rich fresh organic matter. The horizontal TP distribution is reflected in different correlations of lake sediments and the rest of the samples. Extraction experiments indicated that most sedimentary P was Fe-bound.

INTRODUCTION

Area description

The shallow Frisian lakes are a part of the 'boezem', a system of interconnected canals and lakes with a total water area of 140 km^2 (Fig. 1A). The boezem is mainly used for regulating the water table of Friesland. Generally, during the summer period (April-October), inflow of relatively Cl^--rich water from Lake IJsselmeer occurs, while in the winter period (October-April), when rainfall exceeds evaporation, humic-rich superfluous water of the surrounding polders is pumped into the boezem. In summer inflow of boezem water into the surrounding polders occurs and in winter the excess of boezem water is pumped into IJsselmeer or flows into the Waddensea.

In the research area, with a total water surface area of 40 km^2, five adjacent lakes (Tjeukemeer, Slotermeer, Groote Brekken, Koevorder Meer, and Brandemeer) and interconnecting canals are located near one of the major inflow and pumping stations of the Frisian boezem (Fig. 1B). As far as known the lakes originated by excavation of surface peat for fuel, by peat burning and by floods from the sea. The thickness of the peat layer limited the mean depths of the lakes to 1-2 m. The underlying layers consist of sand, clay and loam, so that the lake sediments are a mosaic of peat, sand, loam and clay. The fortuitous creation of the lakes caused their irregular shapes and sizes (Beattie *et al.*, 1978).

The seasonally inverse water flow is reflected in the Cl^- concentration and the humus concentration. In Tjeukemeer, for example, in summer the Cl^- concentration can reach values of more than 200 mg.l^{-1}, while in winter the concentration drops below 50 mg.l^{-1}. In winter the optical density of the water at 365 nm (E365), increases two to four fold (De Haan, 1982). The high nutrient concentrations in the polder water, sometimes exceeding 1.0 mg.l^{-1} of TP (TP) and 10 mg.l^{-1} of total nitrogen (TN), probably are the result of processes such as leaching and surface runoff. The eutrophic nature of the inflowing IJsselmeer water is partly due to the inflow of nutrient-rich haline River Rhine water into the IJsselmeer.

Thus, the man-made water regime leads to highly eutrophic lakes. The TP and TN concentrations may exceed 0.15 and 2.0 mg.l^{-1}, respectively, which are the basic water quality standards for these parameters laid by the Water Action Programme 1985-1989 of the Dutch Government. These high nutrient levels lead to maximum summer chlorophyll-a concentrations of over 150 μg.l^{-1} with occasional pH rises beyond 10.0. The pH of the lake water does not drop below 7.0. For more details about the hydrology and water regime, limnology, water quality parameters, eutrophication and algal periodicity of the Frisian lakes see Beattie *et al.* (1978), Leenen (1982), Moed and Hoogveld (1982), De Haan and Moed (1985), Claassen (1986) and Van Huet *et al.* (1987) and Van Huet (1990). However, the role of the sediments in the eutrophication process, for example the influence of P-release, remained obscure.

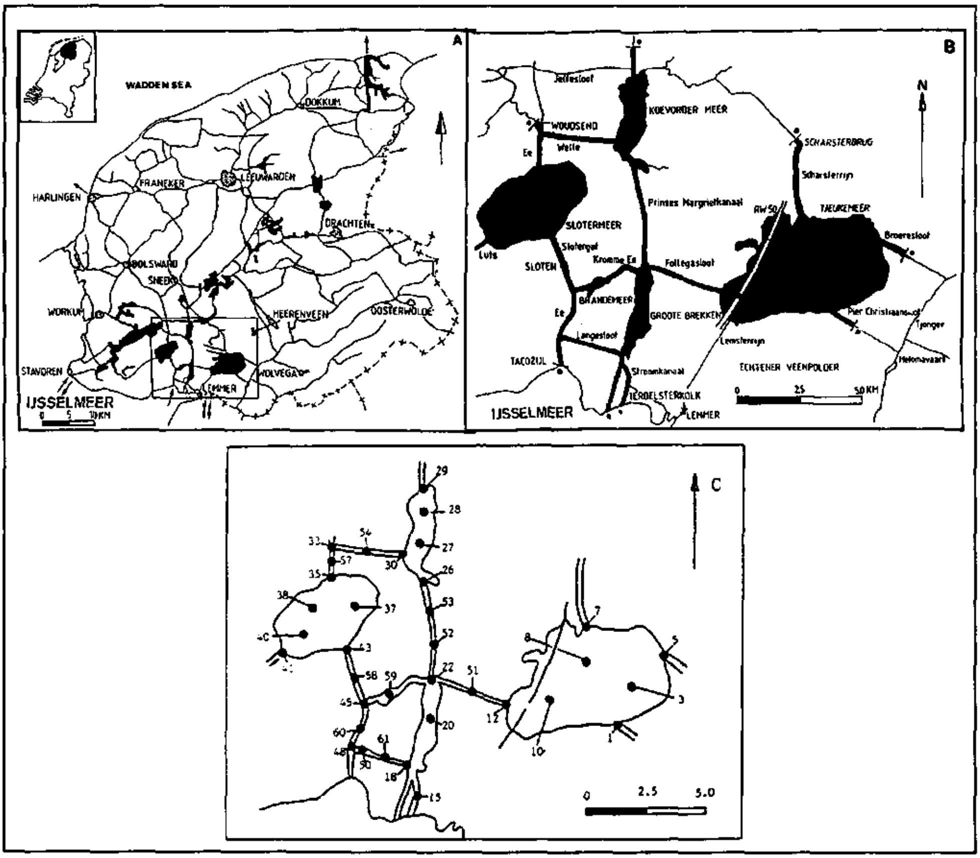

Fig.1. A: The province of Friesland and its boezem system. B: The south-western lake district (●_: system boundaries; RWZI: waste water treatment plants; RW50: motorway, from Van Huet *et al.*, 1987). C: Sediment sampling stations.

P dynamics in sediments

P dynamics in sediments are complex and a result of physical processes (sedimentation, resuspension, seepage, diffusion, erosion, mixing, external loading), chemical processes (adsorption, desorption, redox reactions, precipitation) and biological processes (mineralization, bioturbation). P release may be influenced by pH (Lijklema, 1980; Boers and Van Liere, 1986), temperature (Kelderman, 1984; Boers, 1986), oxygen contents in the upper sediment layer (Theis and McCabe, 1978; Bostrom, 1984), age of sediments (Lijklema, 1980; Herodek and Istvanovics, 1986), groundwater movements (Van Liere and Mur, 1982; Van Raaphorst and Brinkman, 1984), P concentrations in overlying water (Kelderman, 1984) and P concentrations in interstitial water (Brinkman and Van Raaphorst, 1986).

In this paper the results of the study of distribution and speciation of sedimentary P in the sw Frisian lake district are reported. Emphasis was given to the possible relation between horizontal and vertical distribution of sedimentary P and the morphometry and hydrology of the area. A P speciation study of a few sediment types was done in order to obtain a general impression. Additionally, we studied whether TP was related to other sediment characteristics such as dry weight (DW), Loss on ignition (LOI), Kjeldahl nitrogen (KjN) and sediment type.

The results of this distribution study and of a P-release study, which is in progress, should lead to quantification of the sedimentary P contribution and the impact on the eutrophication in the research area.

MATERIALS AND METHODS

Sampling

In order to study the distribution of sedimentary TP, 34 sampling stations were selected so as to cover the five lakes, their inflow and outflow locations, and their interconnecting canals (Fig. 1C). During 1984-1987 sediments were sampled in spring, summer, and autumn. Because of technical reasons data of spring 1984 and summer 1985 are lacking, as well as canal data of summer 1984.

For the TP speciation study four sampling sites were selected. Three of them (8, 40, and 59) lie in lakes, while sampling site 61 is a canal station. Sampling occurred on December 10, 1984. Sediment sampling was conducted according to Van Raaphorst and Brinkman (1984). The sampler consists of a stainless steel cutter head and a separate perspex inner tube (length = 40 cm; diameter = 5 cm). The sampler is driven into the sediment by hand. In this way relatively undisturbed samples can be taken.

Visual sediment characterization and analysis

Each sediment sample was characterized visually on its contents of mud, peat, clay, loam and sand. The sampled cores were cut into three segments: 0-2, 2-5, and 5-10 cm from the upper surface. These subsamples were analyzed for DW, LOI, TP, and KjN.

DW was determined by drying at 103 °C. Organic matter was estimated as LOI upon heating at 600 °C during 45 minutes. TP in sediments was determined after hydrolysis to PO_4-P. Wet sediments were analyzed by suspending 10 g in 250 ml of water. From this suspension, 5 ml, diluted with 15 ml of water, were hydrolysed with 2 ml of 7N H_2SO_4 containing 135 $g.l^{-1}$ of K_2SO_4 during three times 30 minutes at 125, 150 and 200 °C and 90 minutes at 370 °C. After hydrolysis the samples were replenished up to 75 ml. The hydrolysates were neutralised and analyzed for

PO_4-P with molybdenum blue after Murphy and Riley (1962). The hydrolysates were analyzed for NH_4-N with sodiumsalicylate and sodium-dichloro-cyanurate, according to the Dutch Standard Methods.

P speciation studies

The sediment samples were successively extracted with 1 M NH_4Cl, 0.1 M NaOH, and 0.5 M HCl after the stepwise fractionating scheme of Hieltjes and Lijklema (1980). Per mg of dry sediment 1 ml of extractant was used. In this way it was tried to fractionate sedimentary P into loosely adsorbed P, Fe and Al bound P, and P incorporated in (mainly) Ca compounds, respectively. Phosphorus included in clays and other minerals resistant against NaOH and HCl are not extracted by this method. The residual part, TP minus the sum of the other fractions is often considered to be organically bound P (Bostrom, 1984; Pettersson, 1984; Jansson, 1988). The extracts were analyzed for TP.

RESULTS AND DISCUSSION

Reproducibility

Although every possible effort was made to sample each time at the same locations, this was not always possible because of, for example, waves and navigation problems. By way of experiment, on one occasion two samples were taken 2 or 3 meters apart at three locations, in order to test the variability induced by sampling. It appeared that large differences in P contents may occur between these 'duplicates' (Table 1). This might be the result of an irregular pattern of the bottom. For example, deeper parts can contain muddy sediments with high TP contents (*see the section Horizontal P distribution, sediment type and influence of water transport*). Therefore, conclusions based on individual measurements at individual locations are unreliable. Large spatial variability must be kept in mind in interpreting results. However, the detrimental effect of the sampling variability is considerably mitigated by the large number of sampling locations involved, and by the repetition over a number of years. Therefore, a statistical correlation analysis of our results would give a fair impression of relation between sediment characteristics.

Table 1. Sedimentary TP contents (mg.g^{-1} DW) of 'duplicate' samples from three locations.

Location	10		18		38	
Subsample	1	2	1	2	1	2
Layer 0-2 cm	0.10	0.81	1.50	1.49	0.29	0.38
Layer 2-5 cm	0.14	1.14	1.03	0.29	0.22	0.17
Layer 5-10 cm	0.19	0.43	1.22	0.36	0.20	0.19

Visual sediment characterization

Fig. 2 shows an impression of the sediment type of lake stations, stations at inflow/outflow sites and stations in canals at the ten dates. Although this visual characterization is the result of a subjective observation, it gave a rather consistent pattern within the three groups, as well as of the separate sampling sites. Fig. 2 shows that lake sediments are sandy and to a lesser extent peaty and/or muddy. Most sediments at the inflow/outflow points are muddy, while sediments in the canals are muddy, sandy and/or peaty. On the whole, the composition of the lake sediments appeared to be most variable. This result may partly be due to the larger difficulty of finding the right position while being on a lake, and partly because of wind-induced transport of sedimentary material.

Mean values for DW, LOI, TP and KjN

Table 2 shows the number, minimum, maximum, means, population standard deviation and coefficient of variation (standard deviation divided by the mean value x100%) of DW, LOI, TP, and KjN of all analyzed samples. The range for TP is 0.01- 7.78 mg.g^{-1} DW, which does not differ much from literature ranges (Dutch lakes: Hieltjes, 1980; Boers *et al.*, 1983; Klapwijk and Bruning, 1986; other European or American lakes: Theis and McCabe, 1978; Hakanson, 1984; Herodek and Istvanovics, 1986; Ostrovsky, 1987; Nurnberg, 1988). There are large differences in minimum and maximum values, leading to rather high standard deviations. The coefficient of variation is highest for TP, intermediate for KjN and LOI, and lowest for DW. Klapwijk and Bruning (1986) and Siebers (1985) also report a rather high variability of P in sediments of Dutch lakes. The distribution for TP data was examined (all values as well as values per group and per layer, see below), by use of the Wilk-Shapiro statistic and rankit plots. The rankit plots of the log transformed values showed straight lines, while the Wilk-Shapiro values were close to 1, indicating that TP values were approximately log-normally distributed.

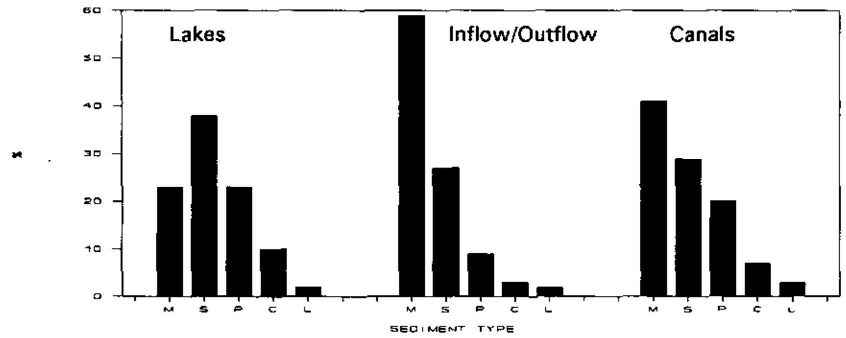

Fig. 2. Sediment type in % of lake sediments, sediments at inflow/outflow sites of lakes and canal sediments (M = mud; S = sand; P = peat; C = clay; L = loam).

Table 2. Number of data, minimum, maximum, means, standard deviation and coefficient of variation for DW, LOI, TP and KjN of 34 stations sampled ten times during 1984-1987.

	DW (%)	LOI (% of DW)	TP (mg.g^{-1} DW)	KjN (mg.g^{-1} DW)
Number	976	901	976	976
Minimum	5.7	0.1	0.01	0.01
Maximum	88.7	95.5	7.78	47.85
Mean	33.3	24.9	0.63	4.61
Stand. dev.	20.5	23.4	0.79	4.66
Coeff. Var.(%)	61.6	94.0	125.4	101.1

Table 3 shows the mean values of DW, LOI, TP and KjN for all layers together and for each layer separately for all stations and per group of stations. It can be concluded that DW, LOI and KjN in lake sediments deviate in their depth profile from the two other groups. Organic matter, measured as LOI, in lake sediments is increasing with depth, reflecting the peat origin of the lakes.

As in this paper the sedimentary TP contents are emphasized, a further analysis was made of these values. The calculated mean values in Table 3 are not indicative for the status, as the distribution is log-normal. Therefore, in Table 3 also the geometrical means of TP are given, which might lead to a clearer interpretation. It can be concluded that, the trends for TP are the same in the averages as in the geometrical mean values.

Further statistical analysis, by applying an analysis of variance (F-test) to the log transformed TP values, indicated that a significant decrease with depth occurred for all groups of stations ($p=0.0162$). In addition, also the values within each group decreased significantly with depth.

Table 3. Mean values of DW, LOI, TP, and KjN of all groups (All), all layers (A.L.), and of separate groups and layers (the numbers in brackets are geometric means).

	DW (%)				LOI (% of DW)				TP (mg.g^{-1} DW)				KjN (mg.g^{-1} DW)			
	All	Lak	I/O	Can	All	Lak	I/O	Can	All	Lak	I/O	Can	All	Lak	I/O	Can
A.L.	34	37	31	33	25	27	21	28	0.63(.34)	0.42(.24)	0.86(.51)	0.55(.31)	4.61	4.23	5.09	4.37
0-2 cm	35	40	31	30	21	16	20	27	0.75(.40)	0.47(.26)	1.04(.57)	0.67(.39)	4.72	3.09	5.84	4.92
2-5 cm	33	36	31	33	26	30	20	28	0.59(.33)	0.39(.23)	0.80(.48)	0.51(.29)	4.60	4.54	4.87	4.32
5-10cm	34	35	31	35	28	35	22	28	0.55(.31)	0.41(.23)	0.72(.47)	0.46(.25)	4.51	5.08	4.57	3.88

Horizontal P distribution, sediment type and influence of water transport

Table 3 and Fig. 3 show that the mean P contents are highest in the sediments of the inflow/outflow group (0.86 mg.g^{-1} DW), intermediate in the canal sediments (0.55 mg.g^{-1} DW) and lowest in the lake sediments (0.42 mg.g^{-1} DW). The difference in P contents may be due to different organic material: the peaty sediments contain relatively much humic substances, while the muddy sediments contain much fresh organic material. This will be discussed in the section *Correlation analysis*.

Fig. 3 shows that the P contents of sediments of Tjeukemeer (3,8,10) are higher than those of Slotermeer (37,38,40). Probably this difference is due to their peaty and sandy structure, respectively. However, another reason could be the very high values for sampling sites 8 and 10 in spring 1987 (see also Fig. 4b). No explanation could be found for these high values. The sediments of lakes Groote Brekken (20) and Koevorder (27,28) are sampled close to the navigation channels. In navigation channels sedimentation of fine particles with high P contents may occur (Hieltjes, 1980), and this may influence the P values. Sediments of the Brandemeer (59) are very peaty and P content values are average within the lake group.

The P contents of sediments of stations at inflow/outflow sites of the lakes generally show relatively high values. Fig. 2 shows that the sediments of this group are relatively muddy. Probably at the inflow/outflow locations water velocities decrease followed by sedimentation of fine particles. Station 41 (Fig. 3) is a good example of this phenomenon. At this site regular dredging is necessary to guarantee free navigation.

The P contents of canal sediments vary (Fig. 3). Two sub-groups can be distinguished: in canals with relatively high water velocities (locations 15,51,52,53; Van Huet, unpublished results) the sediment P contents are relatively low. The opposite pattern is found in canals with relatively low water velocities (45,50,57,58,60,61). At these locations the sediments are muddy and probably there is much sedimentation. The only exception on this phenomenon shows station 54: despite low water velocities the sediments are sandy, and consequently the P content is low.

On the whole, these results suggest that there is an increasing P content in the sequence sandy, peaty and muddy and that water transport can influence the P contents.

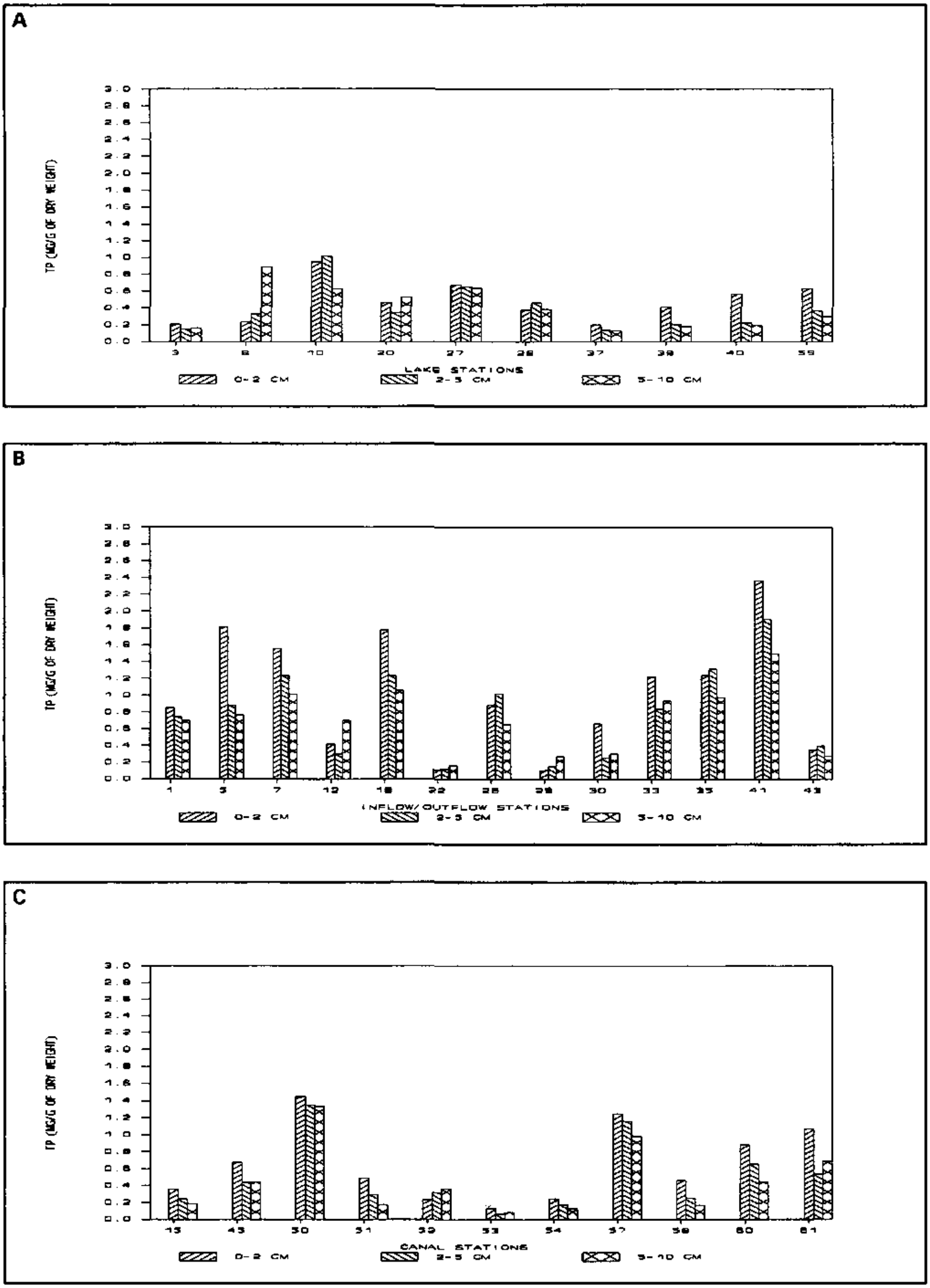

Fig. 3. Total P contents (mg.g^{-1} of DW) of all stations, averaged for all dates. A: lake stations (3-59); B: stations at inflow/ outflow sites of lakes (1-43); C: Canal stations (15-61).

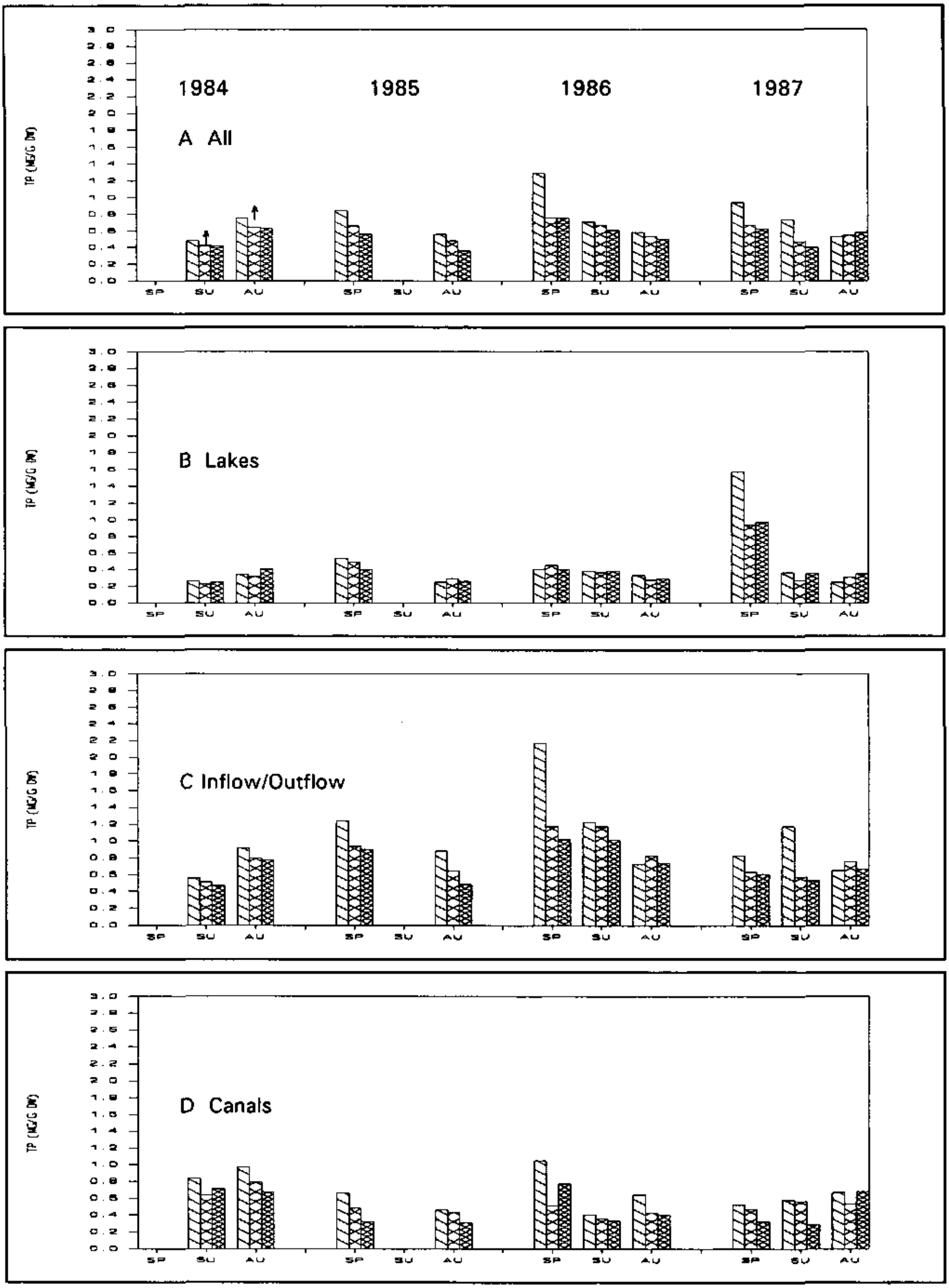

Fig. 4. A: Total P contents (mg.g^{-1} of DW) of all dates, averaged for sediments of all stations. The same expressed for the lake sediments (B), the inflow/outflow sediments (C), and the canal sediments (D). Sp: Spring. Su: Summer. Au: Autumn.

Vertical P distribution

In general, the mean P contents are decreasing with depth. The muddy sediment composition is probably responsible for the elevated P-levels in the top layer, as compared to the other layers. However, other possibilities exist to explain why the P content is generally decreasing with depth. For instance, due to the anoxic conditions in the deeper parts, P binding could be less effective, so that phosphorus migrates to the top layers where it is trapped. Sediments of the two largest lakes in the area, however, show some differences: the mean P contents in the Slotermeer sediments (37,38,40) clearly decrease with depth, while this pattern does not hold for the Tjeukemeer sediments (3,8,10).

Temporal P variation

Figs. 4A-4D show the distribution of the mean P contents over the seasons, for all sampling sites together and for each group of sediments separately. It should be noticed that data for spring 1984 and for summer 1985 are lacking. In the summer of 1984 most canal stations were not sampled. The canal sediments appeared to have intermediate P contents (Table 2). Therefore, probably the mean values for the summer of 1984 are higher (see arrows in Fig. 4A). The high mean P contents of the lake sediments in spring 1987 are caused by the P contents of stations 8 and 10 (Fig. 3). Also these figures show the characteristic differences in the P contents among the groups.

P contents in spring are higher than in autumn, which suggests that there is a cyclic variation throughout the year. The fluctuation in P contents might partly be do to adsorption of P in winter and release of P in summer (Uunk, 1979; Kelderman, 1984; Boers and Van Liere, 1986). However, sampling took place during only four years. Extended time series and studying P dynamics in sediments (see *Introduction*) may lead to better interpretations.

P speciation

Knowledge of the TP content of the sediment as such is not sufficient to judge the potential for P release. For this purpose information on the various binding forms of P and P-release studies are needed. Therefore, in order to obtain an impression, on the two top-layers of 2 cm each of four sediment cores (stations 8,40,59 and 61, sampled December 10, 1984), chemical fractionation was attempted by applying the extraction scheme according to Lijklema and Hieltjes (1980). The sediment of station 8 consisted of mud on peat, the one of station 40 of sand on peat, the one of station 59 of peat and the one of station 61 of peat and mud. The results are shown in Fig. 5, together with the vertical TP and LOI distribution (Van Straten and Visscher, 1985).

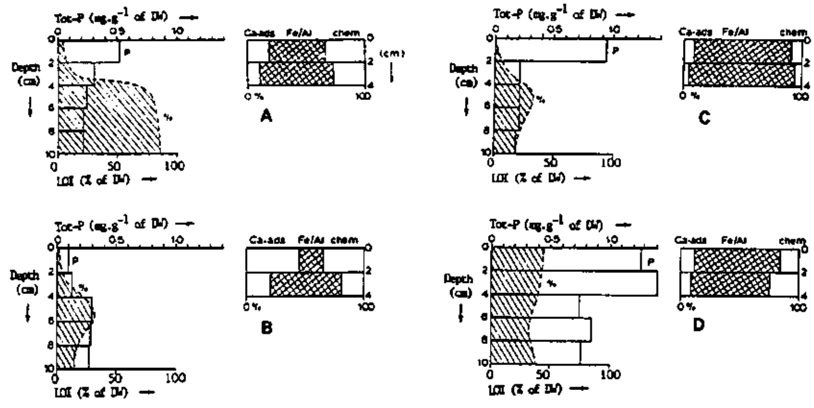

Fig. 5. Sediment composition and results of extraction experiments (December 10, 1984). A: Tjeukemeer (8); B: Slotermeer (40); C: Brandemeer (59); D: Langesloot (61), (from Van Straten and Visscher, 1985).

The phosphorus is to a great extent iron- and aluminium bound, except for station 40 (Slotermeer), where predominantly loosely bound P is measured. The top layers of sediments of the Tjeukemeer (8) and Slotermeer (40) have lower P contents than sediments of the Brandemeer (59) and Langesloot (61). Exact interpretations of the results cannot be made because it is known that the extraction method does not hold very well for humic sediments (Klapwijk *et al.*, 1982; Van Liere *et al.*, 1982; Boers *et al.*, 1984) and other approaches are possible (Golterman, 1988).

Preliminary results of P-release studies are reported by Van Straten and Visscher (1985) and Brinkman *et al.* (1988). They concluded that P fluxes were low (1-2 $mg.m^{-2}.d^{-1}$), while mineralisation played an important role in the P-release process. Also Boers and Van Liere (1986) concluded that peaty sediments of the research area showed low P release. Further investigations are in progress.

From bio-assay experiments with peaty sediments of Loosdrecht Lakes (The Netherlands), Boers *et al.* (1984) concluded that P bio-availability was low (< 6%), while Klapwijk and Bruning (1986) reported upon a range of 10-45% for eight lakes in The Netherlands. Three of them had peaty sediments. They also concluded for these eight lakes that organic matter content (LOI) was strongly negatively correlated with the available P, indicating that high organic matter content tends to diminish the availability of the sedimentary P. In our study the highest LOI values are found in the canal sediments and the 5-10 cm layer of the lake sediments. However, in general, the LOI range is not very wide and no general conclusions can be drawn from these values.

Correlation analysis

In order to investigate if P in sediments was related to other sediment characteristics, a correlation study was done. Table 4 shows the linear correlation matrix of DW, LOI, TP and KjN. It can be concluded that, except for LOI and TP, the sediment variables are highly interrelated. The correlation between DW and LOI is highly significant for all layers and all groups of sediments. The correlation between DW and TP is lowest in the lake sediments, while the highest correlation coefficients were found for the upper sediment layer. The opposite can be concluded for the correlation between DW and KjN. Similarly KjN is more closely correlated to LOI than is TP. Here again the results of the lake group are deviating. Finally, except for the lakes, a highly significant relation is found between TP and KjN.

Further analysis shows that the correlation coefficients of DW/TP and LOI/TP are highest for the layer 0-2 cm. In contrast, the correlation coefficients of DW/KjN and LOI/KjN are highest for the layer 5-10 cm. A pattern like this can be expected if the top-layer on average consists mainly of fresh organic material, whereas the deeper layers contain much consolidated organic matter (peat and humic material). In order to further substantiate this point, a separation is made in the TP versus LOI correlation between the lake sediments, which are generally more sandy and/or peaty, and the inflow/outflow sediments, which are usually more muddy (Fig. 6). Fig. 6B shows that high LOI-values almost exclusively appear in the deeper parts of some lake sediments. Here the peat content is likely to be high. In addition the P content is low. On the other end of the LOI- scale the P-contents are equally low, because here the more sandy lake sediments are found. However, in the inflow/outflow samples very high LOI-values do not occur, whereas the P content is higher and more closely correlated to LOI. This result suggests that the muddy sediments at these sites contain more freshly precipitated organic material.

CONCLUDING REMARKS

This phosphorus research showed that there are differences in horizontal and vertical distribution in lakes, canals and inflow/outflow sites, due to differences between sediment types, to water transport, to sedimentation, etc. These storage results should, together with the results of the release and modelling studies (research in progress), lead to more insight in internal loading and the influence of sedimentary P on eutrophication and thus on the lakes trophic level.

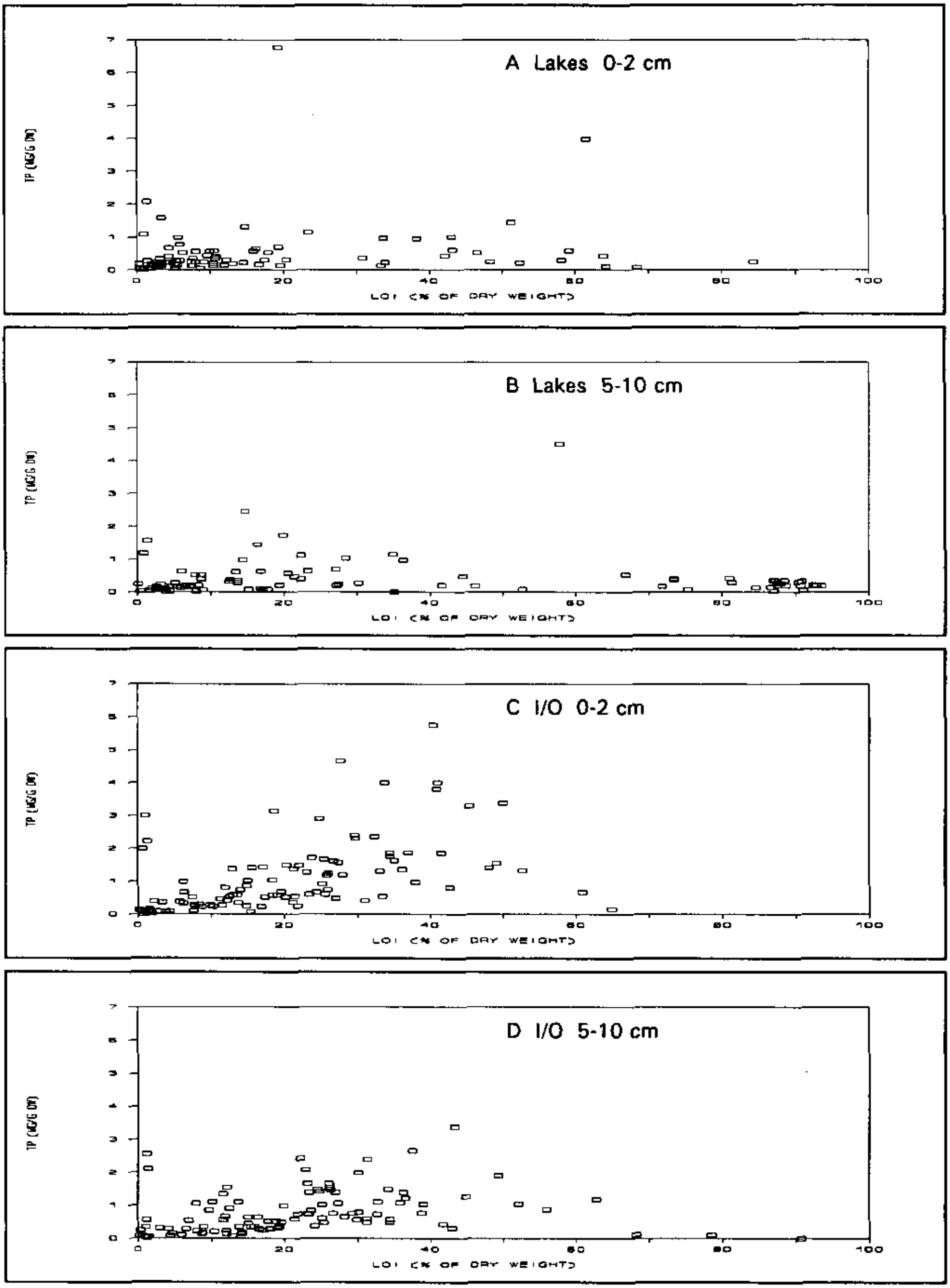

Fig. 6. Relationship between LOI and TP: Lake sediments, layer 0-2 cm (A), and layer 5-10 cm (B); Inflow/outflow sediments, layer 0-2 cm (C), and layer 5-10 cm (D), (a: $p<0.001$; c: $p<0.05$; d: $p>0.05$).

Table 4. Matrix of correlation coefficients of DW, LOI, TP and KjN (all values: $p<0.001$, except: b: $p< 0.01$, c: $p<0.05$, d: $p>0.05$. Rn: 1: number of samples in range 89-127; 2: 268-380; 3: 899-976).

		LOI								TP								KjN							
		All		Lakes		In/Out		Canals		All		Lakes		In/Out		Canals		All		Lakes		In/Out		Canals	
		Rn	r	Rn	r	Rn	r	Rn	r	Rn	r	Rn	r	Rn	r	Rn	r	Rn	r	Rn	r	Rn	r	Rn	r
DW	A.L.	3	-.69	2	-.79	2	-.67	2	-.68	3	-.45	2	-.25	2	-.55	2	-.51	3	-.63	2	-.75	2	-.59	2	-.63
	0-2	2	-.68	1	-.78	1	-.68	1	-.66	2	-.50	1	-.32b	1	-.57	1	-.58	2	-.61	1	-.77	1	-.60	1	-.62
	2-5	2	-.71	1	-.82	1	-.74	1	-.68	2	-.44	1	-.22c	1	-.58	1	-.51	2	-.62	1	-.75	1	-.57	1	-.61
	5-10	2	-.72	1	-.81	1	-.70	1	-.71	2	-.41	1	-.25c	1	-.54	1	-.43	2	-.69	1	-.76	1	-.64	1	-.67
LOI	A.L.									3	.11b	2	.01d	2	.33	2	.16b	3	.49	2	.83	2	.39	2	.42
	0-2									2	.28	1	.18d	1	.50	1	.21c	2	.42	1	.73	1	.52	1	.35
	2-5									2	.06d	1	-.06d	1	.33	1	.16d	2	.50	1	.82	1	.39	1	.45
	5-10									2	.05d	1	-.03d	1	.20c	1	.13d	2	.61	1	.85	1	.37	1	.50
TP	A.L.																	3	.63	2	.10d	2	.84	2	.66
	0-2																	2	.74	1	.25c	1	.86	1	.72
	2-5																	2	.53	1	.05d	1	.81	1	.59
	5-10																	2	.52	1	.08d	1	.83	1	.67

Chapter 4

Phosphorus loads from peaty polders in the sw Frisian lake district, The Netherlands

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PHOSPHORUS LOADS FROM PEATY POLDERS IN THE SW FRISIAN LAKE DISTRICT, THE NETHERLANDS

Key words: peaty polders, phosphorus, gross and net loads, water balances, water quality, eutrophication

ABSTRACT

The purpose of this study was to quantify discharges and P-loads from peaty polders (total surface area 11560 ha) surrounding lakes in south-western Friesland, and to examine whether processes inside the polders contribute to the P-loads to the lakes. A detailed study in the Echtener Veenpolder (2850 ha), the largest polder in the study area, showed annual gross P-loads of 1.3 to 1.83 kg $P.ha^{-1}$ polder area and net P-loads of 0.63 to 1.48 kg $P.ha^{-1}$. Processes inside this polder, such as leaching, surface runoff, resuspension, spreading manure and fertilizers, can result in high total P concentrations (TP) in discharged polder water (up to 0.9 $mg.l^{-1}$) and therefore contribute to the P-load from the polder to lake Tjeukemeer. During 1984-1987 the averaged TP concentrations in polder water were higher than in lake Tjeukemeer water: 0.37 $mg.l^{-1}$ and 0.28 $mg.l^{-1}$, respectively. The annual gross P-loads from 11 other polders ranged from 1.01 to 4.13 kg $P.ha^{-1}$ polder area, while TP concentrations reached values up to 3.0 $mg.l^{-1}$. The P-loads from five polders to lake Tjeukemeer were high compared with the loads to the other lakes in the district. Particularly, during the winter period (October-April) P-loads were highest: up to 3.13 kg $P.ha^{-1}$. This paper shows that hydrological measures and the reduction of the concentrations are important to combat the eutrophication problem in the lakes. However, for an optimally integrated water management of the polders, further research is needed to develop, for example, dynamical water and P balances in order to gain a better insight into the role of agriculture.

INTRODUCTION

Phosphorus eutrophication and study objective

In the 1970's strategies to reduce P eutrophication in The Netherlands were mainly focused on the reduction of P in detergents and reduction of P-loads from waste water treatment plants. However, since the early 1980's attention is paid to a more integrated strategy to combat the eutrophication problem. It became clear, that in areas with water quality problems the role of, for example, sediments, nutrient loads from agricultural districts, hydrology and influence of main rivers had to be considered too.

In 1984 a eutrophication study started in the lake district of the province of Friesland (Figure 1B), in order to model the complex hydrology and P dynamics and to quantify water and P balances. The main purpose of this study was to predict impacts of water quality and quantity scenario's for management and policy. This paper focuses on the quantification of discharges and P-loads from 16 peaty polders to the lakes during 1984-1987, while also the results of a detailed study in the Echtener Veenpolder (Figure 2B), the largest polder in the area, are reported. The aim of the detailed study was to examine whether there was a P contribution from the polder. Special attention is paid to both summer as well as winter loads, because of the difference in hydrology in the canal-lake system between these seasons.

Area description and hydrology

The south-western Frisian lake district (surface water area 40 km^2) is a part of the 'boezem': a system of interconnected shallow lakes (1-2 m) and canals (1-4 m) for water table regulation and superfluous polder water. The main lakes are Tjeukemeer, Slotermeer, Groote Brekken and Koevorder (Figure 1B). In summer blue-green algal blooms occur in the nutrient-rich boezem water (De Haan and Moed, 1985; Moed and Hoogveld, 1982). The area lies below sea level. It is part of the Frisian peaty grassland area, where mainly cattle farming takes place.

The hydrology in the canal-lake system is complex, mainly because of an alternating precipitation deficit or excess and the man-made water table regime. In general there is a summer situation (April-October) with inflow of chloride-rich water from the IJsselmeer, originating from the river Rhine and a winter situation (October-April) with pumping of boezem water into Lake IJsselmeer or a free discharge to the Wadden Sea (Figure 1A). The climatological influence and therefore the seasonal variation is also reflected in the water regime of other surrounding polders: in the summer period mostly inflow of boezem water into the polders takes place and in the winter period pumping of humic-rich polder water into the boezem.

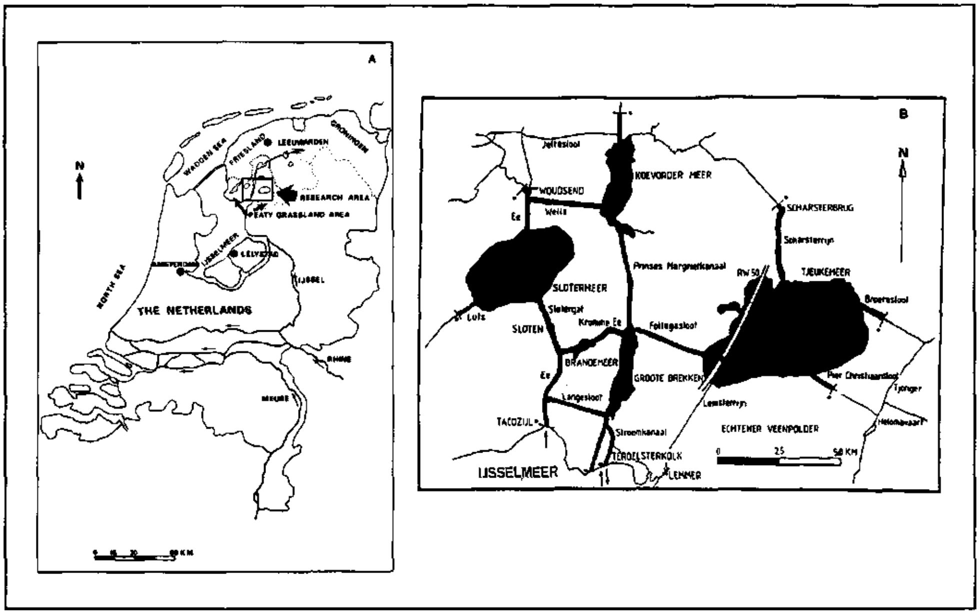

Figure 1. **A**: Map of The Netherlands with the main inflowing rivers Rhine and Meuse, Lake IJsselmeer and the research area (Lelystad and Leeuwarden are meteorological stations of the Royal Netherlands Meteorological Institute). **B**: The south-western lake district (after Van Huet, 1990). RW50: motorway; -●: border of the study area; →: inflow stations for IJsselmeerwater; ←: pumping station for superfluous boezem water.

The water target levels for Lake IJsselmeer, the boezem system and the polders are about 0.2-0.4 m, 0.5-0.54 m and 0.6-2.5 m below NAP (the Dutch Mean Sea Level reference), respectively. The variation of polder water level, with differences up to one meter, particularly occurring in the eastern part of the research area, is the result of higher and lower lying peaty grasslands. Most polders are (partly) surrounded by boezem water, so small dikes are necessary. It is only in the western part of the district that a peaty/sandy gravitational discharge area with direct runoff and discharge of water towards the boezem system occurs. There is only a slight seepage or infiltration in the area. However, individual polders may have relatively high values (maximum 0.3 $mm.d^{-1}$ and 1.5 $mm.d^{-1}$, respectively; Broers, 1987).

In the Echtener Veenpolder (2850 ha) a network of ditches is found with high and low water levels as a result of high and low lying parcels (Figure 2B). Generally, inflow of boezem water can take place in the high level ditches, while the low level ditches (mostly inside the polder) discharge water in the direction of the pumping station in the north. The hydrology in the polder is very complex because of the meteorological processes, the local seepage and infiltration situation, a system of culverts and spillways. Consequently the following occurs: a) water table regulation by

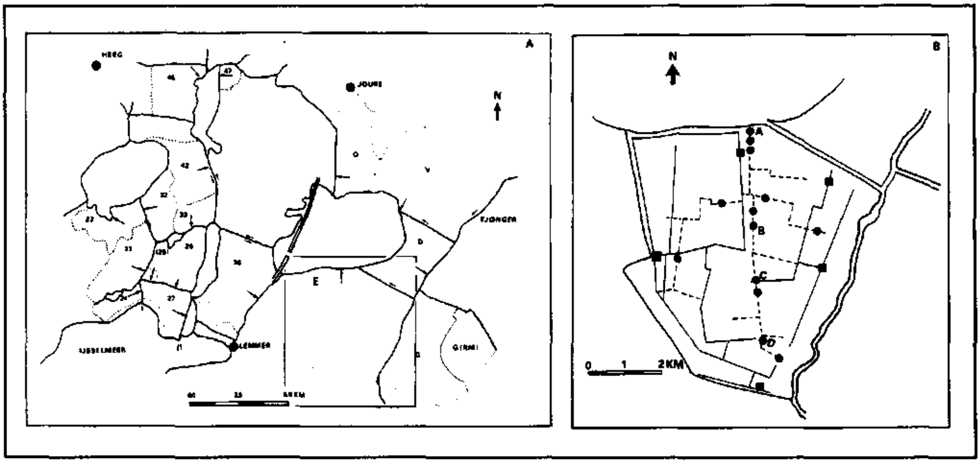

Figure 2. **A**: The south-western lake district and 16 of its surrounding polders. Names and numbers according to the information of the Water Boards: E (Echtener Veenpolder), D (Delfstrahuizen), V (Vierhuis), O (Oldeouwer) and 22-47. The arrows mark the locations of the pumping stations or the main flow direction in the canals. G: Groote Veenpolder, RM: nature reserve Rottige Meente. Lemmer, Heeg and Joure are stations of the Royal Netherlands Meteorological Institute. **B**: The Echtener Veenpolder (2850 ha) ---: polder ditches with low water levels; —— : polder ditches with high water levels. ● : sampling station in a low level ditch. ■ : sampling station in a high level ditch. A,B,C and D are sampling stations in the main polder ditch.

the Water Board and farmers, b) inlet of water by individual farmers, c) pumping of superfluous water d) flushing and irrigation.

MATERIALS AND METHODS

The capacities as well as the number of electrical operation hours of the pumping stations were obtained from the regional Water Boards. These values were used to calculate the daily (Echtener Veenpolder: September 1984-December 1987) or monthly (Echtener Veenpolder: January 1980-August 1984; polders D, V, and O: 1984-1987; polders 22-47: April 1985-December 1987) discharges. *Because of technical and hydrological reasons it was impossible to register the values* for all surrounding polders and/or for all months. For example, no information was obtained about the polders north-west of Tjeukemeer. Yet, in this way approximately 70% (11560 ha) of the polder area with a direct pumping of superfluous water into the south-western boezem system was covered resulting in a unique data set for a peaty district.

Weekly sampling took place in the main polder ditches in direct connection with the pumping stations, about 50-100 m inside the polders. Sampling started in September 1984 (Echtener Veenpolder) or May 1986 (polders 22-47) up to December 1987. Polders D, V, O and 46 were not sampled because of technical reasons. About 10 liters of the upper 50 cm of the water column were taken and a sub-sample of 100 ml was extracted. The samples were analyzed for total phosphorus. In the detailed Echtener Veenpolder study also locations in the high and low water level ditches were sampled. No sampling took place during ice periods. Occasionally some other investigations took place such as registration of inflowing water quantities and measurement of electrical conductivity in the polder ditches.

Phosphorus was analyzed colorimetrically either manually or using a Technicon AA II autoanalyser. Total phosphorus was measured after hydrolysis for 2.5 h at 110°C in acidic (0.15 M H_2SO_4) persulphate (5%). Colorisation of phosphate took place with a molybdate reagent (Murphey and Riley, 1962).

RESULTS AND DISCUSSION

Introduction

The first part of this section deals with the detailed Echtener Veenpolder study, while the second part treats the other 15 polders. Where meaningful a comparison is made with the Echtener Veenpolder. Generally, the P-loads in this paper are gross P-loads per ha polder area, while concentrations are TP concentrations. Some preliminary results of the 1985 polder research were reported by Van Huet (1990).

Water balances and discharges of the Echtener Veenpolder

The contributions to the water balance of the Echtener Veenpolder (2850 ha) were quantified. The water balance equation is:

$$St = Q_p + Q_{in} + Q_w - Q_e - Q_{out} - Q_i \qquad (1)$$

where, St = Water storage (mm.yr^{-1} or m^3.yr^{-1})
Q_p = Precipitation ("), average value of stations Lemmer, Heeg and Joure
Q_{in} = Inlet of boezem water (")
Q_w = Domestic waste water ("), ignored (Steenvoorden, 1977)
Q_e = (Evapo)Transpiration ("), average value of stations Leeuwarden and Lelystad
Q_{out} = Discharge of polder water pumped into the boezem system (")
Q_i = Infiltration ("), 0.1 mm.d^{-1} (Broers, 1987)

The contribution of the water storage (St), per month, is unknown. However, assuming that the same maximum water levels in the ditches and soil occur in the winter periods, St can be assumed to be zero in yearly water balances. Yet, differences of some centimeters may occur, but this value is low as compared to most other contributions to the water balance (Table 1). Therefore, on a yearly basis Q_{in} is the only unknown contribution of the water balance:

$$Q_{in} = Q_{out} - (Q_p - Q_e) + Q_i \tag{2}$$

In Table 1 the contributions of the yearly balances are given for the period 1980-1987. It can be concluded that inlet of boezem water was low in 1985 and 1987 and relatively high in 1980. Figure 3A shows the monthly discharges from the polder into the boezem (Q_{out}). Generally, monthly discharges were highest during winter periods, due to a precipitation excess. This does not hold, however, for the years 1985 and 1987: during the summer periods of these years precipitation excess occurred and therefore monthly Q_{out} values were relatively high. During the summer periods of 1980-1984 and 1986 a precipitation deficit occurred, resulting in relatively high water inlet values (Q_{in}). Moreover, in the polder even periods occurred with both inlet and pumping, due to a bad coordination of these processes. Even in times of precipitation deficit the pumping station can be in operation or in times of precipitation excess inlet can take place. Basic discharges of approximately 15 mm.mo^{-1} or 0.5 mm.d^{-1} were quantified. Consequently, insight into the pumping and inlet regime is necessary for an optimum management. An important question for the decision makers in water quality and quantity management is: what can be done to reduce these values? To answer this question a dynamic analysis of the processes that lead to the complex hydrology is needed. This analysis is beyond the scope of the polder research.

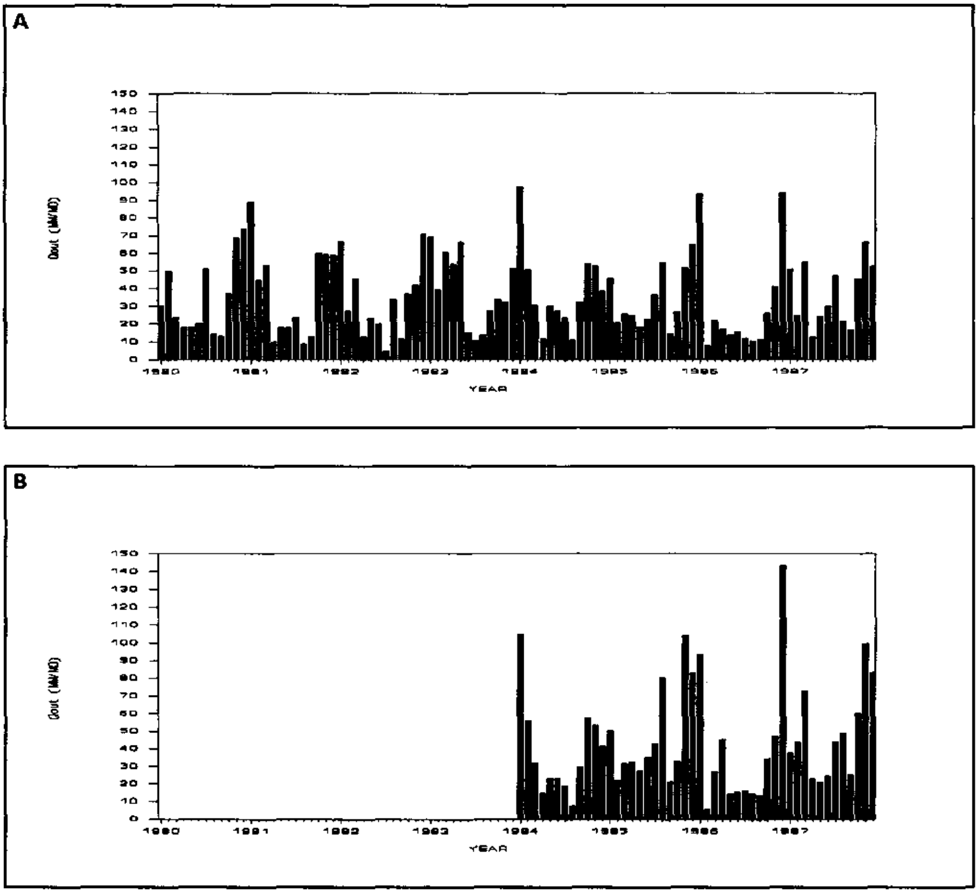

Figure 3. Time pattern of discharges in mm.mo^{-1} during 1980-1987. A: Discharges from the Echtener Veenpolder into Tjeukemeer. B: From other polders into the boezem system (for explanation see text).

Table 1. Water balances contributions in 10^6 m^3.yr^{-1} (a) and mm.yr^{-1} (b) of the Echtener Veenpolder (Q_p = precipitation; Q_{in} = inlet of boezem water; Q_e = (evapo)transpiration; Q_{out} = discharge of polder water; Q_i = infiltration).

	In:				Out:					
	Q_p		Q_{in}		Q_e		Q_{out}		Q_i	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
1980	19.9	698	9.5	333	16.4	575	12.0	421	1.0	35
1981	24.3	853	4.8	168	15.1	530	13.0	456	1.0	35
1982	20.7	726	8.0	281	16.4	575	11.3	396	1.0	35
1983	22.9	804	7.7	270	16.1	565	13.5	474	1.0	35
1984	24.7	867	2.9	102	13.7	481	12.9	453	1.0	35
1985	25.3	888	0.9	32	13.6	477	11.6	407	1.0	35
1986	21.9	768	4.7	165	15.2	533	10.4	365	1.0	35
1987	24.1	846	1.3	46	11.6	407	12.8	449	1.0	35

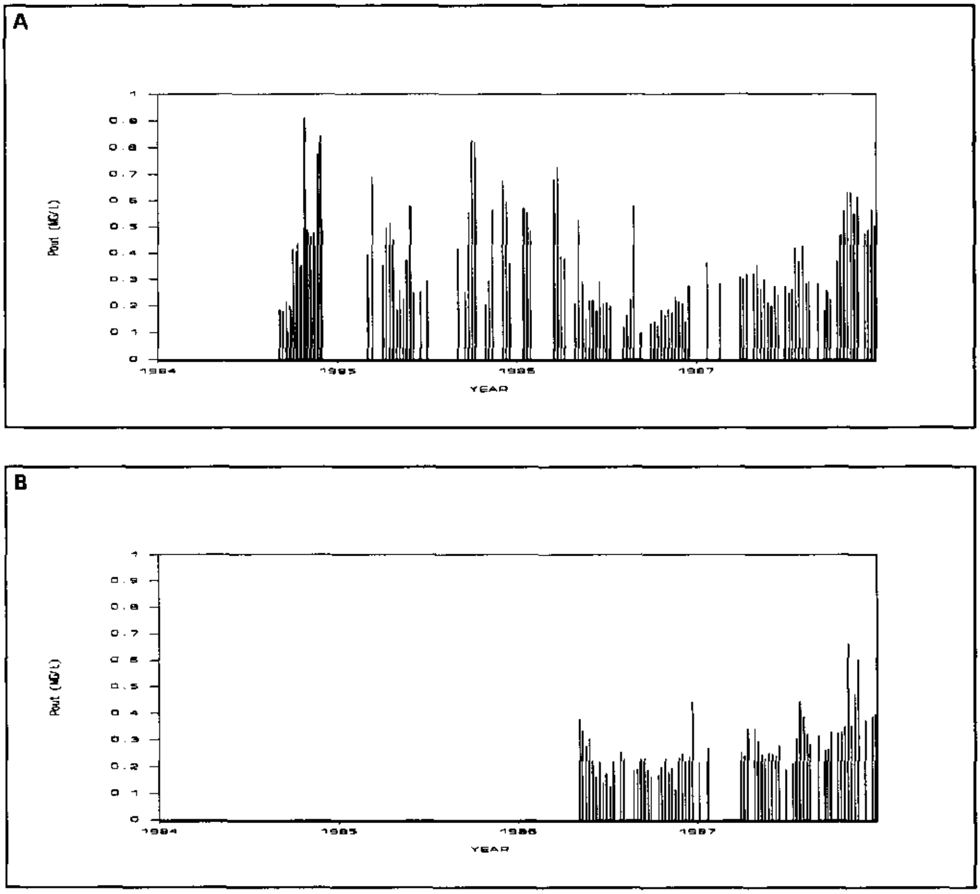

Figure 4. TP concentrations in mg.l^{-1} in discharged polder water. **A**: Echtener Veenpolder, per sampling date. **B**: Polders 22-47 (except 46), averaged per sampling date.

TP concentrations and gross P-loads of the Echtener Veenpolder

Figure 4A shows the TP concentrations in the polder water pumped into the boezem (P_{out}). The concentrations were highest in the winter period (up to 0.9 mg.l^{-1}), and lowest in the summer period. The high winter values are probably caused by processes as runoff and leaching, release from sediments and/or resuspension. The contribution of the surface runoff is hard to quantify. Peak runoffs are likely in periods with high precipitation quantities on soils with a reduced water permeability for water due to soil physical characteristics or a high groundwater table. Spreading of slurry under these circumstances will lead to high TP concentrations in runoff water. This process can occur in the winter period, particularly when the ground is frozen. On the contrary the relatively

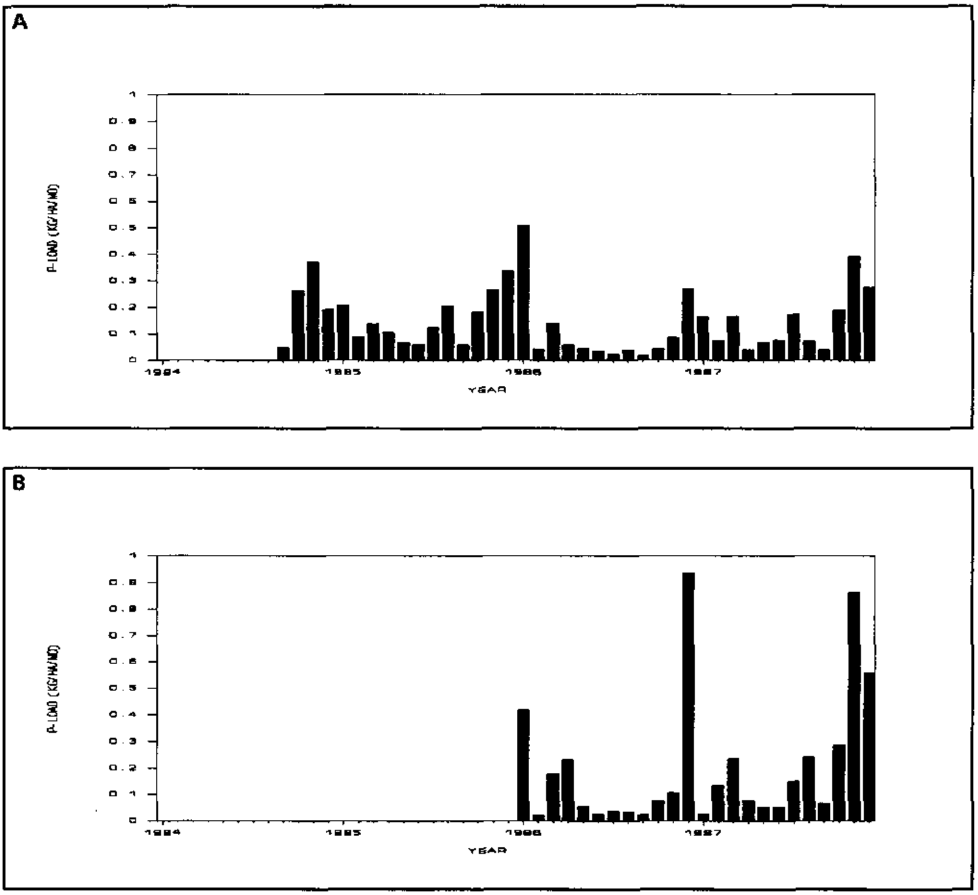

Figure 5. P-loads in kg P.ha^{-1}.mo^{-1}. **A**: From the Echtener Veenpolder into Tjeukemeer. **B**: From other polders into the boezem system (average loads from polders 22-47, except 46).

low values in the summer period of 1986, are probably caused by low runoff quantities and inlet of boezem water. The average TP concentration of the Echtener Veenpolder water during 1984-1987 was 0.37 mg.l^{-1}, while the average TP concentration in the Tjeukemeer was 0.28 mg.l^{-1}.

Van Huet (1990) reported upon significantly higher concentrations during September-December 1984 when the pumping station was in operation, probably due to high runoff rates caused by precipitation. Also resuspension of P can play a role: resuspension takes place above a critical bottom shear stress value.

Figure 5A shows the monthly P-loads for the Echtener Veenpolder as far as data were available. The P-loads are calculated from daily discharges and interpolated weekly TP concentrations (P-load

$= Q_{out} * P_{out}$). Because of both high Q_{out} values and TP concentrations in the winter periods, monthly P-loads were highest in these periods. However, also during the summer periods of 1985 and 1987 monthly P-loads were relatively high because of precipitation excess.

In Table 2 the yearly and half-yearly loads for 1985, 1986 and 1987 are given. These results are important because of the characteristic hydrology in the canal-lake system. Table 2 shows that *during the winter periods P-loads were highest.*

Table 2. Yearly and half-yearly gross and net P-loads from the Echtener Veenpolder to the Tjeukemeer.

	Gross P-load		Net P-load	
	kg P	kg $P.ha^{-1}$	kg P	kg $P.ha^{-1}$
1985	5201	1.82	4226	1.48
1986	3709	1.30	1787	0.63
1987	4924	1.73	3887	1.36
Winter (Oct. 1984 - Apr. 1985)	3580	1.26	-	-
Summer (Apr. 1985 - Oct. 1985)	1755	0.62	-	-
Winter (Oct. 1985 - Apr. 1986)	4188	1.47	-	-
Summer (Apr. 1986 - Oct. 1986)	614	0.22	-	-
Winter (Oct. 1986 - Apr. 1987)	2278	0.80	-	-
Summer (Apr. 1987 - Oct. 1987)	1335	0.47	-	-

Net P-loads and P contributions of the Echtener Veenpolder

The purpose of the detailed study in the Echtener Veenpolder was to examine whether or not there were P contributions from processes inside the polder. Insight into these processes is needed for an optimum management. The calculated P-loads in the previous part of this paper are gross loads. *Table 2 also shows an approximation of the net P-loads. These loads are calculated according* equation 3:

$$P\text{-}load_{net} = Q_{out} * P_{out} - Q_{in} * P_{in} - (Q_p * P_p - Q_i * P_i) \tag{3}$$

where, $P\text{-}load_{net}$ = Net P-load of the Echtener Veenpolder (kg P)

Q_{out} = Discharges of polder water (m^3)

P_{out} = TP concentration in discharged water (kg $P.m^{-3}$)

Q_{in} = Inlet of boezem water (m^3)

P_{in} = TP concentration in inlet (boezem) water (kg $P.m^{-3}$)

Q_p = Precipitation (m^3)

P_p = Measured TP concentration in precipitation water (kg $P.m^{-3}$), 0.04 $mg.l^{-1}$
Q_i = Infiltration (m^3)
P_i = TP concentration in infiltration (boezem) water (kg $P.m^{-3}$)

Hence, the net P-load is calculated by subtracting the (more or less) natural contributions from the gross P-load. Although it should be realized that the net P-load values are only rough approximations, Table 2 shows that there was a polder P contribution. Half-yearly net loads could not be quantified because monthly storage is not known. The polder contribution is probably the result of spreading manure and fertilizers, import of cattle food and processes such as runoff, leaching, resuspension, etc. Consequently, this shows the influence of agriculture, and the contribution of peaty soil.

A detailed P balance study of the Echtener Veenpolder took place in 1984 (Van der Molen, 1984). The surface water P balance (December 1983-November 1984) showed that large quantities of the incoming P accumulate in the sediment and soil (estimated at 30-40%). The contribution of the precipitation was negligible, and that of agriculture was estimated at 25%-40%.

In order to verify the influence of the polder P sources, during two periods (September- December 1984 and half of May-half of July 1986) two groups of polder ditches were sampled on TP. The first group consisted of 5 locations in polder ditches with relatively high water levels, while the second group consisted of 10 locations in ditches with low water levels (see Figure 2B and Area description and hydrology). For both periods averaged TP concentrations in the low level ditches were higher than those in the high level ditches (Table 3), due to the fact that high level ditches generally contain more boezem water and low level ditches (generally more deeper in the polder) contain runoff water, waste water, etc. Table 3 again shows the differences between TP concentrations in a winter period and a summer period: the 1984 concentrations were high, probably because of precipitation excess, and runoff, while the 1986 concentrations were relatively low because of precipitation deficit and consequently, inlet of and flushing with boezem water. These results show again that processes within the polder contribute to the P load to Tjeukemeer.

Table 3. Average TP concentrations in $mg.l^{-1}$ in polder ditches during 1984 and 1986 (n = the number of samples; for locations see Figure 2B).

	High level ditches	Low level ditches	n
4 Sep - 29 Nov 1984	0.25	0.33	13
14 May - 9 Jul 1986	0.18	0.19	9

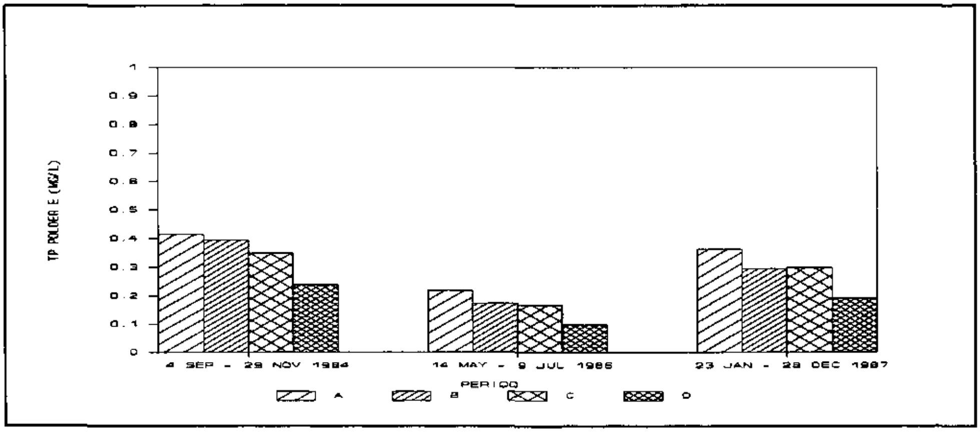

Figure 6. TP concentrations of four stations in the main polder ditch (low level) of the Echtener Veenpolder (for locations see Figure 2B).

Figure 6 shows a third indication of the polder P contribution. This figure shows TP concentrations of four stations in the main polder ditch (low level) that discharge water towards the pumping station. Several other low level side-ditches discharge their water into this main ditch. The TP concentrations in the water of the southern sampling station (location D, Figure 2B, most remote from the pumping station, with relatively low influences of the side-ditches and therefore processes within the polder) were significantly lower than the concentrations in the water of the northern sampling stations (location A, B and C).

Water discharges of other polders

Figure 3B shows the monthly discharges (Q_{out}), averaged over a number of polders (January 1984 - April 1985: polders E, D, V, and O; April 1985 - December 1987: all 16 polders). For the period April 1985 - December 1987 nearly all discharges of all polders (11560 ha) could be quantified. Only 6% of the values are missing. For these values the averaged values of the other polders were used. Figure 3B shows that also for the other polders discharges were highest in the winter period. The relative discharges of the individual polders were in good agreement with each other. The five largest polders (polders E, D, V, O and 36) discharge their water into Tjeukemeer. Therefore, this lake received relatively much polder water, compared with the other lakes Slotermeer, Groote Brekken and Koevorder. The averaged value of all polders for this period of 33 months was 53 $mm.mo^{-1}$, with a standard deviation of 17 $mm.mo^{-1}$. The climatological differences between the years 1986 and 1987 are reflected in the total discharges of all 16 polders: 54.3 10^6 $m^3.yr^{-1}$ (470 mm) and 67.5 10^6 $m^3.yr^{-1}$ (584 mm), respectively.

TP concentrations and gross P-loads of other polders

Figure 4B shows the average TP concentrations in discharged water of 11 polders (P_{out} 22-47, except 46), with a total surface area of 4200 ha. The averaged concentrations in 1986 and 1987 were 0.22 and 0.32 $mg.l^{-1}$. However, individually measured TP concentrations reached values up to 3.0 $mg.l^{-1}$. Sampling did not take place during January-April 1986, while during January-March 1987 only twice was sampled. Therefore, the real average TP concentrations are probably higher. For these years the average TP concentrations in boezem water was 0.26 $mg.l^{-1}$. In order to calculate the annual P-loads, the measured concentrations of the Echtener Veenpolder were used (see Figure 4A) for the missing values. Table 4 shows the yearly and half-yearly P-loads, while Figure 5B shows the monthly loads per ha. Again, the loads were highest in the winter period. The high loads in December 1986 and November 1987 are caused by very high measured TP concentrations in polder 36. No explanation could be found for these high values. The overall averaged loads for 1986 and 1987 were 1.86 and 2.41 kg $P.ha^{-1}.yr^{-1}$, respectively. The loads for the Echtener Veenpolder (total polder area 2850 ha) in 1986 and 1987 were 1.3 and 1.73 kg $P.ha^{-1}.yr^{-1}$, respectively (Table 2).

Recently some other investigations took place in peaty polders with agricultural land use (polders 23-26) and in nature reserves in the province of Friesland (Province of Friesland, unpublished results). P-loads were in agreement with the results reported in this paper or even higher (up to 5.7 kg $P.ha^{-1}.yr^{-1}$). It was concluded that the contribution of agriculture and leaching together could be very high (up to 85%) and that leaching of P in the polders with agricultural activities was on the same level as in nature reserves.

Table 4. Yearly and half-yearly gross P-loads in $kg.ha^{-1}$ from polders 22-47 to boezem water.

Polder	22	23	24	25	26	27	32	33	36	42	47
1986	1.01	1.10	1.31	1.42	1.50	1.46	2.47	1.92	4.13	1.64	2.46
1987	1.63	3.65	1.18	2.88	1.71	1.15	3.20	2.34	3.79	2.51	2.51
Summer (Apr. 86 - Oct. 86)	0.22	0.20	0.22	0.34	0.32	0.27	0.53	0.29	0.68	0.30	0.97
Winter (Oct. 86 - Apr. 87)	0.75	0.90	0.73	0.97	0.92	0.71	1.67	1.34	3.13	1.07	1.40
Summer (Apr. 87 - Oct. 87)	0.51	0.90	0.46	0.77	0.18	0.28	0.88	0.49	0.68	0.68	0.80

CONCLUSIONS

This paper shows that high P-loads occur from polders to the boezem water. The loads are highest in the winter period, while the loads to the Tjeukemeer are very high compared with the loads to other lakes in the research area. Particularly in winter, the TP concentrations in discharged polder water are higher than in boezem water. Therefore, a reduction of these concentrations can be important in combatting the eutrophication problem in the lakes. Bots et al (1978) concluded that TP concentrations in polder water were lower than in boezem water, which is in contradiction with the results of this paper. This could mean that within the elapsed period of about 15 years the polder water quality (regarding P) has deteriorated.

The environmental and agricultural policy have contradictory interests (Van Bakel, 1988; Terwan, 1988; Steenvoorden and Bouma, 1987), and more research is needed. However, this research was beyond the scope of this study. Because of management reasons, the role of agriculture and physico-chemical processes such as accumulation, local leaching, runoff and the adsorption capacities of soils (Van der Zee, 1988) need more attention. Also dynamic water and P balances are necessary for an optimum water quality and quantity management in the polders. The complex hydrology in, for example, the Echtener Veenpolder or the Groote Veenpolder (nature reserve Rottige Meente, Jansen, 1988b) and consequently the changing character of the several contributions of the water balance do not lead to an optimal water regime (e.g. simultaneous pumping and inflow of water may occur).

The calculated discharges and P-loads were used for balances and models of the canal-lake system. The direct contribution of polder P-loads to the P balances during the period 1985-1987 was estimated at 4% in the summer period and 27% in the winter period (Van Huet, unpublished results). Moreover, the canals Broeresloot and Pier Christiaansloot, east of Tjeukemeer, also discharge polder water of the river Tjonger (Figure 1B) which has a catchment area of about 30 10^3 ha. Therefore, inflow of this water into the Tjeukemeer can be regarded as an indirect P-load from polders. In this way the total polder P-load contribution to the P balance of the south-western lake district reached values up to 99% in November 1987.

Chapter 5

Application of a wind-driven hydrodynamic model for the quantification of transport in an open boundary canal-lakes system in sw Friesland, The Netherlands

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Submitted to Aquatic Sciences

APPLICATION OF A WIND-DRIVEN HYDRODYNAMIC MODEL FOR THE QUANTIFICATION OF TRANSPORT IN AN OPEN BOUNDARY CANAL-LAKES SYSTEM IN SW FRIESLAND, THE NETHERLANDS

Key words: wind-driven hydrodynamic model, sensitivity analysis, water balance, water quality, eutrophication

ABSTRACT

The south western lake district is a part of the 'boezem', a system of interconnected lakes and canals in the province of Friesland. The lake district has open boundaries with the other part of the boezem system. Discharges, however, in the (boundary) canals are unknown. These discharges are needed for modelling the phosphorus (P) dynamics in the study area. Incidental water flow measurements gave a good indication of the complex water transport in the study area, but continuous water flow recording was not possible and, consequently, discharges could not be measured directly. Therefore, it was necessary to model the water transport in the area. This was done by the application of a detailed wind-driven hydrodynamic model. For the model, hourly mean values of wind data and water levels at the boundary locations were used as forcing functions.

The water velocities occasionally measured in the several canals were too infrequent to be used for calibration. Therefore, model tuning was done by comparing observed and computed water levels of three stations within the system. A parameter sensitivity analysis showed that the sensitivity was low for modifications of the wind exponent value and rather high for the bottom roughness coefficient, while model reliability and uncertainty analysis showed that sensitivity for noise at the imposed water levels at the boundary locations was moderate. Simulations with daily or weekly mean wind and water level data resulted in an undesirable loss of detail.

The simulations lead to the quantification of the water balance and water residence times in the lakes. The computed discharges in the boundary and interconnecting canals will be used as input data for a chloride (Cl^-) and P model.

INTRODUCTION

The sw Frisian lake district (water surface area 40 km^2) is a part of the 'boezem': a system of interconnected lakes and canals in the province of Friesland, with a total water surface area of 140 km^2 (Fig. 1). The boezem water is highly eutrophicated: total-P and total-N concentrations are mostly above 0.2 and 2.0 $mg.l^{-1}$, while summer chlorophyll-a concentrations above 150 $\mu g.l^{-1}$ occur (De Haan and Moed, 1985). In 1984 a eutrophication study started, which focused on modelling hydrodynamics, quantification of water and P balances, P dynamics and algal growth. In this paper the results of the hydrodynamic part of the project are reported. For further information about water quality and trophic relationships in the area, see Beattie *et al.* (1978), Moed and Hoogveld (1982), De Haan and Moed (1984), Claassen (1986), Lammens (1986) and Van Huet (1987).

Modelling of the surface water transport of the (whole) boezem system was the subject of former studies (Pellenbarg, 1973; Tuinhof, 1976, Leenen, 1982; Brinkman *et al.*, 1987; Brinkman and Van Straten, 1989; Brinkman and Smeitink, 1989). In general, the results of these models were reasonable satisfactory for the simulation of, for instance, weekly mean discharges in the interconnecting canals and the weekly mean water levels in the system. However, these model simulations did not result in a detailed insight in the water transport in the sw lake district, because among others, no wind-terms were used, the node-link network was less detailed and the flow was assumed to be period-wise stationary. In order to get a better impression of the water transport in the study area, water flow measurements were done, being a part of the above mentioned eutrophication study. In addition, a detailed wind-driven hydrodynamic model was used in order to calculate the water balances of the area and the discharges in the connecting and boundary canals. The quantification of these discharges is necessary for simulating the P dynamics in the lake district (see above and Van Huet, 1990).

AREA DESCRIPTION AND SEASONAL VARIATION

The shallow lakes (water depth 1-2 m; surface water area 3.5-20 km^2) and canals (water depth 1-4 m; width 30-60 m) in the lake district (Fig. 1), originated from excavation of surface peat for fuel and from floods from the sea. Because of the flat character of the surrounding meadow land the wind can have a great influence on the water transport in the boezem system. There are two main canals in the south western boezem part (Fig. 1): Prinses Margrietkanaal (between Lemmer and the province of Groningen) and Follegasloot (between Groote Brekken and Tjeukemeer).

The boezem is used hydrologically for regulating the water table of Friesland, for flushing and for water supply of the province of Groningen. The water surface levels in IJsselmeer can be 0.2-0.4 m minus N.A.P., the target level range in the boezem system is 0.51-0.54 m minus N.A.P., while

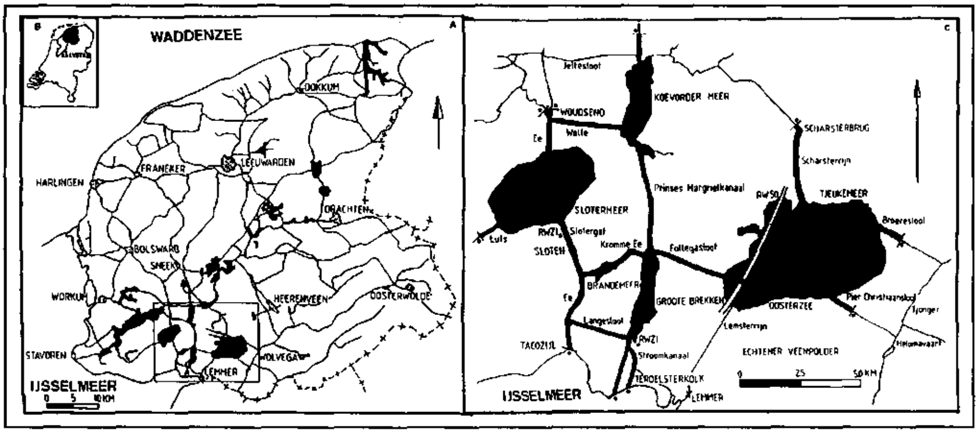

Fig. 1. A. The Frisian 'boezem'. B. Its position in The Netherlands. C. The south western lake district (●_: boundaries research area; RWZI: waste water treatment plants; RW50: motorway 50; from Van Huet *et al.*, 1987).

the water levels in the ditches of the surrounding polders can range from 0.6 m to even 2.5 m minus N.A.P. The water level simulations in this paper are expressed in F.Z.P., where F.Z.P. = 0.66 m minus N.A.P. (N.A.P. and F.Z.P. are the Dutch and the regional water reference levels, respectively).

The regulation of the water table can be done by inflow of IJsselmeer water into the boezem system (near Lemmer, Tacozijl and Stavoren), by inflow of boezem water into the surrounding polders, by pumping of polder water into the boezem system, by pumping of boezem water into IJsselmeer (near Lemmer and Stavoren), by draining off boezem water into the Waddenzee or by the transport of boezem water towards the province of Groningen. These processes are highly influenced by the climatological conditions. Generally, in summer (April-October) inflow takes place, while in winter (October-April) pumping of superfluous water occurs. Inflow and pumping, however, can also occur in winter and summer, respectively. For a survey of the inflow water quantities to the boezem and the quantities pumped into IJsselmeer near Lemmer, Tacozijl and Stavoren during 1984-1986, see Van Huet (1990), and for the polder water quantities Van Huet (b).

The Cl^- concentrations in IJsselmeer water, originating from the river Rhine, can be very high (up to 300 $mg.l^{-1}$), while the polder water can contain much humic substances. Particularly, the fluctuating chloride concentrations in the boezem water can act as a rough indication of the water transport and as a tool for the calibration or the validation of the hydrodynamic model, see the section *Chloride and EC measurements*.

A FIRST ORIENTATION: CHLORIDE AND WATER FLOW MEASUREMENTS

Chloride measurements

Leenen (1982) used the conservative chloride ion as a tracer for studying and modelling flow processes in and around Tjeukemeer. This author concluded that during 1971 the correlation between inflow on the one hand via Lemmer and Stavoren and on the other inflow through Follegasloot was high. Van Huet (1990) showed that during 1984-1986 the chloride sequences in Groote Brekken, Tjeukemeer west, Tjeukemeer east and Slotermeer, agreed very well. Slotermeer seemed to be a relatively isolated lake, while the mean Cl^- concentration in Tjeukemeer west was higher than in Tjeukemeer east, due to processes such as inflow of IJsselmeer and polder water, respectively. During the period 1984-1987 the chloride concentrations in the inflow canal near Lemmer and the concentrations in the Tjeukemeer and the Slotermeer were significantly correlated ($r = 0.63$ and 0.5, respectively; $p < 0.001$).

The correlation between the Cl^- concentration and the electrical conductivity (EC) is very high. For example, during 1984-1987 Cl^- and EC in the Tjeukemeer were significantly correlated ($r = 0.98$, $p < 0.001$), indicating that even simple EC measurements at several locations in the area are a valuable tool for an impression of the water transport processes. Measurement of these parameters give some idea of the origin of the water, but do not result in detailed information about the water transport. For a better insight and for the quantification of this process, water flow measurements and modelling are necessary.

Water flow measurements

Water flow measurements were done six times during daily periods, simultaneously in several canals of the sw lake district. During these days the water flow direction and the water transport time at several depths was registered by using a simple semi-floating object. The quantification of the discharges in the canals was done by using this information, as well as, the information of measurements of cross sectional areas.

The water flow measurements covered both usual circumstances as well as very characteristic circumstances such as maximum inflow near Lemmer and Tacozijl, maximum pumping of water into IJsselmeer near Lemmer and Stavoren, and periods with high wind velocities. An impression of the results of three characteristic circumstances is given in Van Huet *et al.* (1987). In Fig. 7 the water flow directions and discharges in some canals are shown in the case of inflow of IJsselmeer water near Lemmer and Tacozijl. More frequently, water flow measurements were done in Follegasloot (Fig. 2). Here we will restrict ourselves to the main conclusions deduced from these measurements.

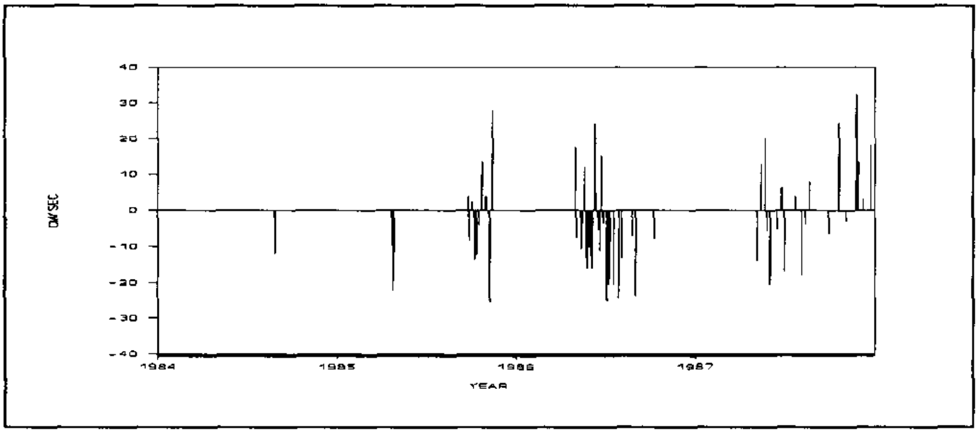

Fig. 2. Depth averaged water velocities in cm.sec^{-1} in the Follegasloot. Occasionally measured during 1984-1987 (+: water flow in direction Groote Brekken; -: water flow in direction Tjeukemeer).

The following conclusions can be drawn: 1) During the characteristic circumstances rather consistent results were found, due to the unequivocal conditions. 2) The measurements showed the influence of the pumping station Stavoren: when this station was in operation, especially west of the Prinses Margrietkanaal and even north of the Tjeukemeer water flowed in direction Stavoren. 3) Water transport was highest in Prinses Margrietkanaal and Follegasloot in the case of the characteristic circumstances, indicating that the water quality in the Tjeukemeer is highly influenced by water transport through Follegasloot. 4) Wind and other phenomena as the draining off of boezem water into the Waddenzee may have influence on the water transport. 5) Within a daily period the water flow direction can change. 6) Fig. 2 shows a water velocity range of -30 to +30 cm.s^{-1} in Follegasloot. Similar ranges were found in the other canals.

These results indicate that the water transport in the area is a complex process. Incidental flow measurements result in a reasonable survey, but do not lead to the detailed water discharges data necessary for simulating the P dynamics. On the whole, flow measurements were difficult and laborious. Detailed information can only be obtained by continuous measurements by using more sophisticated techniques and this was not possible. An alternative is the application of a water transport model, using much easier obtainable continuous level records.

THE HYDRODYNAMIC MODEL

Introduction

The model that was used is a simplification of the node-link dynamic water movement model of Orlob (1972), which also was applied by Lijklema and Van Straten (1975, 1978) and Rengersen (1980) to a similar canal-lake system in north-west Overijssel, The Netherlands. A rather extensive model description is reported by these authors, therefore in this paper only a brief summary is given.

Model description

Fig. 3 shows the node-link network system in the south-west Frisian lake district. This network consists of 53 nodes and 77 links. Each link in the system, corresponding either to a real channel or a lake part, is defined in terms of length, depth, width and the angle to a reference direction. Each node in the system is identified by a water level with respect to a reference level and a surface area, which includes half the surface area of the connecting links. The total water surface area of the network system is 37.3 km^2. Because of technical reasons the network covers only a part of the Koevorder Meer.

The equation of motion in every link is:

$$\frac{\partial u}{\partial t} = - g \frac{\partial H}{\partial x} - \frac{g |u| u}{Ch^2 R} + \frac{c_z \rho_A W^{\epsilon}}{d \rho_W} \cos(\alpha - \theta) \tag{1}$$

in which u = the mean velocity; t = the time; g = the gravitational acceleration; H = the elevation of the water surface above a reference level; x = the distance; Ch = the Chézy coefficient for bottom roughness; R = the hydraulic radius, approximately equal to the depth d for wide shallow canals; c_z = the friction coefficient of the water-air interface; ρ_A and ρ_W = the densities of air and water; d = the water depth; W = the wind velocity; $\in$ = wind exponent; and α and θ = the angle of the wind direction and the link to a reference direction.

The equation for the Chézy-coefficient can be derived from Manning's and Chézy's formulas:

$$Ch = \frac{R^{\frac{1}{6}}}{n} \tag{2}$$

where n is Mannings's coefficient, a function of the absolute roughness of the channel bottom,

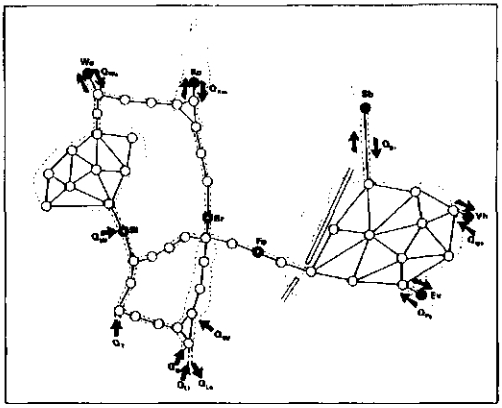

Fig. 3. The node-link network and the locations of the pumping and inflow stations, waste water treatment plants. •: imposed water level data; •: water level data used for model tuning.

which was assumed to be constant.

For every node the continuity equation is applied:

$$\frac{\partial H}{\partial t} = \frac{1}{O}\left(\Sigma\, uA + \Sigma\, Q\right) \tag{3}$$

in which O = the node surface area; A = the cross-sectional area of the connecting link; and ΣQ = the net effect of inputs and outputs to each node excluding the flow through links. For the model simulations a third order Adams-Bashfort numerical integration procedure was used. Coriolis's acceleration and the Bernoulli term were omitted and a constant cross-sectional area was assumed.

Water balance contributions

The inputs and outputs allocated to a node (ΣQ, equation 3) can be part of the several contributions of the water balance. The water balance equation for the total water area is:

$$St = Q_{Li} + Q_T + Q_{po} + Q_p + Q_w + Q_s - Q_{Lo} - Q_{pi} - Q_e - Q_i \pm \Sigma Q_{bc} \tag{4}$$

The relation between equations 3 and 4 is:

$$St = \Sigma \frac{\partial H}{\partial t} O \tag{5}$$

where St = water storage; Q_{Li} and Q_T = inlet of Lake IJsselmeer water near Lemmer and Tacozijl, respectively; Q_{po} = outlet of polder water (pumped into the system); Q_p = precipitation; Q_w = contribution from waste water treatment plants; Q_s = inlet of Lake IJsselmeer water via sluices near Lemmer; Q_{Lo} = outlet of boezem water (pumped into Lake IJsselmeer); Q_{pi} = inlet of boezem water into the surrounding polders; Q_e = evaporation; Q_i = infiltration. ΣQ_{bc} represents the inflow and outflow through the system boundary canals Broeresloot (Q_{Bs}), Pier Christiaansloot (Q_{Ps}), Scharsterrijn (Q_{Sr}), Koevorder Meer (Q_{Km}) and the canals north of Woudsend (Q_{We}, Fig. 3). However, the ΣQ_{bc} contributions are unknown.

The water system in south-west Friesland is a partly open system. This is an important difference with the north-west Overijssel system where sluices are located at the system boundaries and thus flow through the boundary canals could be registered. Therefore, the water levels in the five sw Frisian boundary canals (stations Ev, Vh, Sb, Ko, Wo, see Fig. 3) were continuously registered and act as input data (forcing functions) for the model. The only exception is the western canal of the Slotermeer (Luts, see Fig. 1), because at this location there is scarcely inflow or outflow. In this way the water discharges in the five boundary links can be calculated and consequently, the simulations result in the complete water balance of the area.

Data registration and collection

For Q_p the mean daily values of the meteorological stations Lemmer, Heeg and Joure were used and for Q_e the mean daily values of stations Leeuwarden and Lelystad (Fig. 1). Hourly wind velocities (W) and direction (α) are also obtained from the stations Leeuwarden and Lelystad. However, as south-western winds are dominating and as the lake district is only separated from Lelystad by Lake IJsselmeer the values of Lelystad were used (see also *Model Tuning*). Q_i was estimated at 0.3 mm.day^{-1} (Broers, 1987). The registration of inlet of water into the surrounding polders is difficult and Q_{pi} was estimated from polder water balances (Van Huet, b). It was assumed that inlet only occurs during summer (April-October) and that daily inlet values are directly proportional to the precipitation deficit. The daily quantities of water pumped from the Echtener Veenpolder (Fig. 1) into the system were obtained from the local Water Boards (Van Huet, b). No such detailed values of other polders were available. The total polder surface area is six times the surface area of the Echtener Veenpolder. Therefore, the total outlet from polders (Q_{po}) was estimated as six times the Echtener Veenpolder discharges and these quantities were allocated to 16 selected nodes that correspond with the locations of the polder pumping stations. The daily contributions from the waste water treatment plants near Lemmer and Sloten (Q_w) as well as the discharges of the inlet stations Lemmer and Tacozijl (Q_{Li} and Q_T, respectively), the pumping station Lemmer (Q_{Lo}) and the sluices near Lemmer (Q_s, Fig. 3.) were obtained from the Department of Water Management of the Province of Friesland. Table 3, part A, shows that Q_i, Q_w and Q_s contribute little to the water balance.

Continuously water level registration in the five boundary canals (Fig. 3) took place with mechanical recorders, which were calibrated in July 1985. From the data of these recorders hourly mean values were calculated. It became apparent that during ice periods the registered data were not reliable. Altogether data of three periods are available for the model simulations, covering almost 25 months: August 8, 1985 - January 31, 1986; April 1 - December 31, 1986 and March 1 - December 20, 1987.

MODEL RESULTS AND DISCUSSION

Model tuning

The empirical wind stress coefficient c_z is dependent on the wind velocities (Banks, 1975). No further information was available, however, about c_z in systems like the south-western lake district. Corresponding to the north-west Overijssel simulations (Lijklema and Van Straten, 1978; Rengersen, 1980), c_z was assumed to be constant ($c_z = 5.7\ 10^{-4}$). For the basic simulation a wind exponent $\epsilon = 2$ was used, also according to the nw Overijssel simulations, while the mean Chézy coefficient was $Ch = 50\ m^{1/2}.s^{-1}$ (equation 2). For the nw Overijssel simulations a constant coefficient $Ch = 36\ m^{1/2}.s^{-1}$ was taken, which refers to a higher bottom roughness.

For model tuning there are two possibilities: comparison of computed and observed a) water levels and b) water flow data. For comparison of water levels hourly mean data of stations Fo, Br and Sl inside the system (Fig. 3) are available. For logistic reasons, water flow measurements at several locations took only place during a few days (see the section *Water flow measurements*). As previously discussed the measured flow data result in a good indication of the water movement in the district, showing that large fluctuations can occur even within half-daily periods. Therefore the range of the measured water flow data is a valuable tool for model tuning but the data are not used directly for this process.

A period of four weeks (October 1 - November 28, 1985) was selected for model tuning. Criteria for the selection were: fluctuations in the imposed water levels and wind velocities and a wide range of some of the most important water balance contributions.

The five boundary stations Ev, Vh, Sb, Ko and Wo (Fig. 3) of which water level data were used for model input, are located relatively close to each other and in some periods water levels were almost similar. Correlation analysis revealed that all imposed water levels are highly correlated, while the correlation coefficient decreases with the distance between the stations. Therefore, another criterion for the selected period was the occurrence of some difference among these imposed levels, see Fig. 4.

The selected period was characterized by high wind velocities in weeks 1, 2 and 3, and lower velocities in week 4 (weekly averages were 7.5, 7.2, 6.6 and 4.6 m.sec^{-1}, respectively). Precipitation was high in week 2 (Q_p = 2.1 10^6 m^3.week^{-1}) resulting in high Q_{po} and Q_{Lo} values (5.3 10^6 and 21.2 10^6 m^3.week^{-1}, respectively).

Fig. 5 shows simulated and observed water levels at station Fo. These levels agree very well. Generally this can also be concluded for all 25 months and for the other two stations inside the system (Br and Sl), indicating that the model results are satisfactory. Table 1 shows that also the computed water levels at locations Fo, Br and Sl are significantly correlated with the imposed levels of the boundary stations.

Table 1. Correlation between computed water levels of three stations within the system (Fo, Br, Sl), and imposed water levels of the five boundary stations (Ev, Vh, Sb, Ko, Wo) during November 1-28, 1985 ($n=672;p<0.001$).

	Ev	Vh	Sb	Ko	Wo
Fo	0.90	0.97	0.93	0.92	0.80
Br	0.93	0.88	0.93	0.98	0.79
Sl	0.86	0.87	0.91	0.91	0.93

In order to further substantiate the model results, in Table 2 *the simulated weekly mean water* velocities in two main canals, Follegasloot and Prinses Margrietkanaal are given (basic simulation, situation A). These values agree with the measured range. Situation B in this table reflects the results using wind data of station Leeuwarden. The highest difference is found in week 2, while in the other three weeks differences are relatively small. Situation C reflects the simulation results allocating the polder discharges (Q_{po}) to all nodes instead of the selected 16 nodes. This was done because polder water might reach the boezem system indirectly. The simulations show that there are no great differences with the basic simulation. Finally situation D reflects the simulation results where Q_{po} is halved: in the basic simulations Q_{po} was estimated as six times the Echtener Veenpolder discharges. There is no information available, however, about the exact polder surface area that discharges water to the boezem system. Table 2 shows that in the selected period halving the Q_{po} value does not greatly influence the water velocities in the two canals, but it is expected that in other periods in the case of very high Q_{po} values, larger differences might occur.

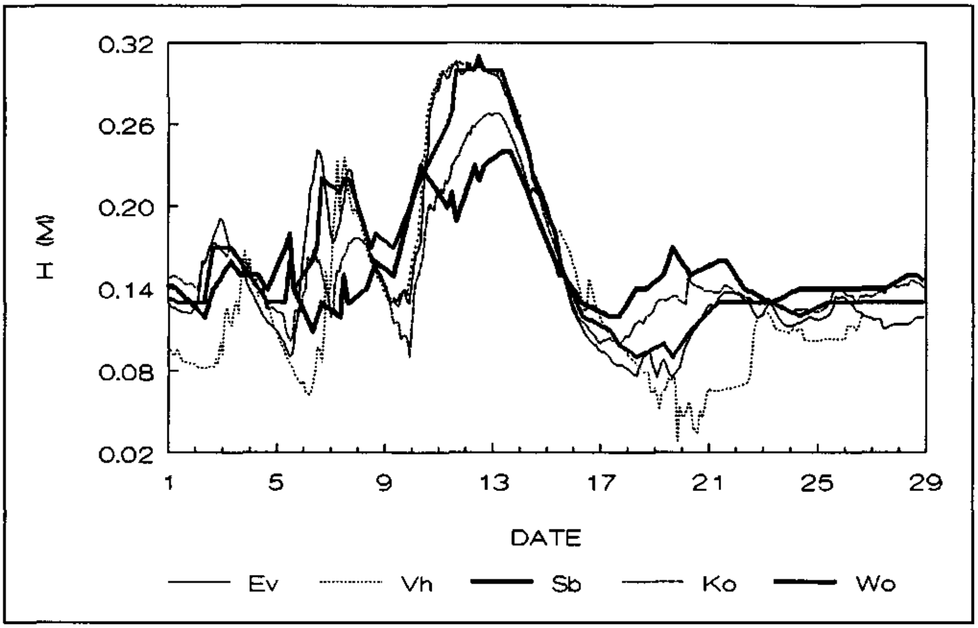

Fig. 4. Imposed water levels of the boundary stations Ev, Vh, Sb, Ko and Wo, during November 1-28, 1985.

Parameter sensitivity analysis

In order to verify further the influence of the wind term (W) and the wind exponent ($\in$) two alternative simulations were performed. Table 2 shows the simulation results in the case of $W=0$ (i.e. the model without a wind term, situation E): big differences with the basic water velocities in the Follegasloot and the Prinses Margrietkanaal occurred. Banks (1975) proposed low exponent values for low wind velocities and high exponent values for high velocities, combined with adjusted values of c_z, the friction coefficient of the water-air interface. Situation F reflects a simulation with $\in=1$ and $c_z = 2.85\ 10^{-3}$ if $W < 5$ m.sec^{-1}, $\in=2$ and $c_z = 5.7\ 10^{-4}$ if $5 \leq W \leq 10$ m.sec^{-1} and $\in=3$ and $c_z = 5.7\ 10^{-6}$ if $W > 10$ m.sec^{-1}. This simulation did not result in deviating water velocities, indicating that the model sensitivity is low with respect to a variable wind exponent and c_z values. From these analyses, it can be concluded that the model without a wind term leads to unrealistic results, while the assumption of a constant wind exponent and c_z value is allowable.

Two other simulations were performed with a relatively low Chézy coefficient (mean value = 30 m$^{1/2}$.s^{-1}, i.e. a high Manning value, meaning a high bottom roughness situation G, Table 2) and a high Chézy coefficient (mean value = 60 m$^{1/2}$.s^{-1}, situation H). The table shows that for this

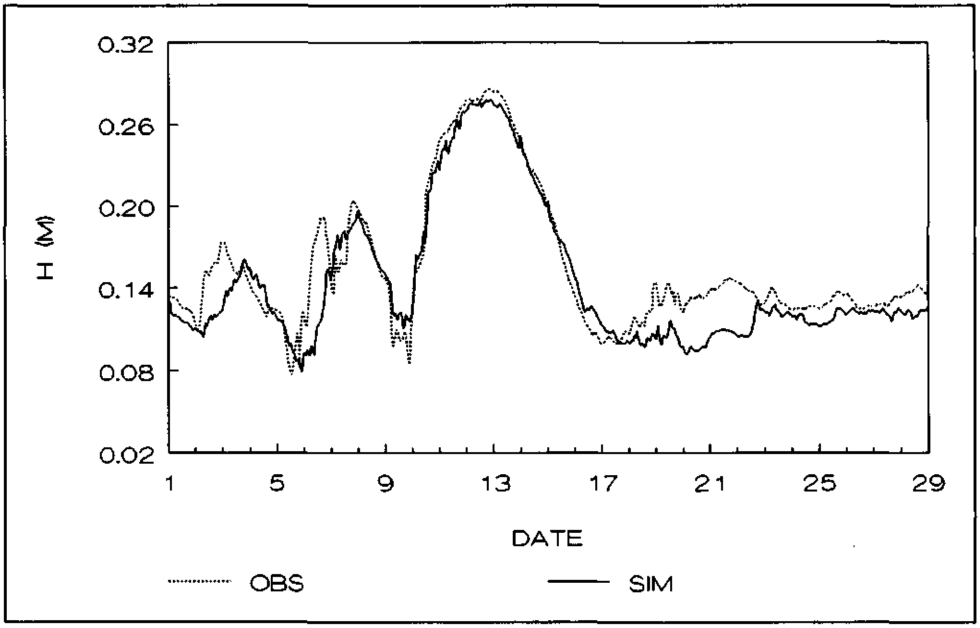

Fig. 5. Observed and simulated water levels at Fo (Follegasloot) during November 1-28, 1985.

parameter model sensitivity is high. The high-value simulations lead to a relatively high water velocity range in some links (not shown in Table 2).

The sensitivity for doubling the length of the boundary links (situation I) was relatively low in the two canals, but higher differences occurred in the velocities in the boundary links.

Model reliability and uncertainty

In the preceding simulations it was assumed, firstly, that all mechanical level recorders were properly calibrated and, secondly, no data registration and interpretation errors occurred. No systematic error could be found in the comparison of the imposed water levels of the five boundary stations. However, waves caused by boats and high wind velocities might lead to registration as well as interpretation errors, which are estimated as maximum deviations of ± 2 cm. Therefore, two further simulations were performed with a random (not correlated) first order filtered noise of ± 1 cm and ± 2 cm among the five forcing functions (situations J and K, respectively, Table 2). The differences in water velocities in the two canals with regard to the basic simulations were not high, the highest differences were found in the boundary canals. This result suggests that model sensitivity for inaccuracies in the forcing functions is not very high.

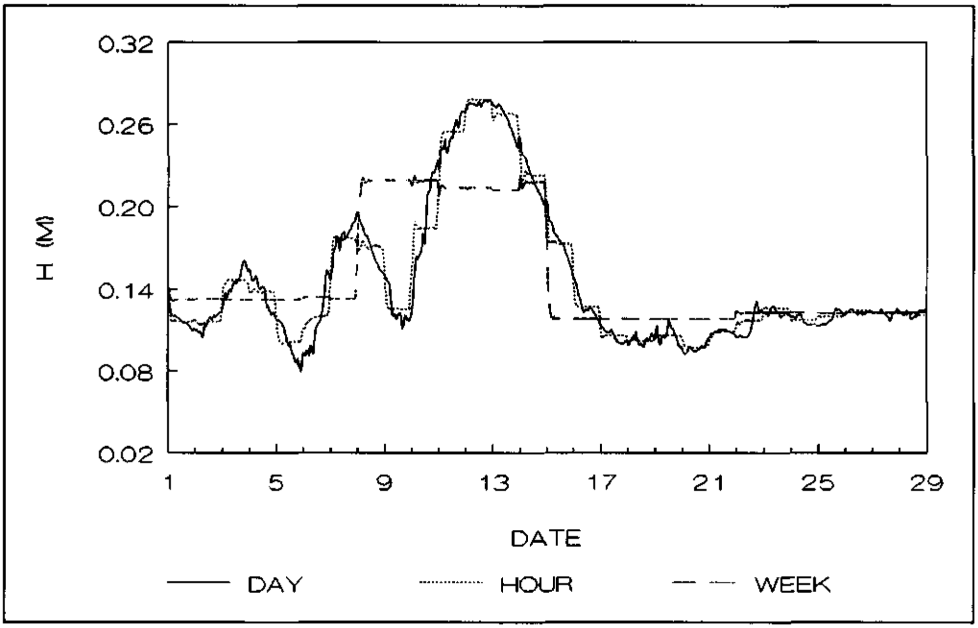

Fig. 6. Simulated water levels at Fo (Follegasloot). Hour: hourly mean wind and water level input data (see also Fig. 6), Day: the same expressed for daily mean data, and Week: the same expressed for weekly mean data.

In the section *Data Registration and Collection* it was mentioned that the simulations were performed by using hourly mean wind velocities, wind direction and water levels. In order to verify the need to use detailed input data, simulations were executed with daily and weekly (vector) meanwind and level input data (simulations L and M, respectively). Fig. 6 shows that both weekly as well as daily mean input data lead to undesirable loss of detail. Table 2 shows that weekly mean input data may lead to unacceptable differences in water velocities. Therefore, the detailed hourly mean data are necessary for optimum simulations.

Final choice of parameters

The above tuning and calibration of the model resulted in the final 25-months simulations for the calculation of water balances and the input discharges of a P mass-balance model. The simulations were performed with hourly input data. The wind data of station Lelystad were used and the polder discharges were allocated to the selected 16 nodes. The most realistic boundary link dimensions were used, as far as these could be measured. A wind exponent $\in = 2$, a water-air friction

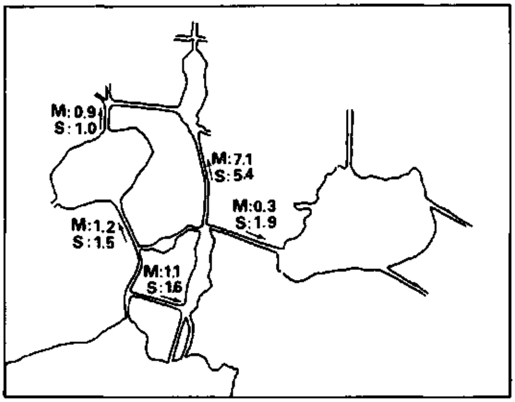

Fig. 7. Measured (M) and simulated (S) water discharges in 10^4 $m^3.hr^{-1}$ in the system during inflow of IJsselmeer water ($Q_{Li}=6.7$ 10^4 $m^3.hr^{-1}$, $Q_T=2.0$ 10^4 $m^3.hr^{-1}$; October 8 1986).

coefficient $c_z=5.7$ 10^{-4} and a bottom roughness coefficient $Ch=40$ $m^{1/2}.s^{-1}$ were used. The simulations result in realistic water levels at the nodes and acceptable water velocity ranges in the links.

Fig. 7 shows that the measured and simulated discharges and water flow directions agreed quite well during a characteristic and consistent situation, namely at inlet of IJsselmeerwater near Lemmer and Tacozijl on October 8, 1986 ($Q_{Li}=$ 6.7 10^4 $m^3.hr^{-1}$, $Q_T=$ 2.0 10^4 $m^3.hr^{-1}$). This comparison was done for a final test of the model, although it was discussed in the section *Model tuning*, that water flow measurements lead to an indication and that only the measured water flow ranges were used for model tuning.

APPLICATION OF MODEL RESULTS

Water balances

Part B of Table 3 shows the discharges in the five boundary canals, which were quantified with the help of the hydraulic model. Furthermore, the table shows all water balance contributions of the study area, including the water storage. It can be concluded that relatively large quantities of water flowed in or out of the system through the boundary canals. The discharges in the Pier Christiaansloot (Q_{Ps}), Broeresloot (Q_{Bs}) and Koevorder Meer (Q_{Km}) were highest, which was similar to the impression that was obtained during the water flow measurements.

The quantified discharges in the boundary and interconnecting canals were used as forcing functions for a chloride and P mass-balance model, which lead to an acceptable similarity in observed and simulated concentrations in the lakes (Van Huet, c).

Table 2. Weekly mean water velocities in cm.sec^{-1}, as a result of the model simulations, in the Follegasloot (+ = water flow in direction Groote Brekken) and Prinses Margrietkanaal (+ = water flow in direction Koevorder Meer) during October 1-28, 1985. * = deviation from the period range > 10%. MT = see section model tuning. SA = see section sensitivity analysis. RU = see section model reliability and uncertainty. See text for further information.

	Mean water velocities (cm.sec^{-1})							
	Follegasloot				Prinses Margrietkanaal			
Simulation description	Week1	Week2	Week3	Week4	Week1	Week2	Week3	Week4
MT A Basic simulation	-17.0	11.5	-4.3	-13.3	-7.6	-9.8	1.0	-4.0
MT_B Wind station Leeuwarden	-15.0	16.2*	-7.0	-14.3	-7.2	-8.0*	0.0	-4.4
MT C Evenly distributed polder discharges	-16.9	11.7	-4.2	-13.3	-7.8	-10.4	0.9	-4.0
MT D Lower polder discharges	-17.1	11.6	-4.3	-13.3	-7.8	-10.5	0.8	-4.1
SA E No wind	-10.1*	19.9*	-10.3*	-15.0	-5.4*	-6.5*	-1.4*	-4.6
SA F Other wind exponent	-18.2	-10.4	-3.4	-13.3	-8.0	-10.3	1.3	-4.0
SA G Low Chézy coefficient	-10.6*	9.5*	-2.6	-8.1*	-4.5*	-9.8	0.8	-2.3*
SA H High Chézy coefficient	-20.8*	12.9	-5.2	-16.3*	-8.8*	-9.5	1.1	-4.5
SA I Longer lengths boundary canals	-16.7	11.2	-3.6	-12.7	-9.4*	-9.6	1.0	-4.9
RU J Input noise ± 1 cm	-17.1	11.5	-5.3	-13.6	-7.5	-9.8	0.2	-4.4
RU K Input noise ± 2 cm	-17.5	11.9	-4.0	-12.4	-8.1	-9.6	1.0	-4.2
RU L Daily mean input values	-17.6	11.2	-4.6	-14.8	-7.9	-9.9	0.9	-4.4
RU M Weekly mean input values	-20.0*	14.8	-10.0*	-15.4	-8.4	-7.1*	-1.2*	-4.4

Residence times

Table 4 shows the mean water residence times in three lakes during the three simulation periods. These residence times were calculated according to the following equation:

$$\tau = \frac{V}{Q} \qquad (6)$$

where, τ = the water residence time; V = the lake volume, which was assumed to be constant and Q = the mean inflow discharge. The residence times in the Groote Brekken are short (mean value 5 days) because this lake is closely connected with the inflow or pumping station at Lemmer. It is expected that residence times in the Koevorder Meer are also short, because this lake is connected with the Groote Brekken by the Prinses Margrietkanaal, which is the main canal in the study area. The residence times in the largest lake, Tjeukemeer, are relatively short (mean value 20 days), while those in the Slotermeer are relatively long (mean value 54 days). Table 4 also shows the differences within a year, due to the changing climatological conditions. This result confirms the difference between these lakes, which was found also in other studies (Van Huet, 1990, Van Huet and De Haan, a, and Van Huet, b).

Table 3. Water balance contributions in 10^6 $m^3.month^{-1}$. Part A is the partly water balance, already known before modelling. Part B reflects the results after modelling. See also the section *Water balance contributions*. *: August 1985: simulated period 24 days; December 1987: simulated period 20 days.

		A										B					
		In						Out				In/Out					
Year	M	Q_{U}	Q_T	Q_{po}	Q_p	Q_w	Q_s	Q_{Lo}	Q_{pi}	Q_e	Q_i	Q_{Pe}	Q_{Be}	Q_{Sr}	Q_{Km}	Q_{We}	St
1985	A*	1.0	0	5.0	2.9	0.1	0.2	0	-1.5	-2.5	-0.3	-14.2	-22.0	15.0	5.4	10.5	-0.3
	S	0	0	2.4	1.6	0.1	0.2	0	-1.9	-1.9	-0.3	-3.5	-27.3	8.6	15.3	7.7	0.7
	O	0	0	4.6	1.7	0.1	0.1	0	-0.9	-0.9	-0.4	15.5	-52.7	13.6	4.8	14.4	-0.1
	N	0	0	8.9	4.1	0.2	0.0	-21.2	0	-0.2	-0.3	8.6	-34.7	10.3	17.8	6.6	-0.1
	D	0	0	11.1	2.9	0.4	0.0	0	0	-0.1	-0.4	-17.7	7.3	5.5	-2.0	-6.9	0.2
1986	J	0	0	16.0	3.8	0.2	0.0	-62.4	0	-0.2	-0.4	-5.0	23.0	-4.5	37.1	-6.4	1.3
	F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	A	0.9	0	2.9	1.2	0.1	0.1	0	-2.5	-2.2	-0.3	-1.5	-6.6	0.5	-3.8	10.9	-0.5
	M	25.0	0	2.4	1.8	0.1	0.2	0	-5.7	-4.4	-0.4	-23.1	18.6	1.3	-36.7	20.7	-0.1
	J	28.1	19.1	2.7	1.9	0.1	0.2	0	-5.7	-4.9	-0.3	0.6	-5.3	-2.8	-39.6	6.6	0.7
	J	35.2	15.2	2.0	2.1	0.1	0.2	0	-5.7	-4.1	-0.4	-3.0	-14.1	2.1	-38.4	9.1	0.3
	A	36.0	20.4	1.7	2.7	0.1	0.2	0	-5.3	-3.5	-0.4	-16.4	5.7	2.2	-55.2	12.0	0.2
	S	14.2	0	1.9	1.5	0.1	0.2	0	-4.9	-2.0	-0.3	-15.1	16.5	0.0	-26.4	14.2	-0.4
	O	32.5	0.8	4.4	3.7	0.2	0.1	0	-2.6	-1.0	-0.4	-35.5	22.6	3.0	-39.7	13.3	1.5
	N	0	0	7.0	2.7	0.1	0.0	0	0	-0.3	-0.3	-37.3	31.0	0.2	-14.3	9.8	-1.2
	D	0	0	16.1	5.6	0.2	0.0	-42.7	0	-0.3	-0.4	-40.7	60.6	-1.0	3.4	6.8	7.8
1987	J	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	M	0	0	9.4	2.5	0.2	0.1	0	0	-1.3	-0.4	-24.2	51.0	-4.8	-56.7	23.4	-0.9
	A	3.9	0	2.1	0.9	0.1	0.1	0	-2.0	-2.3	-0.3	-20.5	12.6	-3.9	-1.1	10.9	0.5
	M	9.4	0	4.1	2.1	0.1	0.2	0	-3.9	-2.7	-0.4	-3.3	30.3	-14.5	-24.6	3.6	0.5
	J	1.7	0	5.1	3.5	0.2	0.2	0	-3.6	-2.6	-0.3	-32.2	51.2	-6.3	-35.6	18.1	-0.7
	J	17.5	0	8.1	5.9	0.2	0.2	0	-3.6	-3.4	-0.4	-18.1	31.3	-11.3	-36.8	11.4	1.0
	A	0.4	0	3.7	2.7	0.2	0.2	0	-3.8	-2.5	-0.4	-16.5	-7.5	0.2	28.3	-5.7	-0.7
	S	0	0	2.9	2.4	0.1	0.2	0	-3.7	-1.9	-0.3	-38.2	50.6	-11.3	-6.9	7.4	1.1
	O	0	0	7.8	3.1	0.2	0.1	0	-1.8	-1.1	-0.4	-50.4	38.0	-0.8	1.9	3.3	-0.1
	N	0	0	11.4	3.5	0.2	0.0	-26.2	0	-0.3	-0.3	-37.3	67.6	-11.5	-4.8	-2.1	0.2
	D*	0	0	5.6	1.4	0.1	0.0	0	0	-0.1	-0.2	-24.5	36.5	-9.7	-2.0	-2.8	4.2

Table 4. Mean water residence times in days in thre lakes.

	Period 1 (1985)	Period 2 (1986)	Period 3 (1987)	All periods
Tjeukemeer	18	23	19	20
Groote Brekken	4	4	6	5
Slotermeer	53	54	55	54

CONCLUDING REMARKS

Some important conclusions can be drawn:

1) Water transport in the open boundary sw Frisian lake district is complex, with high variations in flow rate as well as flow directions.

2) Water flow measurements lead to an indication of the water transport in the area but are very laborious.

3) Because of lack of continuously registered water flow data a wind-driven hydrodynamic model is applied, which leads to quantification of discharges in the boundary and interconnecting canals of the lakes and to the quantification of water balances. Discharges into Tjeukemeer are high when compared with Slotermeer.

4) Model sensitivity is low for modifications of the wind exponent value and rather high for the bottom roughness coefficient, while sensitivity for noise at the imposed water levels at the boundary locations appears to be moderate.

5) Simulations with daily or weekly mean wind and water level data results in an undesirable loss of detail.

6) Water residence times are short in Groote Brekken and Tjeukemeer (mean values 5 and 20 days, respectively), and relatively long in Slotermeer (mean value 54 days).

7) Altogether water transport modelling lead to satisfactory simulation results. The computed discharges will be used as forcing functions for a chloride and P mass-balance model.

Chapter 6

Phosphorus eutrophication in the sw Frisian lake district during 1984-1987. 1. Monitoring program and assessment of a mass balance model

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PHOSPHORUS EUTROPHICATION IN THE SW FRISIAN LAKE DISTRICT DURING 1984-1987: 1. Monitoring program and assessment of a dynamic mass balance model

Key words: eutrophication, lakes, phosphorus, chloride, loading, dynamic mass balance model, dispersion, sensitivity analysis

ABSTRACT

In 1984 a frequent monitoring program started in the hypertrophic sw Frisian lake district, with emphasis on chloride (Cl^-) and total phosphorus (TP). The main objective of the study was to gain more insight into the trophic levels of the lakes and to model P dynamics as a tool for management.

The sampling program reflected the seasonal variability in the lakes, due to the man-made hydrology dominated by the reception of humic-rich polder water, mainly in relatively wet periods (winter) and inlet of chloride-rich IJsselmeer water, mainly in relatively dry periods (summer). The yearly mean TP concentrations in the lakes Tjeukemeer, Groote Brekken and Slotermeer ranged from 0.23 - 0.29 $mg.l^{-1}$. However, peak concentrations of 0.9 $mg.l^{-1}$ were measured in periods with high inflow of polder water.

The simulations with the mass balance model showed an acceptable similarity between measured and simulated concentrations, for TP as well as for Cl^-. Cl^- was modelled to verify whether flows calculated by a hydrodynamic model were sufficiently accurate. Further analysis showed that dispersion terms in the models can be neglected. A sensitivity analysis of the apparent settling rate in the P model showed that sensitivity was lowest in simulations of Groote Brekken and highest in simulations of Slotermeer. This difference could be attributed to the influence of the water residence time. The model was found to be appropriate for simulating management scenarios.

INTRODUCTION

In 1984 a eutrophication project started in order to study phosphorus (P) water pollution in the sw Frisian lakes (Fig. 1). The main objective of the project was to simulate scenarios for policy and management, by means of a P model. In order to support this model, the distribution of P in the sediments and the P loads from the surrounding polders were investigated, while the water transport in the area was simulated by use of a hydrodynamic model. Details of these investigations will be published elsewhere (Van Huet and De Haan, a; Van Huet, b, and c). For a survey of the preliminary results of the project, see Van Huet (1990).

This paper focuses on a) a brief description of the total phosphorus (TP) concentration and some other water quality parameters of the lakes during 1984-1987, and b) the results of a dynamic mass balance model, with emphasis on TP concentrations.

AREA DESCRIPTION AND SEASONAL VARIATION

The sw Frisian lakes and interconnecting canals (water surface area 4000 ha) are part of the 'boezem', a water network in the province of Friesland with a total water surface area of 14000 ha, which is used for water table regulating in the surrounding polders and for flushing. Table 1 shows the depth, surface area, catchment area and water residence times of the shallow lakes Tjeukemeer, Groote Brekken and Slotermeer, being the lakes that will be modelled.

Yearly, at usual climatological conditions, a precipitation deficit in the polders occurs and boezem water is let in into the polders in summer (April-September). To supply the loss, chloride-rich water from IJsselmeer, originating from the river Rhine, is let in at Lemmer, Tacozijl and Stavoren. In winter (October-March), precipitation exceeds evaporation and humic-rich water from the polders is pumped into the boezem system, while, in turn, boezem water is pumped out into IJsselmeer at Lemmer and Stavoren or is released into the Waddenzee (Fig. 1). Thus, man, driven by climatological conditions, strongly influences the hydrology of the lake system. In addition, the wind has considerable influence on the short-term water transport. For detailed information about the boezem system and hydrology, see Leenen (1982a) and Van Huet (1990).

In Table 1 the main differences between the three lakes are given. The influence of polder water in Tjeukemeer in winter is high and relatively low in Slotermeer. The influence of water from IJsselmeer in summer is great in Groote Brekken and less in Tjeukemeer and in Slotermeer (see also Table 2). The mean water residence time is short in Groote Brekken and long in Slotermeer. Tjeukemeer can be regarded as a typical polder lake, while Slotermeer can be seen as a relatively isolated lake in the area. Measurements indicated that water residence times and influence of polder and IJsselmeer water in Koevorder Meer, the fourth main lake in the area, are similar to those of

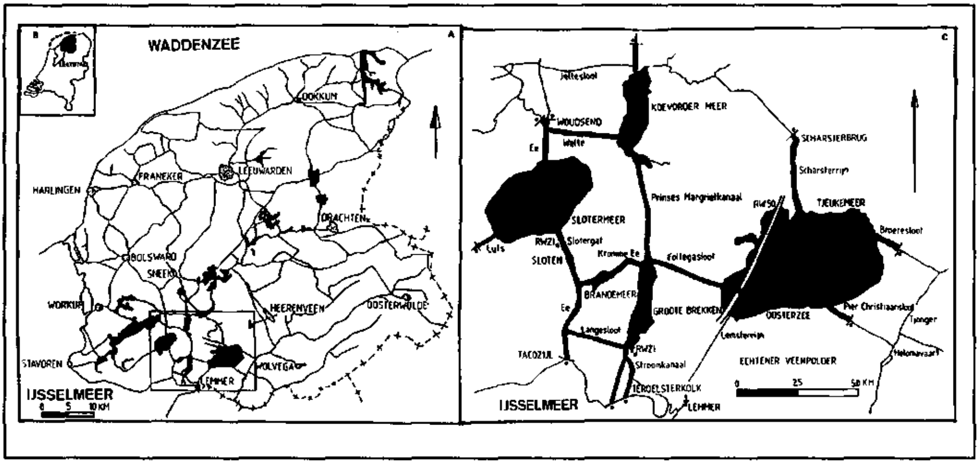


Fig. 1. A. The Frisian 'boezem'. B. Its position in The Netherlands. C. The sw lake district (●_: boundaries research area; RWZI: waste water treatment plants; RW50: motorway 50; from Van Huet, 1990).

Groote Brekken. Despite a bottom composition difference between these two largest lakes, sedimentary TP contents do not differ very much (Van Huet and De Haan, a).

Table 1. Lake parameters of Tjeukemeer, Groote Brekken and Slotermeer (*: after Brinkman *et al.*, 1989; **: Van Huet, c).

	Tjeukemeer	Groote Brekken	Slotermeer
Surface water area (ha)**	1958	300	1100
Catchment area (ha)*	50000	5000	3800
Mean depth (m)**	1.75	2.0	1.65
Bottom structure (>50%, <50%)	Peat, sand	Sand, peat	Sand, peat
Mean water residence time (days)**	28	7	93
Relative influence of polder water (winter)	High	Moderate	Low
Relative influence of IJsselmeer water (summer)	Moderate	High	Moderate
Number of lake chloride sampling stations	8	3	6
Number of lake TP sampling stations (mixed sample)	3	3	3

EUTROPHICATION AND USE OF MODELS

The water in the Frisian lakes is highly eutrophicated. More often than not TP and TN (total nitrogen) concentrations exceed 0.2 and 2.0 $mg.l^{-1}$, respectively, while summer chlorophyll-a contents often exceed 150 $\mu g.l^{-1}$. The lake ecosystems are dominated by the blue-green alga *Oscillatoria agardhii*, the zooplankton species *Bosmina coregoni, Chydorus sphaericus* and *Daphnia hyalina*, bream (*Abramis brama*), and pike perch (*Stizostedion lucioperca*), see Moed and Hoogveld

(1982), De Haan and Moed (1984), Claassen (1986), Lammens (1986) and Van Huet (1990). Eutrophication, chemistry, fish communities and trophic relationships were previously described by Beattie *et al.* (1978), De Haan (1982, 1988), Vijverberg and Van Densen (1984), Lammens (1986, 1990), Klink and Claassen (1988) and Moed *et al.* (1988).

In Dutch lakes, including the sw Frisian lakes, a significant correlation between TP concentrations and chlorophyll-a contents was found. This correlation suggests that reducing the TP concentrations will be followed by a corresponding reduction in chlorophyll-a. Moreover, there are indications that undesirable blue-greens will no longer dominate if TP concentrations can be reduced to $<0.07 mg.l^{-1}$ (Lijklema *et al.*, 1988). In this paper I therefore focus on TP concentrations and assume that reducing P levels in the Frisian lakes will eventually lead to a limitation of this nutrient and, finally, to lake restoration.

Golterman *et al.* (1980) used a Cl^- mass balance model to quantify the water balances of Tjeukemeer and the P loads to this lake during 1969-1975. They concluded that for reliable model results Cl^- concentrations have to be measured frequently (weekly or fortnightly) at several stations of the lakes and their inflow and outflow canals. Frequent sampling is necessary because of the spatial and temporal variability of Cl^- and TP concentrations, due to inflow of polder water and IJsselmeer water. This variability was also reported by other authors (Leenen, 1982a; De Haan and Moed, 1984).

In May 1984, a frequent Cl^- and TP sampling program started. Cl^- was measured because time series of Cl^- concentrations can lead to an indication of the water transport, and the origin of water in the lakes, because of the concentration differences between polder water and IJsselmeer water. The monitored Cl^- concentrations were also used to verify the results of the hydrodynamic model (see the section assessment of a Cl^- model). TP concentrations were measured for the calibration of the mass balance model and for an indication of the lake trophic levels. For the latter purpose Secchi disk transparencies and pH values were also measured.

MATERIALS AND METHODS

During May 1984 - December 1987, 50 stations in the sw lake district, were weekly sampled and Cl^- concentrations, Secchi disk transparency, and pH were analyzed/measured. Also weekly, a mixed sample of the lake stations was analyzed on TP concentrations, while fortnightly samples of the inflow and outflow sites of the lakes were analyzed on TP. Samples were taken with a plexiglass tube (length 1 m) from a boat. Transparency and pH were measured in situ. Cl^- was titrated with Ag^+-ions. Phosphorus was analyzed colorimetrically applying autoanalyser systems. The total concentration was measured after hydrolysis in acidic persulphate. Colorization took place with the usual molybdate reagent (Murphey and Riley, 1962). Description of sampling polders is in *progress (Van Huet, b).*

WATER QUALITY DURING 1984-1987

Results of the monitoring program

Van Huet (1990) reported upon Cl^- and TP concentrations during 1984-1986. In Table 2 further information about the water quality parameters in the three lakes during 1984-1987 is given. It can be concluded that: a) TP concentrations in polder water were higher than in IJsselmeer water (for example, the mean values in 1985 were >0.4 and 0.2 $mg.l^{-1}$, respectively); b) during relatively dry periods, high Cl^- concentrations occur, due to inlet of IJsselmeer water, and during relatively wet periods, high TP concentrations occur, due to the pumping of polder water into the system; c) on average, Tjeukemeer is influenced most by polder water, while Groote Brekken and to a lesser extent Slotermeer are influenced most by IJsselmeer water; d) concentrations in Tjeukemeer fluctuated more than in Slotermeer, while differences in concentrations occurred between Tjeukemeer west and Tjeukemeer east; e) Secchi disk transparencies were low and pH values were highest in summer.

Table 2. Water quality parameters in Tjeukemeer (Tj), Groote Brekken (GB) and Slotermeer (Sl) during 1984-1987 (*: sampling started on May 14, 1984; **: mean value of mixed samples; ***: mean value of all lake stations).

	TP ($mg.l^{-1}$)**			Cl^- ($mg.l^{-1}$)***			Secchi (cm)			pH		
	Tj	GB	Sl	Tj	GB	Sl	Tj	GB	Sl	Tj	GB	Sl
1984*	0.25	0.23	0.24	98	177	130	28	33	28	9.0	8.8	8.8
1985	0.29	0.24	0.24	56	131	101	37	35	27	8.5	8.6	8.6
1986	0.28	0.24	0.26	105	153	120	32	32	29	8.7	8.8	8.6
1987	0.29	0.24	0.23	59	113	96	30	30	25	8.6	8.7	8.7
Apr.84-Sep.84*	0.24	0.23	0.25	102	206	122	26	34	27	9.5	9.2	9.0
Apr.85-Sep.85	0.30	0.26	0.26	61	146	102	29	33	26	8.8	8.8	8.7
Apr.86-Sep.86	0.25	0.22	0.25	99	155	105	34	31	28	9.0	9.1	8.8
Apr.87-Sep.87	0.27	0.23	0.22	64	131	96	29	29	25	8.9	8.9	9.0
Oct.84-Mar.85	0.27	0.25	0.23	81	125	130	34	32	29	8.1	8.3	8.6
Oct.85-Mar.86	0.32	0.24	0.24	45	101	97	47	35	26	7.9	8.2	8.4
Oct.86-Mar.87	0.32	0.26	0.27	113	154	145	30	33	30	8.3	8.5	8.3

MODELLING PHOSPHORUS DYNAMICS

Introduction

Generally, two types of models are used in lake eutrophication modelling: empirical, steady state models and theoretical, dynamic models. The empirical models are derived from statistical analysis of data from large numbers of lakes. In general, these models give good predictions for a group of lakes, but might lead to large errors while being applied to individual lakes. Simple empirical models have advantages over complex theoretical models. Few data and simple mathematics are needed and they show generality (Kamp-Nielsen, 1985). However, their limitations are the steady state assumptions and the poor resolution in time and space. The theoretical models are based on (detailed) mathematical descriptions of the nutrient and population dynamics. Hence, these dynamic models can differ in complexity, from simple input-output models using a single net loss term to large ecological n-layer, n-box, n-compartment ecological models, describing spatial variability of several variables. The dynamic models do not have the limitations of the empirical models, but may have disadvantages in their complexity and use of extensive data sets. Furthermore, these models may not be fully adequate, because of lack of knowledge about processes such as, for example, sedimentation, resuspension and P-release from sediments. For a review of model types, their steady state solutions, advantages, disadvantages and results see Golterman (1980), Golterman and Kouwe (1980), Jørgensen (1983), Reckhow and Chapra (1983a, 1983b), Van Straten (1983), Imboden and Scharzenbach (1985), Kamp-Nielsen (1985), Teruggi (1986), Ahlgren *et al.* (1988) and Prairie (1988, 1989).

Model choice

The model choice depends on several criteria such as model use, complexity of the system (for example, occurrence of stratification and the hydrodynamic character of the aquatic ecosystem), availability of data sets, etc. A first choice that has to be made is between an empirical or a theoretical model. Empirical models are often applied if only annually mean values are of interest, which is not the case in the Frisian situation. Moreover, the steady state approach is not realistic for modelling the P levels in the Frisian lakes because of the seasonal patterns of loading. Therefore a dynamic model was preferred.

An important criterion is the use of the model. Will the model be used for research or for management purposes (or possibly both)? Models for research purposes may have objectives like, for instance, identification and hypotheses testing. Management models generally focus more on the prediction of one or two variables. Therefore, on average, research models are more complex than the (practical) management models. Modelling the P dynamics in the Frisian lakes is important for management reasons. Hence I used a practical management model approach.

Because of the short residence times and the influence of the wind on the water transport in the lakes (Van Huet, c), it is assumed that the lakes are ideally mixed. Thus, the CSTR-approach (continuously stirred tank reactor) was used. Another reason for choosing a simple dynamic model is that the uncertainty in the data does not support detailed modelling (see Fig. 3, and the section *Representativeness of phosphorus concentrations*).

The simple dynamic one-box management model is based on the principle of mass conservation:

$$\frac{d(VP)}{dt} = Input - Output - Net\ loss \tag{1}$$

where, V = the lake volume; P = the lake TP concentration; t = the time.

Net loss occurs due to sedimentation, resuspension and release of P and is influenced by several factors, such as the water residence time, the P loading, lake morphology, oxygen concentration, the pH at the sediment-water interface and wind-induced turbulence. Exact links, however, are largely unknown and generally it is very difficult to describe net loss (Kamp-Nielson, 1985; Bolin *et al.*, 1987; Ahlgren *et al.*, 1988 and Herman *et al.*, 1989).

At this point I will not go into the several aspects of net loss and will use the apparent settling approach (see Appendix I), since it is a physically realistic description (Rechhow and Chapra, 1983a). Net loss is assumed to be a first order process, that is, the apparent settling velocity is directly proportional to the TP concentration in the lake.

Model description

For each lake (Tjeukemeer, Groote Brekken and Slotermeer) the following basic equations were used:

$$\frac{d(VP)}{dt} = \Sigma Q_{in,j} P_{in,j} - P\Sigma Q_{out,j} - v_s A P \tag{2}$$

$$\frac{d(VP)}{dt} = V\frac{dP}{dt} + P\frac{dV}{dt} \tag{3}$$

$$\frac{d(V)}{dt} = \Sigma Q_{in,j} - \Sigma Q_{out,j} - Q_e \tag{4}$$

where, V = lake volume (m^3); P = lake TP concentration ($mg.l^{-1}$); $P_{in,j}$ = TP concentration in influent j ($mg.l^{-1}$); $Q_{in,j}$ = inflow discharge j ($m^3.d^{-1}$); $Q_{out,j}$ = outflow discharge j, except Q_e ($m^3.d^{-1}$); v_s = apparent settling rate ($m.d^{-1}$); A = lake surface area (m^2).

The discharges $Q_{in,j}$ and $Q_{out,j}$ are defined to be positive. For example, if there is water transport through Follegasloot (Fig. 1) from Groote Brekken in direction Tjeukemeer (discharge Q_{Fol}), then for Tjeukemeer $Q_{in,Fol} = Q_{Fol}$ and $Q_{out,Fol} = 0$ is valid, while for Groote Brekken $Q_{in,Fol} = 0$ and $Q_{out,Fol}$ =

Q_{Fol} is valid. This example also shows that the TP concentrations in one lake can be influenced by the concentrations in the two other lakes.

From equations 2, 3 and 4, the rate of change of the P mass can be expressed as:

$$V\frac{d(P)}{dt} = \Sigma\{Q_{in,j}(P_{in,j} - P)\} + Q_e P - v_s A P \qquad (5)$$

In the equations the contribution of the evaporation (Q_e) was described separately because in this way the simulations led to a realistic increase of lake TP concentrations if only evaporation occurs.

Model inputs

The P dynamics in the three lakes could be modelled, because the inflow and outflow discharges were available from a hydrodynamic model during three periods (August 8, 1985 -January 31, 1986; April 1 -December 31, 1986; March 1 - December 20, 1987). The periods are separated because during February 1 - March 31, 1986 and January 1 - February 28, 1987 the ice cover present at the time led to unreliable model results. Altogether, the hydrodynamic model and consequently the mass balance model covered about 25 months of the research period. Table 3 shows the model sources ($\Sigma Q_{in,j}$) and sinks ($\Sigma Q_{out,j}$) and concentrations in sources. For a description of the hydrodynamic model and contributions to the water balance, see Van Huet (c). Most inputs were daily available, while for not daily available inputs and concentrations calculations were made with interpolated values. For the concentrations in sinks the model concentrations were used, according to the model definition. The model calculations started each simulation period with the measured concentrations in the lakes (initial conditions).

MODELLING RESULTS AND DISCUSSION

Assessment of a chloride model

Prior to the P mass balance model, simulations were made with a similar Cl^- model. This was done in order to verify whether the daily mean discharges, from the hydrodynamic model, were sufficiently accurate for model input. Cl^- was modelled as a conservative material, that is, it was assumed that no net loss took place. Therefore, the Cl^- model corresponds with the P model with an apparent settling rate $v_s = 0$. Thus the Cl^- model equation is:

$$V\frac{d(Cl^-)}{dt} = \Sigma\{Q_{in,j}(Cl^-_{in,j} - Cl^-)\} + Q_e Cl^- \qquad (6)$$

in which Cl^- = the lake Cl^- concentration ($mg.l^{-1}$) and $Cl^-_{in,j}$ = the Cl^- concentration in influent j ($mg.l^{-1}$). In this way, for each lake the Cl^- concentration was simulated.

Table 3. Model sources and sinks and concentrations in sources. (D = daily available; B = biweekly available; T = available every decade; DPWE = Department of Public Works and Environment of the Province of Friesland; RNMI = Royal Netherlands Meteorological Institute).

Q_{Li} = inlet of Lake IJsselmeer water near Lemmer;
Q_T = inlet of Lake IJsselmeer water near Tacozijl;
Q_{ip} = polder water pumped into the system;
Q_p = precipitation;
Q_w = contribution from waste water treatment plant near Lemmer;
Q_s = inlet of Lake IJsselmeer water via sluices near Lemmer;
Q_{Lo} = outlet of boezem water (pumped into Lake IJsselmeer);
Q_{op} = outlet of boezem water into the surrounding polders;
Q_e = evaporation;
Q_i = infiltration;
Q_c = inflow and outflow through the system boundary canals Broeresloot, Pier Christiaansloot, Scharsterrijn, Koevorder Meer and the canals north of Woudsend.

Source /sink		Range 10^6 $m^3.mo^{-1}$	Comment	Concentr. (ranges) TP $mg.l^{-1}$	Cl^- $mg.l^{-1}$	Comment
Q_c	(D)	-56.7-67.6	Hydrodynamic model	0.06-0.92	28-250	Measured
Q_{Li}	(D)	0-36.0	Obtained from DPWE	0.08-0.38	57-250	Measured
Q_T	(D)	0-20.4	Obtained from DPWE	0.08-0.38	57-250	Measured
Q_s	(D)	0- 0.2	Obtained from DPWE	0.08-0.38	57-250	Measured
Q_w	(B)	0.1- 0.4	Obtained from DPWE	0.6 -4.0	150	Obtained (DPWE)
Q_p	(D)	0.9- 5.9	Obtained from RNMI (stations Lemmer, Heeg and Joure)	0.04	10	Measured at station Spannenburg (Fig. 1)
Q_{ip}	(D)	1.7-16.1	*	0.06-1.1	150	**
Q_{Lo}	(D)	-62.4-0	Obtained from DPWE	Model	Model	
Q_{op}	(D)	-5.7-0	It was assumed that inflow occurred only during April-September and that inflow was directly proportional to the precipitation deficit.	Model	Model	
Q_i	(D)	-0.3	Estimated (Broers, 1987)	Model	Model	
Q_e	(T)	-0.1--4.9	Obtained from RNMI (stations Lelystad and Leeuwarden, Fig. 1).	-	-	

* Obtained from Water Boards. Water quantities pumped from the Echtener Veenpolder into Tjeukemeer. However, only monthly discharges were available, from polders surrounding Groote Brekken and Slotermeer. On average, these discharges agreed well with the monthly discharges of the Echtener Veenpolder. Therefore, for Groote Brekken and Slotermeer the daily Echtener Veenpolder discharges were used (for Groote Brekken estimated at 25% of the Tjeukemeer values and for Slotermeer at 50%).

** For Tjeukemeer, the measured TP concentrations in polder water of the Echtener Veenpolder were used for all three simulated periods. For Groote Brekken and Slotermeer the mean concentrations of the polders surrounding these lakes. However, these polders were not sampled during the first simulated period. Therefore, for this period and for these lakes the Echtener Veenpolder values were used.

Fig. 2 shows a fair similarity between the simulated and observed Cl^- concentrations in the lakes during the three periods. These results suggest that the used boundary discharges are about correct or at least sufficiently accurate for the purpose of model input. Hence, these discharges were also used as forcing functions for the P model.

Another point of discussion is the omission of a dispersion term in equations 5) and 6). This subject is discussed in Appendix II. In this appendix the physical dispersion in the Follegasloot (dispersion due to gradients in the water velocity), as well as the so-called equivalent dispersion in this canal (due to the fluctuating flow between Tjeukemeer and Groote Brekken) are estimated and compared with the advective water transport. It is concluded that the dispersion terms can be neglected.

Representativeness of phosphorus concentrations

An important question for model calibration is how reliable are the data sets? To get some insight into this question, two available different data sets of lakes were compared. Fig. 3A shows TP concentrations in Tjeukemeer during the three simulated periods. The concentrations differ probably due to a) a different mixing program (● FF: mixing water samples of 3 lake stations as previously described; + LI: mixing water samples of 10 stations, for a description see De Haan (1982) and to b) probably differences in the storage and handling program and analyses in different laboratories. Figs. 3B and 3C show TP concentrations in Groote Brekken and Slotermeer, respectively, which only differ in the mixing program (● FF: a mixed sample of 3 stations; + PF: a sample of a single station). Although there were of course also differences in the sampling dates, the figures clearly show that different programs might lead to a different interpretation of the lake TP levels. This point should be kept in mind when calibrating the model: the mean deviation between model and data can not be expected to be lower than the mean difference between the data sets.

Calibration of the phosphorus model

The most important parameter for calibration of the P model is v_s for each lake. Fig. 3 shows that, with an apparent settling rate $v_s = 0.015\ m.d^{-1}$, the simulated TP concentrations in the three lakes agreed rather well with the measured concentrations. Fig. 4 shows that the model v_s-sensitivity was highest for the TP concentrations in Slotermeer, moderate in Tjeukemeer and lowest in Groote Brekken. This result can be explained by analyzing the steady state solution of equation 5 ($dP/dt = 0$):

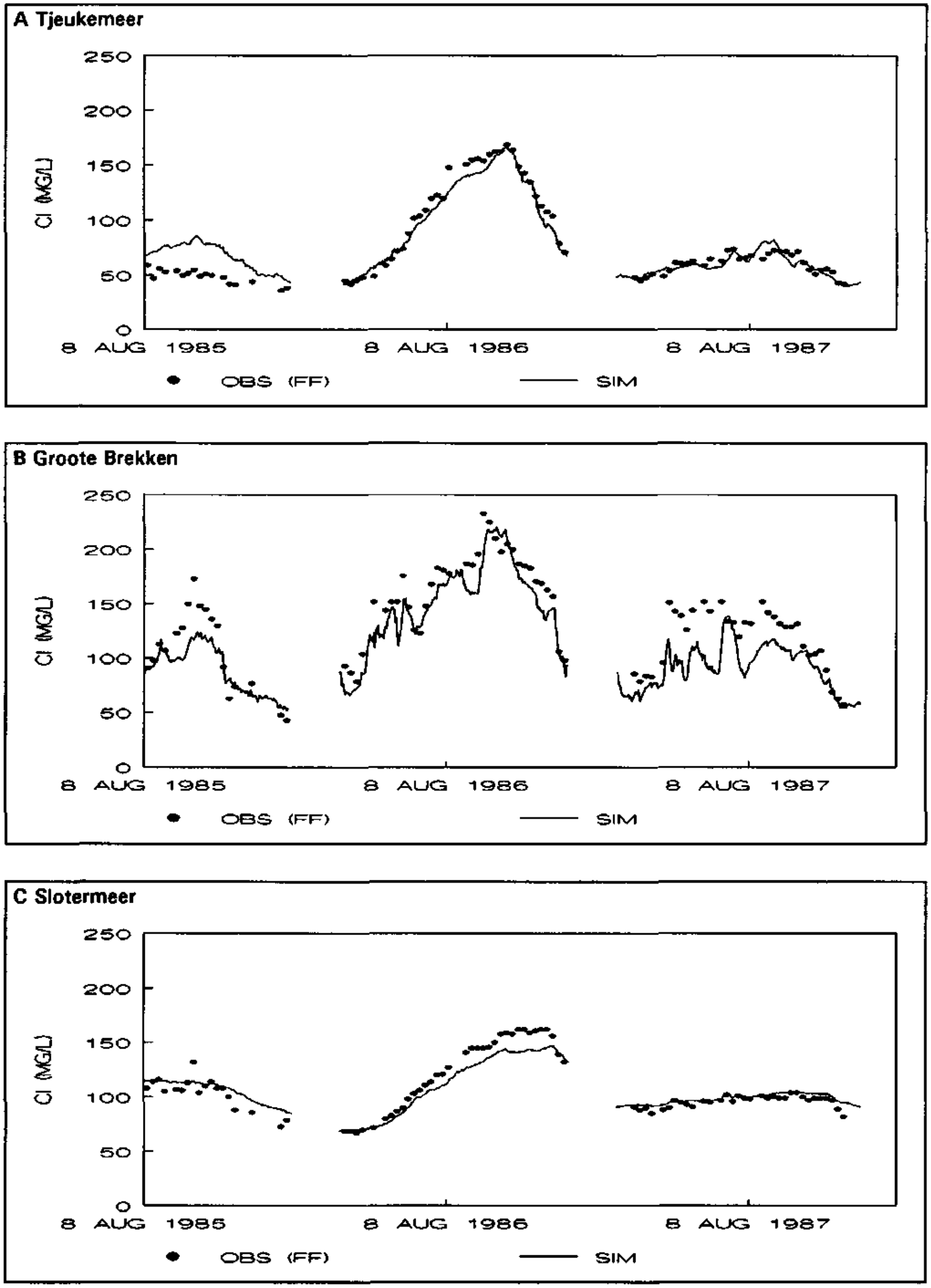


Fig. 2. Observed and simulated Cl^- concentrations during three periods.

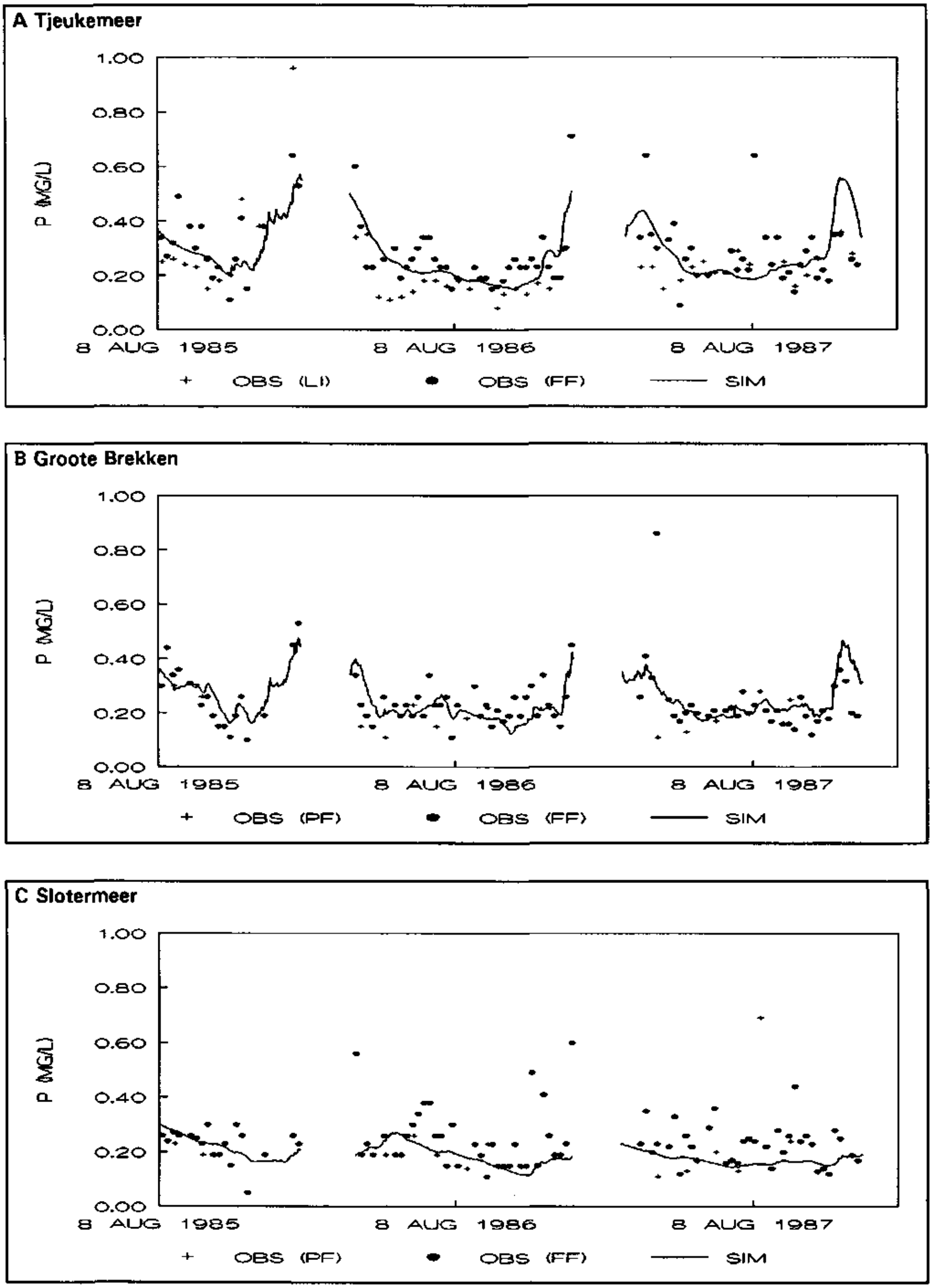
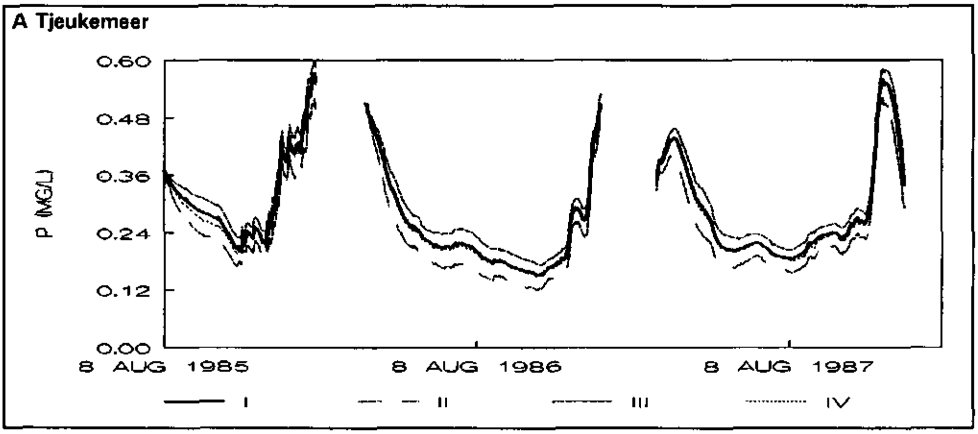
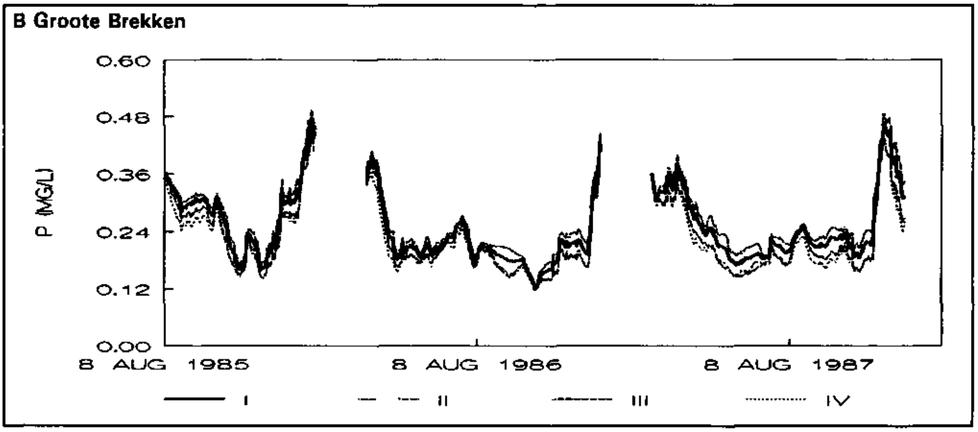


Fig. 3. Observed and simulated TP concentrations during three periods.

A Tjeukemeer



B Groote Brekken



C Slotermeer

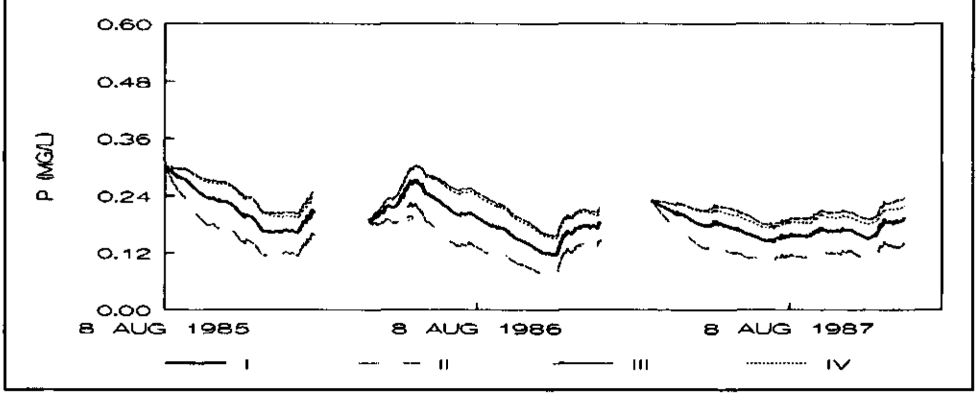


Fig. 4. Simulated P concentrations during three periods. I: v_s = 0.015 $m.d^{-1}$ for all lakes (basic line, see also Fig.3); II: v_s = 0.03 $m.d^{-1}$ for all lakes (bottom line); III: v_s = 0.0075 $m.d^{-1}$ for all lakes (top line); IV: from Van Straten (1989): v_s = 0.015 $m.d^{-1}$ (Tjeukemeer), v_s = 0.063 $m.d^{-1}$ (Groote Brekken), v_s = 0.0075 $m.d^{-1}$ (Slotermeer).

$$P = P_{in}\,\frac{1}{1-\dfrac{Q_e}{\Sigma Q_{in}}+\dfrac{v_s A}{\Sigma Q_{in}}} \approx P_{in}\,\frac{1}{1+\dfrac{\tau\, v_s}{H}} \qquad (7)$$

where $Q_e \ll \Sigma Q_{in}$, H = lake depth (= V/A) and τ = water residence time (= $V/\Sigma Q_{in}$). The water residence times in Groote Brekken were short (Table 1) and consequently $\tau . v_s/H \ll 1$. The TP concentrations in this lake will be dominated by the concentrations in inflowing water (P_{in}), while for the other two lakes the TP concentrations will be dominated less by P_{in}, because of longer water residence times.

Van Straten (1989) used a similar model for a long-term simulation (12 years) of the TP concentrations in the sw Frisian lakes, with decade input discharges from a stationary flow model and different TP data sets. He also used different v_s values for each lake, which were computed by a parameter estimation procedure. Fig. 4 also shows the simulations with these values. It can be concluded that other v_s values or different values for each lake do not lead to a substantial improvement in model results, because the curves are hardly discernable and the range is small as compared to the data range (compare Figs. 3 and 4). This analysis also shows that changing the v_s-value for one lake does not greatly influence the TP concentrations in the other two lakes.

By use of the P mass balance model the TP balances of the three lakes during three periods could be quantified, see Van Huet (e, this Volume).

DISCUSSION AND CONCLUSIONS

As previously discussed, the apparent settling approach is a simplification, because P removal in lakes will in fact be the end result of opposing processes sedimentation, resuspension by wind and release, depending, in their turn upon the fraction particulate P and thus upon algal mass, which all show seasonal variability. In general, there is lack of information about these processes and more research is needed to justify a detailed model. Also the completely mixing approach is a simplification and only a mathematical tool (Leenen, 1982b). A n-segment approach, however, was not possible because of lack of spatial variation in the P data sets. Another point of discussion is the use of detailed input of, for instance, polder water concentrations and discharges. This detailed information is necessary for a reliable estimation of the P-load, but is less important for the calculation of lake TP concentrations, because detailed input will be smoothed due to the completely mixing approach.

Altogether, the simulations show that a simple model approach leads to acceptable results. There is no need for a differentiation in net loss velocities between lakes. The high frequency fluctuations in the data as compared to the model are partly due to measured uncertainty as shown by comparison of data collected by different agencies. In so far they are real, they could only be captured by a much more detailed model, but this is unnecessary from a management point of view. The model was used to simulate management scenarios (see Van Huet, e, this Volume).

APPENDIX I: Phosphorus models

In this appendix we restrict ourselves to a brief survey of three main model types (Reckhow and Chapra, 1983a). These models assume ideal mixing in a lake and net loss. Many other less simple models exist, for instance models that include settling terms for several P fractions. For an extensive review of input-output models, see Vollenweider (1969), Dillon and Rigler (1974), Reckhow and Chapra (1983a, 1983b), Bolin *et al.* (1987), Ahlgren *et al.*, 1988, and Prairie (1988, 1989).

The first model type assumes that the rate of deposition of P to sediments is a function of the mass of P in a lake:

$$V\frac{d(P)}{dt} = W - QP - \sigma VP \tag{I.a}$$

with the steady state solution and time constant:

$$P = \frac{W}{Q + \sigma V} = \frac{L}{z(\frac{1}{\tau_w} + \sigma)} \tag{I.b}$$

$$Time\ constant = \frac{\tau_w}{(1 + \sigma\tau_w)} \tag{I.c}$$

where, V = the lake volume $[L^3]$
P = the lake TP concentration $[M.L^{-3}]$
t = time $[T]$
W = annual mass rate of P inflow $[M.T^{-1}]$
Q = annual volume rate of water inflow $[L^3.T^{-1}]$
σ = the sedimentary loss coefficient $[T^{-1}]$
L = W/A_s = annual areal P loading $[M.L^2.T^{-1}]$
A_s = lake surface area $[L^2]$
z = lake mean depth $[L]$
τ_w = V/Q = hydraulic retention time $[T]$

In the second model type the P balance is described as:

$$V\frac{d(P)}{dt} = W - QP - v_s A_s P \tag{I.d}$$

with the steady state solution and time constant:

$$P = \frac{W}{Q + v_s A_s} = \frac{L}{q_s + v_s} \qquad \text{(I.e)}$$

$$Time\ constant = \frac{\tau_w}{(1 + \frac{v_s}{z}\tau_w)} \qquad \text{(I.f)}$$

where, v_s = the apparent settling velocity $[L.T^{-1}]$
q_s = z/τ_w = Q/A_s = the areal water loading $[L.T^{-1}]$

The difference between these models is based on the depth (in)dependency of the settling velocity σz or v_s: in Equation I.b it is assumed that the settling velocity depends on the depth of a lake, whereas in Equation I.e a constant settling velocity is assumed.

The steady state solution and the time constant of the third model type are:

$$P = \frac{L\tau_w}{z}(1 - R_p) \qquad \text{(I.g)}$$

$$Time\ constant = \tau_w(1 - R_p) \qquad \text{(I.h)}$$

where, R_p = the fraction of influent P retained in the lake, defined as:

$$R_p = \frac{income - outflow}{income} = \frac{W - QP}{W} \qquad \text{(I.i)}$$

It can be shown that, in the case of steady state conditions, R_p can be expressed in terms of σ or v_s.

APPENDIX II: Dispersion

This appendix treats the dispersion. By way of example the dispersion in the Follegasloot, the canal that interconnects Tjeukemeer and Groote Brekken (length l, see Fig. II.1), is considered. It is assumed that dispersion occurs in a canal that is somewhat longer (i.e. that virtually ends some kilometres in both lakes; length L). Furthermore, it is assumed that C_1 is the mean concentration in lake 1 (Groote Brekken) and C_2 is the mean concentration in lake 2 (Tjeukemeer), and that a concentration gradient C_x occurs in the canal. The concentration C_1 corresponds with the Cl^- or P concentration in Groote Brekken, expressed in the terms Cl^- and P in Equations 5 and 6, respectively, while C_2 corresponds with the Cl^- or P concentration in Tjeukemeer.

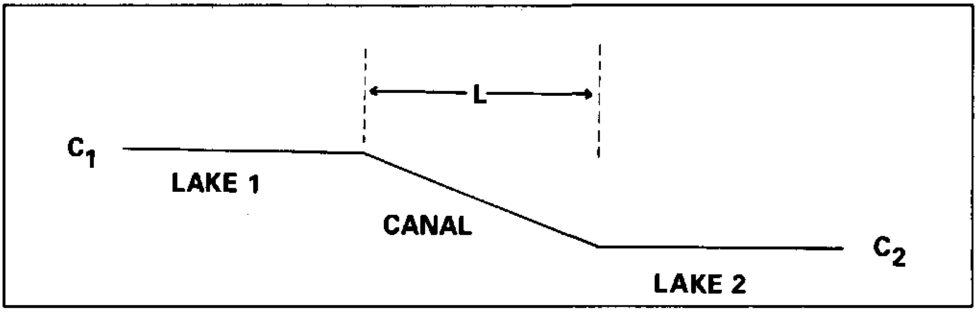


Fig. II.1. Schematic impression of the concentrations levels in lakes Groote Brekken and Tjeukemeer and the concentration gradient in the interconnecting canal Follegasloot.

It is assumed that the wind-induced variation of the water velocity superimposed on the advective transport in the canal is approximately:

$$u(t) = \tilde{U} \sin \omega t \tag{II.a}$$

where, u(t) = water velocity at time t [L.T^{-1}]
ω = oscillation frequency [radians (or degrees)/T]
t = time [T]
$\tilde{u}$ = amplitude of the water velocity [L.T^{-1}]

The movement of the water in the canal can be expressed as:

$$x(t) = \int_0^t u(t')\, d(t') \tag{II.b}$$

where, x(t) = location of water front at time t=0 taken from the right end of the canal, which arrives at this end at time t=t (see Fig. II.1), [L]

The concentration difference with respect to C_2 at the end of the canal, assuming an approximately longitudinal profile, equals (see Fig. II.1):

$$C(L,t) - C_2(t) = C_z x(t) \tag{II.c}$$

The mass flow rate on top of the advective transport leaving the canal can be expressed as:

$$W_c = u(t)\, A C_z x(t) \tag{II.d}$$

where, W_c = mass flow rate in the canal [M.T^{-1}]
A = cross sectional area of the canal [L^2]
C_z = concentration gradient [M.L^{-4}]

As the variations are sinusoidal the mass flow rate has to be averaged over half the period time:

$$\hat{W}_c(\tfrac{1}{2}Pd) = \frac{2}{Pd}\int_0^{\frac{Pd}{2}} u(t)\,AC_z x(t)\,dt \qquad \text{(II.e)}$$

where, $\hat{W}_c(\tfrac{1}{2}Pd)$ = mass flow rate during half the oscillation period $[M.T^{-1}]$
Pd = $2\pi/\omega$ = the period of time over which a complete oscillation occurs [T]

After substitution of equations II.a and II.b it follows that:

$$\hat{W}_c(\tfrac{1}{2}Pd) = \frac{2}{Pd}\int_0^{\frac{Pd}{2}} \hat{U}\sin(\omega t)\,AC_z\left[\int_0^{t} u(t')\,dt'\right]dt \qquad \text{(II.f)}$$

It can be shown that:

$$\hat{W}_c(\tfrac{1}{2}Pd) = \frac{4\,\hat{U}^2 AC_z}{Pd\,\omega^2} = \frac{\hat{U}^2 AC_z Pd}{\pi^2} \qquad \text{(II.g)}$$

The induced mass flow rate into lake 2 during the whole period is (i.e. no inflow occurs during the other half period):

$$\hat{W}_c(Pd) = \frac{\hat{U}^2 AC_z Pd}{2\pi^2} \qquad \text{(II.h)}$$

where, $\hat{W}(Pd)$ = mass flow rate during the whole period $[M.T^{-1}]$

Equation II.h gives the wind induced oscillatory mass flux, which can also be described by an equivalent dispersion term expressed as:

$$W_D \sim AC_z D \qquad \text{(II.i)}$$

where, W_D = mass flow rate due to dispersion $[M.T^{-1}]$
D = dispersion coefficient $[L^2.T^{-1}]$

After comparison of the wind-induced advection (II.h) and the wind-induced dispersion effect (Eq. II.i), obviously the equivalent dispersion equals to:

$$D_{eq} = \frac{\hat{U}^2\,Pd}{2\pi^2} \qquad \text{(II.j)}$$

The time period Pd can be calculated as follows (for this analysis, see also Lijklema and Van Straten, 1975): if in lake 1 (Groote Brekken) the water level is h_1, and in lake 2 (Tjeukemeer) the water level is h_2, then:

$$\rho g \frac{h_1 - h_2}{L} A = A \rho \frac{du}{dt} \tag{II.k}$$

thus:

$$\frac{g}{L}(h_1 - h_2) = \frac{du}{dt} \tag{II.l}$$

where, ρ = water density [M.L^{-3}]
g = gravitational acceleration [L.T^{-2}]
h_1 = water level in lake 1 [L]
h_2 = water level in lake 2 [L]
A_1 = water surface area of lake 1 [L^2]
A_2 = water surface area of lake 2 [L^2]
L = length of the interconnecting canal between lakes 1 and 2 [L]
A = cross sectional area of the interconnecting canal [L^2]
u = water velocity in the interconnecting canal [L.T^{-1}]

Furthermore as:

$$-A_1 \frac{dh_1}{dt} = +A_2 \frac{dh_2}{dt} = uA \tag{II.m}$$

and:

$$A_1 h_1 + A_2 h_2 = constant = c \tag{II.n}$$

it follows that after substitution and rearranging:

$$\frac{d^2 h_2}{dt^2} + \frac{g}{L}\frac{A}{A_1 A_2}(A_1 + A_2)\, h_2 = \frac{g}{L}\frac{A}{A_1 A_2} c \tag{II.o}$$

After Laplace transformation it follows that the frequency of the oscillation (ω) equals to:

$$\omega^2 = \frac{g}{L}\frac{A_1 + A_2}{A_1 A_2} A \tag{II.p}$$

As $\omega = 2\pi/\text{Pd}$, the time period Pd is:

$$Pd = 2\pi\sqrt{\frac{L}{g}\left(\frac{A_1 A_2}{A_1 + A_2}\right)\frac{1}{A}} \qquad \text{(II.q)}$$

As $g = 9.81$ m.s^{-2}, $A_1 = 3\ 10^6$ m^3, $A_2 = 20\ 10^6$ m^3, $A = 117$ m^2 and $L = 8\ 10^3$ m (the length of the virtual canal), it follows that Pd = 7.5 hr.

The amplitude of the water velocity is estimated as $\tilde{u} = 0.1$ m.s^{-1}, while peak amplitudes of 0.3 m.s^{-1} occur (Van Huet, c). Now the equivalent dispersion (Eq. II.j) can be calculated: $D_{eq} = 13.5$ m^2.s^{-1}.

The value of the D_{eq} can be compared with the value of the physical or longitudinal dispersion due to horizontal gradients of velocity. Roughly evaluated values for the longitudinal dispersion coefficient of rivers and streams, comparable with the Follegasloot, ranged from 0.04 to 28 m^2.s^{-1} (Van Straten, 1979). Therefore, value of D_{eq} is within the range of the longitudinal dispersion coefficient.

In order to further analyze if both types of dispersion can be neglected, the dispersion effect are compared with inflow in lake 2, which is:

$$W_2 = (C_1 - C_2)\, A\bar{U} = \frac{C_1 - C_2}{L}\, AL\bar{U} \qquad \text{(II.r)}$$

where, W_2 = mass inflow rate in lake 2 [M.T^{-1}]
C_1-C_2 = concentration difference between lakes 1 and 2 [M.L^{-3}]
$\bar{u}$ = mean water velocity in the canal [L.T^{-1}]

From Fig. II.1 it follows that:

$$C_z = \frac{C_1 - C_2}{L} \qquad \text{(II.s)}$$

After substitution of Eq. II.s in Eq. II.r W_2 can be written as:

$$W_2 = AC_z L\bar{U} \qquad \text{(II.t)}$$

The estimated values of L and $\bar{u}$ are: $L = 8\ 10^3$ m and $\bar{u} = 0.1$ m.s^{-1}. Consequently, W_2 is:

$$W_2 = 800 AC_z \qquad \text{(II.u)}$$

This equation can be compared with Eq. II.i. It can be concluded that the advective flow is much higher than the flow due to equivalent as well as longitudinal dispersion. Consequently the dispersion effect is neglected in Eqs. 5 and 6.

Chapter 7

Phosphorus eutrophication in the sw Frisian lake district during 1984-1987. 2. Phosphorus balances and simulation of reduction scenarios

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To be submitted to Hydrobiologia

PHOSPHORUS EUTROPHICATION IN THE SW FRISIAN LAKE DISTRICT DURING 1984-1987: 2. Phosphorus balances and simulation of reduction scenarios

Key words: eutrophication, phosphorus balance, modelling, polders, scenarios, static gain, restoration

ABSTRACT

The lakes and interconnecting canals in the sw Frisian lake district are highly eutrophicated. Therefore, in the middle of the 1980's a phosphorus (P) eutrophication and lake restoration research project started. This project aimed at modelling water transport, P dynamics and simulating management scenarios. A simple dynamic P balance model was used for calculating the total phosphorus (TP) balances and for simulating three TP concentration reduction scenarios in three lakes (Tjeukemeer, Groote Brekken and Slotermeer) in the research area. The model covered three periods in 1985, 1986 and 1987. The external loads to Tjeukemeer are highest, moderate to Groote Brekken, and lowest to Slotermeer. The major P sources in the area are discharges from the surrounding polders, used mainly for agriculture, and P imported with water from outside the area (IJsselmeer).

Even with a 75% TP-reduction in water from the surrounding polders the 0.07 $mg.l^{-1}$ target level could be reached only incidentally in Tjeukemeer, while in the other two lakes this level was not approximated. The effect of a 75% TP reduction in water from IJsselmeer was highest in Groote Brekken (but again approximating the target only incidentally), moderate in Tjeukemeer and poor in Slotermeer. The simulations showed that only a combination of at least a 75% reduction in both external loads will lead to achieving the target level in Tjeukemeer and Groote Brekken during the summer periods. In Slotermeer, a relatively isolated lake, other measures are necessary to reach the target level. The results are confirmed by an approximate theoretical analysis of the effects of load reduction.

INTRODUCTION

Restoration of eutrophic aquatic ecosystems can be seen as a set of measures that aims at reducing nutrient concentrations and algal biomass. Measures proposed include dredging (Ryding, 1982; Björk, 1985; Andersson, 1988), chemical treatment (Hoekstra and Maiwald, 1984; Foy, 1985; Foy and Fitzsimons, 1987; Balmér and Hultman, 1988), control of discharges and reducing point sources (Ahlgren, 1988; Cullen and Forsberg, 1988), biomanipulation (Richter, 1986; Van Densen *et al.*, 1986; Andersson, 1988; Van Donk *et al.*, 1989), artificial mixing and input of oxygen (Imboden, 1985), sewage effluent diversion (Edmondson, 1985), isolation (Burdon *et al.*, 1987; De Haan *et al.*, 1988), aeration (Björk, 1985) and flushing (Hosper, 1984). By the application of these techniques, deterioration might be stopped successfully. Phosphorus (P) is often seen as the critical nutrient in determining the degree of lake eutrophy and therefore, many restoration programmes concentrate on P control.

By the mid 1970's the problem of eutrophication became evident in the sw Frisian lake district. Reducing P concentrations was the main objective to combat the eutrophication problem. Therefore, in 1979 dephosphorization of waste water in the area started, but this measure alone did not lead to perceivable results. In 1984 a research project started that focused on a more integrated approach. Investigation of the role of sediments and P-loads from surrounding peaty polders were part of this project, while modelling the water transport and P dynamics were seen as a tool for a better understanding of the eutrophication process. The sedimentary P distribution, polder P-loads, a water transport model and a P dynamics model, were previously described by Van Huet and De Haan (a) and Van Huet (b, c and d), respectively. In this paper this set of tools is used to assess effects of various options for P-load control.

MATERIALS AND METHODS

Area description

Fig. 1 shows the four main lakes (Tjeukemeer, Slotermeer, Groote Brekken and Koevorder, depth 1-2 m), canals (depth 1-4 m, width 20-50 m) and system boundaries of the sw Frisian lake district. This area is part of the 'boezem': the canal-lake system in the province of Friesland, used for water table regulation and flushing. The man-made water regime is strongly influenced by the climatological conditions, resulting in a complex hydrology in the system. Two different situations occur. Firstly, in the case of a precipitation deficit, IJsselmeer water is let in near Lemmer and Tacozijl into the boezem (Fig. 1) and from there inlet into the surrounding polders takes place (generally in the summer period, April-October). Secondly, in the case of a precipitation excess, polder water is pumped towards the boezem and from there into IJsselmeer near Lemmer (generally

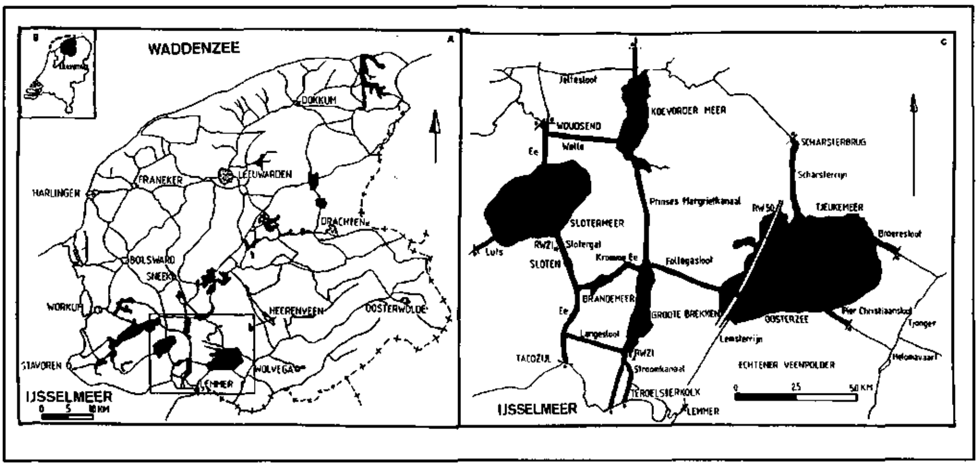


Fig. 1. A. The Frisian 'boezem'. B. Its position in The Netherlands. C. The sw lake district (●_: boundaries research area; RWZI: waste water treatment plants; RW50: motorway 50; from Van Huet, 1990).

in the winter period, October-April). For further information about this seasonal variation, hydrology, eutrophication and limnology of the lakes, see Beattie *et al.* (1978), Moed and Hoogveld (1982), De Haan and Moed (1984), Van Huet (1990, and d, this Volume).

Application of a phosphorus model

For the simulations a dynamic P balance model was used (Van Huet, d, this Volume, and Eq.1). The model focuses on phosphorus, under the assumption that there is a significant correlation between TP concentrations and chlorophyll-a contents. Chlorophyll-a, as an estimate of phytoplankton biomass, can be used as an approximate criterion of biological response (Lambou *et al.*, 1983). Results of a survey over 35 Dutch lakes indicate that TP concentrations below 0.07 $mg.l^{-1}$ will lead most likely to a situation where blue-green algae no longer dominate (Lijklema *et al.*, 1988).

The model inputs were inflow and outflow discharges from a hydrodynamic model (Van Huet, c) and TP concentrations in inflow discharges. In the model, an overall net loss term is used to describe the combined effect of sedimentation, resuspension and release of P. The simulations were run over 2.5 years, with interruptions in periods of ice cover.

Table 1 shows the mass balance that could be calculated by use of the model. It can be concluded that the loads towards Tjeukemeer are highest, mediate towards Groote Brekken and lowest towards Slotermeer. Moreover, two external loads dominate. Firstly, the loads discharged through the Broeresloot and/or the Pier Christiaansloot into Tjeukemeer (Fig. 1) are high (highest mean value in the third period, being 875 kg.d^{-1}). These loads can be considered as indirect polder loads (i.e. loads from polders east of the study area). Secondly, in the second period the load from IJsselmeer into Groote Brekken is high (mean value 190 kg.d^{-1}).

Inside the system the mass flow rates in the Follegasloot and the Prinses Margrietkanaal dominate. The contributions from precipitation, inlet via sluices and from the waste water treatment plant near Lemmer are relatively low. The contribution of direct polder TP loads is highest for Slotermeer, although it should be realized that the loads into Slotermeer are estimated at half of the loads into Tjeukemeer. However, as the indirect polder loads into Tjeukemeer are very high, this lake can be considered as the typical polder lake in the area, and Slotermeer only to a lesser extent. The contribution of net loss is relatively highest for Slotermeer. The influence of the net loss in Slotermeer is discussed in Van Huet (d, this volume).

Table 1. TP balances of three lakes during three periods.

Tjeukemeer				Groote Brekken				Slotermeer			
Period	1	2 (kg.d^{-1})	3		1	2 (kg.d^{-1})	3		1	2 (kg.d^{-1})	3
IN				IN				IN			
Follegasloot	170	129	111	Follegasloot	121	100	198	Ee	54	97	81
Pier Christiaansloot	151	68	41	Langesloot	31	83	46	Slotergat	22	31	36
Broeresloot	281	443	834	Kromme Ee	27	44	35				
Scharsterrijn	104	57	28	Prins. Margrietkan.	222	65	114				
Polders	37	14	33	Polders	9	6	8	Polders	19	7	14
Precipitation	2	3	3	Precipitation	0	4	1	Precipitation	1	2	2
				Inlet IJsselmeer	1	190	36				
				Inlet sluices	1	5	7				
				Waste water plant	9	1	1				
TOTAL	745	714	1050	TOTAL	421	498	446	TOTAL	96	137	133
OUT				OUT				OUT			
Follegasloot	121	100	198	Follegasloot	170	129	111	Ee	21	21	25
Pier Christiaansloot	170	288	484	Langesloot	4	5	12	Slotergat	45	54	56
Broeresloot	286	124	46	Kromme Ee	15	15	24				
Scharsterrijn	32	53	154	Prins. Margrietkan.	49	249	228				
Polders	4	22	15	Polders	1	3	2	Polders	2	11	6
Infiltration	2	2	3	Infiltration	0	0	0	Infiltration	1	1	1
				Pumping into IJsselm.	168	75	54				
Net loss	95	115	145	Net loss	13	16	20	Net loss	35	49	48
TOTAL	710	704	1045	TOTAL	420	492	451	TOTAL	104	136	136
STORAGE	35	10	5	STORAGE	1	6	-5	STORAGE	-8	1	-3

Phosphorus load reduction scenarios

In scenario studies two approaches are possible. The first approach is to define a scenario and evaluate whether under this scenario a target level is attained. The second starts at a target level and then seeks to a (combination of) scenario(s) that satisfies this level. For the second method an operational definition on what is meant by 'satisfies a level' is needed, while the set of satisfactory combinations can be very large. Since in this study a limited set of reasonable scenarios can be formulated relatively easily, and the main objective is no more than an illustration of the kind of response that can be achieved by P reduction, the more practical first approach was followed.

The simulated scenarios focus on the reduction of the two main external P-loads, particularly on the reduction of TP concentrations in inlet water from IJsselmeer and in water pumped from the polders into the system. Peak loads from IJsselmeer occurred in the summer of 1986, and from polders mainly in the winters (especially the indirect polder contribution, see above).

Preliminary simulations showed that small TP concentration reductions in the main loads and 100% reductions in for example the waste water effluent did not result in perceivable changes in P-levels in the system (see also Table 1). Apparently, only large reductions were likely to have effects, so for this reason the reduction levels in the various scenarios were set arbitrarily at 75% throughout. The model is approximately linear concerning TP concentrations and therefore allows a crude estimate of the effects of larger or smaller reduction levels from the effects. The simulated scenarios are:

1) A 75% TP-reduction in indirectly discharged polder water .

2) A 75% TP-reduction in both indirectly discharged and directly pumped polder water.

3) A 75% TP-reduction in inlet water from IJsselmeer.

4) A 75% TP-reduction in both water from all polders and from IJsselmeer.

RESULTS AND DISCUSSION

The three simulation periods cover both normal situations (P-loads from polders in winter and from IJsselmeer in summer), and unusual situations, such as high polder P-loads in summers of 1985 and 1987, due to precipitation excess.

Figures 2-4 show the results of the scenario simulations. Each figure shows the following lines: a) a line that corresponds with the actual basic water quality standard in The Netherlands for the summer period (0.15 $mg.l^{-1}$), b) a line that corresponds with the target TP concentration of 0.07 $mg.l^{-1}$, c) a basic line that corresponds with simulation of the actual TP concentrations during the three periods (see Van Huet, d, this volume), and d) one or more lines that correspond with the 75% reduction scenarios.

Fig. 2 shows that a 75%-reduction of TP concentrations in indirectly discharged polder water (scenario 1) has, as expected, the greatest effect on the P-level in Tjeukemeer. In this lake, TP concentrations below the actual standard of 0.15 $mg.l^{-1}$ can be achieved, while the 0.07 $mg.l^{-1}$ target level is approximated. In Groote Brekken the 0.15 $mg.l^{-1}$ standard is approximated incidentally. In this lake the effect is highest in the third period due to high loads discharged through

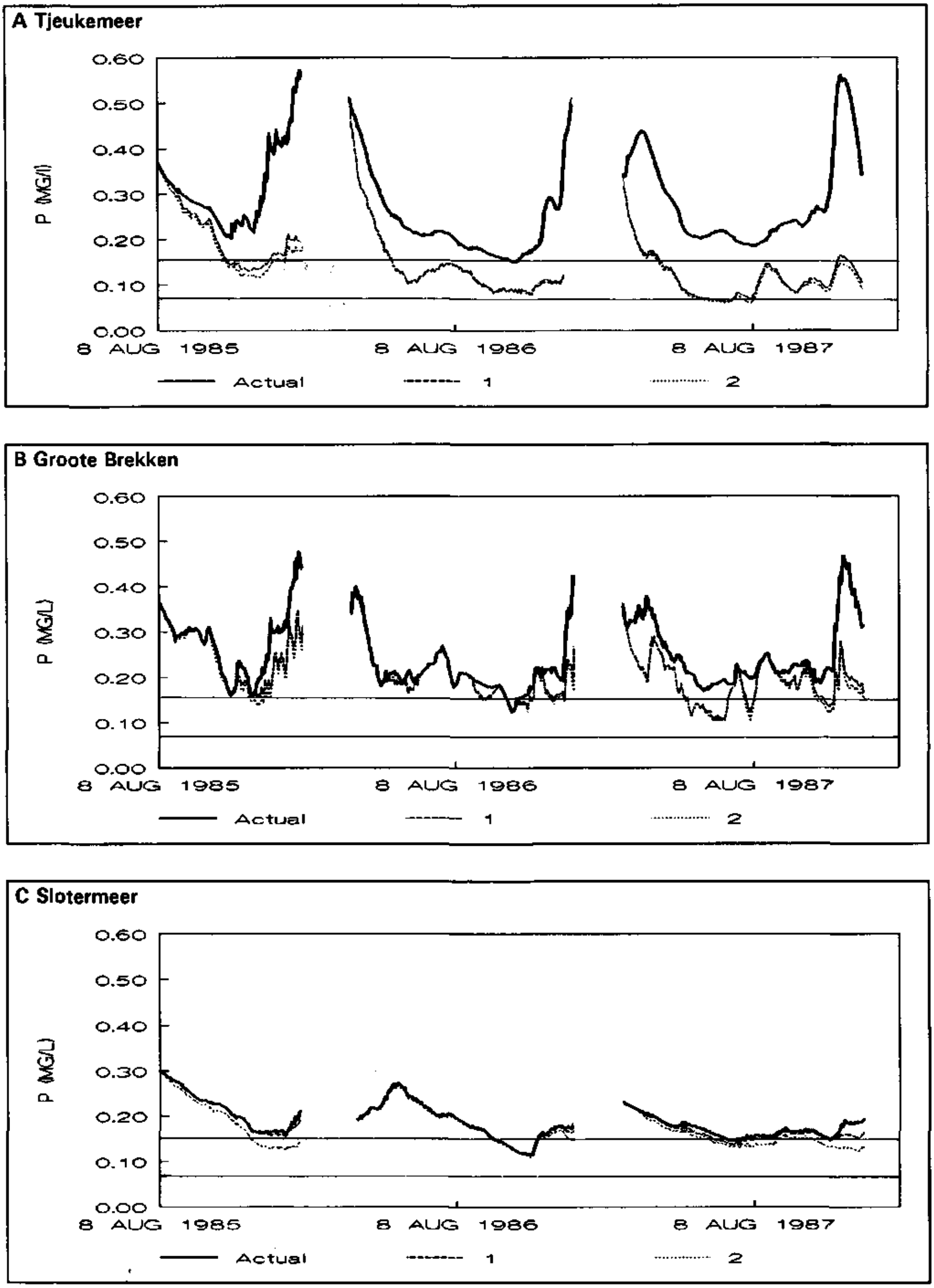


Fig. 2. Effects of 75% TP-reduction in indirectly discharged (1) and both indirectly discharged and directly pumped polder water (2), during three simulated periods. Actual: simulation of the actual TP concentrations.

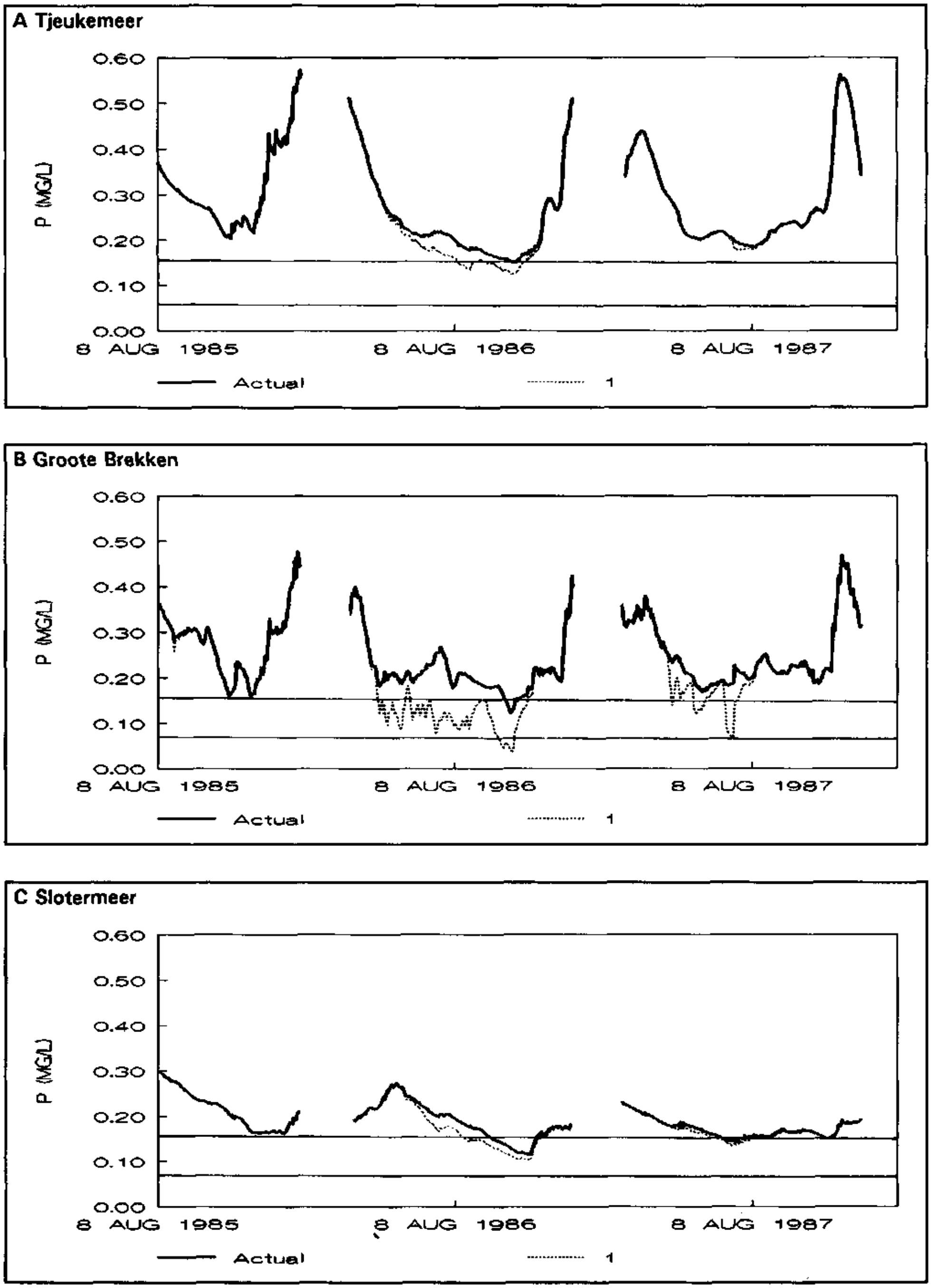
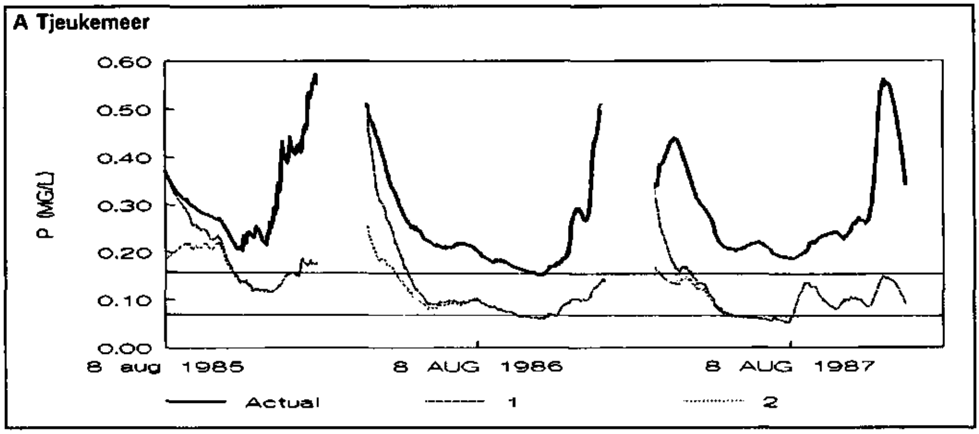
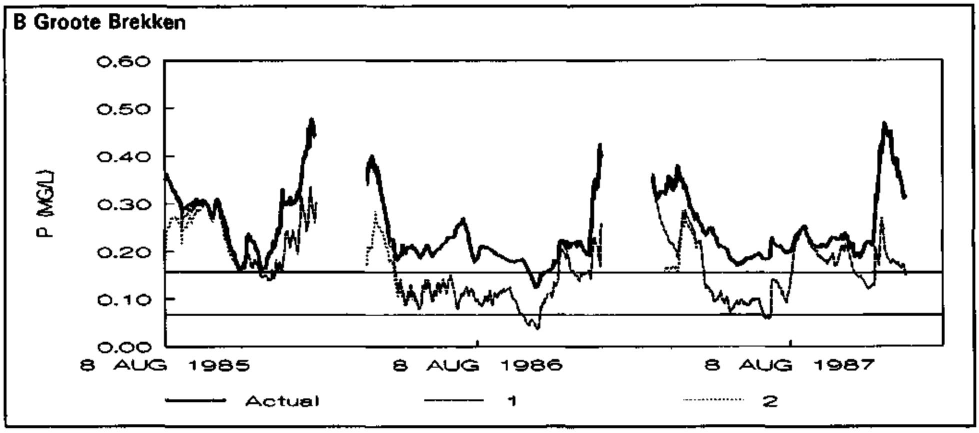


Fig. 3. Effect of 75% TP-reduction in inlet water from IJsselmeer (1), during three simulated periods. Actual: simulation of the actual TP concentrations.

A Tjeukemeer



B Groote Brekken



C Slotermeer

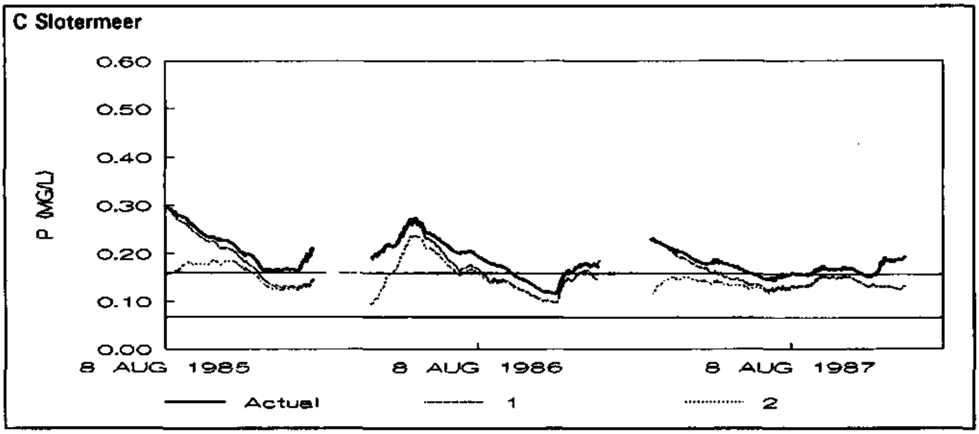


Fig. 4. Effects of 75%-reduction in both polder water and water from IJsselmeer (1) and the same expressed in the case of halving the initial TP concentrations (2), during three simulated periods. Actual: simulation of the actual TP concentrations.

Follegasloot (198 kg.d^{-1}). In Slotermeer the effects of scenario 1 are poor, as expected, because the distance from Broeresloot and Pier Christiaansloot is long. The further reduction of TP concentrations in polder water directly pumped into the system (scenario 2) does not substantially increase the effect of scenario 1 in Tjeukemeer and Groote Brekken, while the effect is relatively highest in Slotermeer (see also the TP-balance, Table 1).

A reduction of TP concentrations in inlet water from IJsselmeer (Fig. 3, scenario 3) has, as expected (see Table 1), the greatest effect in Groote Brekken. In this lake the 0.15 mg.l^{-1} standard is achieved, and incidentally the 0.07 mg.l^{-1} target level is approximated. In Tjeukemeer only in the summer period of 1986 the 0.15 mg.l^{-1} standard is achieved, while the effect in Slotermeer is relatively low.

Fig. 4 shows the effects of all reductions together (scenario 4). It can be concluded that in this way the results satisfy the 0.15 mg.l^{-1} standard in Tjeukemeer and Groote Brekken, while incidentally the 0.07 mg.l^{-1} target level can be reached. Slotermeer responds only to a small extent to these measures.

The simulations started in each period with the actual (measured) TP concentrations in the lakes, while the 75%-reductions were assumed to come into effect at the beginning of each period as well. Consequently, the results represent the short-term transient effects for each simulated period separately. In order to get an impression of the measures already in effect before, Fig. 4 also shows simulations where the initial TP concentrations in each lake are set to 50% of their original value. As expected, the initial condition effect is overruled by the discharged loads within a period of some months.

The dynamic behaviour can be explained by considering the dynamic mass balance equation for each lake, derived at Van Huet (d, this Volume):

$$AH\frac{dP}{dt} = \Sigma\{Q_{in,j}(P_{in,j} - P)\} + Q_e P - v_s A P \qquad (1)$$

where, A = lake surface area (m^2); H = water depth (m); P = lake TP concentration (mg.l^{-1}); $P_{in,j}$ = TP concentration in influent j (mg.l^{-1}); $Q_{in,j}$ = inflow discharge j (m^3.d^{-1}); Q_e = evaporation (m^3.d^{-1}); v_s = apparent settling rate (m.d^{-1}).

In general, the transfer function from load discharges and load concentrations to in-lake concentration is not easy to evaluate from Eq.1, because both $Q_{in,j}$, $P_{in,j}$ as well as P and H are functions of time, and consequently Eq.1 is non-linear. Also, for the three lakes the equations are coupled. A full analysis would require the linearization of the equations around a suitable point, e.g. the period-wise average, followed by calculation of the deviation in output P concentrations vs. deviations in Q_{in} and P_{in} in the Laplace domain. A crude appraisal, however, is possible by observing that AH = V = volume is approximately constant in the long term, and by combining all different loads into one single term:

$$L = \Sigma Q_{in,j} P_{in,j} \tag{2}$$

Treating each lake independently, then, with some algebra, Eq.1 can be written in the standard form of a first order dynamic mass system:

$$\theta \frac{dP}{dt} + P = k_p L \tag{3}$$

where θ = the effective time constant:

$$\theta = \tau \frac{1}{1 + \frac{v_s}{H}\tau} \tag{4}$$

and τ = the adapted hydraulic residence time:

$$\tau = \frac{V}{\Sigma Q_{in,j} - Q_e} \tag{5}$$

and k_p = the static gain:

$$k_p = \frac{\theta}{V} \tag{6}$$

Eq.3 shows that each lake roughly follows a first order dynamics. The response time of the TP concentration in the lake to a step change in external load is directly related to θ (95% of the ultimate response is reached in about 3θ time units). Eq.4 shows that the effective time constant is at most equal to the adapted hydraulic residence time, but usually smaller because of the net loss to the sediment (if $v_s = 0$ then $\theta = \tau$, in all other cases with positive v_s $\theta < \tau$). The final concentration effect is k_p units per unit step loading change (i.e. mg.l^{-1} concentration effect per kg.d^{-1} load reduction).

The average values of the effective time constant and static gain were calculated for each of the lakes in each of the three periods. The results are shown in Table 2. With these results the graphical output can easily be understood. Of all lakes, Groote Brekken has the fastest dynamics with effective time constants fewer than 5 days. This explains why P concentrations in this lake show many more 'nervous' variations than in Tjeukemeer and in Slotermeer. Load variations are not as strongly attenuated as in the two larger lakes. In particular the P-behaviour of the model for Slotermeer is very smooth, due to the effective time constants in the order of 50 days. It is interesting to note that in contrast to the model the real data show appreciate fluctuations in time. This can occur if a) there are strong fluctuations in load, or b) the assumption of complete mixing is occasionally violated. In view of the location of the sampling points, there are, in fact, reasons to believe that the data are influenced by local effects due to intermittent discharges of polder water.

The static gains of the three lakes are also quite different. In fact, the final concentration effect in Slotermeer is about 4 times as large per $kg.d^{-1}$ load reduction. That this cannot be seen in Fig.4 is due to the fact that a 75% load reduction does not correspond to the same amount of mass reduction for the three lakes. From the mass balance data presented in Table 1 it is obvious that the mass load to Slotermeer is much less than to Tjeukemeer, and consequently a 75% reduction has much less effect despite the larger static gain. A direct comparison of the load effect calculated from the static gain with those seen in the figures is not easy, because the lakes are interconnected. A true first order response can only be expected if the lake acts as the upstream end of the interconnected system. This is the case with Tjeukemeer, when there is no IJsselmeer inlet, and with Groote Brekken when there is IJsselmeer inlet. For example, when looking at the independent loads due to indirectly and directly discharged and pumped polder water into Tjeukemeer in period 2, the mass balance data show that this amounts to 525 $kg.d^{-1}$ in the untreated situation. A 75% reduction would thus be about 394 $kg.d^{-1}$, leading to a concentration effect of 0.22 $mg.l^{-1}$, based on the calculated static gain. Comparing this value with the results in Fig. 2 shows that the true effect is smaller, because of the capacity of the connected lakes. Similarly, for Groote Brekken in the second period, when there is considerable inlet of IJsselmeer water, the 75% load reduction for this source amounts to about 143 $kg.d^{-1}$, leading to a calculated response of 0.1 $mg.l^{-1}$, quite similar to the result obtained in the simulation. With more complex hydrologic conditions the simple analysis above is not applicable, and the simulation model must be used instead.

It should be said that the calculated effects of external load reduction, in reality will probably partly be counteracted by an increase of internal loading, because at lower TP levels in the lakes P release is likely to increase (Marsden, 1989). Should this occur, even larger load reductions would be needed. Therefore, the calculations provide an impression of what at least would be required to achieve an appreciable improvement in water quality.

Table 2. Calculated values for the adapted hydraulic load, the effective time constant and the static gain.

Period				1	2	3	1	2	3	1	2	3
	V	H	v_s	τ			θ			k_p		
	(10^6 m^3)	(m)	($m.d^{-1}$)	(d)			(d)			(10^{-3} $mg.l^{-1}$)/($kg.d^{-1}$)		
Tjeukemeer	34.4	1.76	0.015	18	23	19	16	19	16	0.45	0.56	0.47
Gr.Brekken	6.0	2.01	0.015	4	4	6	4	4	6	0.65	0.65	0.96
Slotermeer	18.1	1.64	0.015	54	59	58	36	38	38	2.00	2.12	2.10

The role of the bottom, long-term effects and water transport manipulation (hydrological scenarios) could not be simulated with the model. These scenarios were roughly simulated by Brinkman *et al.* (1989), who used a similar model, covering one long period (1974-1986). They concluded that reduction of lake sedimentary P release, as well as hydrological measures, such as increase or decrease of inlet from IJsselmeer, did not result in TP concentrations below 0.15 $mg.l^{-1}$. Only P-load reduction measures in the same order of magnitude as investigated here had an appreciable effect on P levels. The results of Brinkman *et al.* concerning long-term scenarios agreed well with the short-term results in this paper.

Simulations for the whole boezem network were done with a set of other models (Delft Hydraulics Laboratory, 1986; Brinkman *et al.*, 1987). These simulations indicated that flushing the system with water from IJsselmeer in the years 1976 and 1977 seemed to have a positive effect on the shift from a blue-green algal dominance towards green algae due to the shorter residence times. However, the TP model results, especially in the northern part of the boezem, were not satisfactory, probably because the set of models did not cover sediment-water P-exchange processes, thus calling the conclusions into question. Moreover, 1976 was an unusual year, because of a large precipitation deficit in the summer period.

CONCLUDING REMARKS

The results of the scenario model study show that only a combination of measures can lead to acceptable TP-levels in the canal-lake ecosystem. Large (75%) TP-reductions in water from IJsselmeer and from polders are necessary to achieve a response and, finally, restoration. The effects in the two largest lakes in the area, Tjeukemeer and Slotermeer, differ. In Tjeukemeer the 0.07 $mg.l^{-1}$ target level can be approximated by the 75%-reduction scenarios, while in Slotermeer only the 0.15 $mg.l^{-1}$ standard is achieved. Tjeukemeer is largely influenced by the polder loads, Groote Brekken by the IJsselmeer loads, while Slotermeer seems a relatively isolated lake in the area. The results are very similar to the results of a long-term model.

Chapter 8

Epilogue

EPILOGUE

Modelling water transport and P dynamics: starting from scratch.

Although much information was available about the trophic status in the sw Frisian lakes and interconnecting canals, there was a lack of information about the TP dynamics. For example, TP levels in the four main lakes and interconnected canals were known, but no detailed insight was available into the origin of the P-loads. So, a modelling approach could be of great value for water quality decision makers, who could use models as tools for simulating management scenarios. This approach was new in the strategy to diminish eutrophication in the Frisian water system. However, the application and assessment of models meant that an intensive and frequent monitoring program had to be started. In fact, the modelling approach meant a start from scratch in 1984.

In Chapter 1 (*General Introduction*) it was discussed that the approach required the solution of at least three problems. Firstly, there was lack of knowledge about the role of sediments. Secondly, no information was available about the time variable TP loads from polders. Thirdly, the discharges in the boundary canals of the open system were unknown.

In this chapter the approach and the remaining methodological questions are discussed. Also, it is made plausible that although certain choices had to be made, the trends, as simulated by use of the mass balance model, will remain the same if, for instance, more extensive input data sets would have been available.

This chapter also goes into some options for further research that can lead to more insight into the underlying processes, such as accumulation, runoff and leaching of TP in polders, that cause the high TP loads. Also some management options are given.

Discussion of the approach

The first problem that was defined was the lack of knowledge about sedimentary TP processes. Phosphorus balance studies of the whole Frisian boezem during 1973-1977 showed that half of the incoming phosphorus was left behind in sediments (Claassen, 1979). For 1983 the contribution was 34% (Province of Friesland, 1989). More knowledge of the processes in sediments would be of great value for a better insight.

In Chapter 3 the TP distribution in sediments is described. Only little information is available about processes such as release and speciation. However, measures such as reducing sedimentary P release will not influence the main trends of the management scenarios, because it is very clear that there are two main external P-loads in the research area: from IJsselmeer and (directly or indirectly) from polders. Therefore, combating eutrophication can only be achieved if, in any case, these loads are reduced. Only large reductions of inflow TP concentrations will lead to acceptable P-levels. However, these measures might lead to an increase in P-release. Brinkman *et al.* (1989) estimated that the P supply in the upper 5 cm of the sediments is 12 g.m^{-2}, and that approximately 10% is available in the short term. They concluded that P release could influence the effects of external load reductions during a long period. Should this occur, additional research might be justified in order to judge the cost effectiveness of further measures.

The second problem was that there were time variable TP polder loads. In Chapter 4 the gross and net loads are quantified from weekly measured TP concentrations and daily or monthly discharges. No attention was paid to the statistics of these values. At present the daily load estimates may be biased due to the extrapolation of weekly P concentrations. By considering the correlation between P concentrations and flow rate in the polder discharges the accuracy of the time pattern could be improved. Because of the lack of detail simulated P patterns are more smooth than in reality, although a dynamic analysis shows (see Van Huet, e) that the effect will be small. Due to the long effective time constants in most lakes a larger time detail in the load data will not influence the main conclusions that can be drawn from the scenario calculations.

The third problem was the open system. Moreover, discharges in the boundary canals were unknown. Modelling of water transport in the whole Frisian water network did not lead to a detailed insight into the surface water hydrology in the south-western part of it (Pellenbarg, 1973; Tuinhof, 1976; Brinkman *et al.*, 1987). Consequently, the problem had to be solved by the application of the detailed wind-driven hydrodynamic model, using water levels in the boundary canals as forcing functions. This approach is new. Of course, the question may arise whether flow can be reliably calculated from the small level differences observed. Certainly, this question can be approached through a detailed dynamic analysis. In the present work this was not done. However, there were two indications that the results are reliable. Firstly, the model sensitivity was investigated and appeared to be low for errors in the water level data. Secondly, the application of a chloride mass balance model, using the quantified output discharges, showed a good similarity between measured and simulated chloride concentrations.

In this thesis a simple relationship between TP and algal biomass was taken as the basis. This is definitely a sound approach for the overall assessment of P load reductions. Should, however, the Water Board require indications on the effect on algal composition and succession (e.g. blue-greens), then further research involving a far more complicated model would be needed.

Another subject that needs more attention is the water quality in Slotermeer and the origin of TP, although the yearly averaged TP concentrations are lowest in this lake. The effect of even reductions of up to 75% in TP from polders and from IJsselmeer was relatively low. Apparently, other measures are necessary. Slotermeer is influenced by inlet of IJsselmeer water near Tacozijl. However, inlet did only occur during the summer period of 1986. Probably Slotermeer is influenced more by pumping and inlet of water near Stavoren, located in the area west of this lake.

An important question for management and policy is: what could be done to reduce TP concentrations in water from IJsselmeer? This is (partly) an international problem, because this lake contains water from the river Rhine. The reduction of phosphorus in detergents and dephosphorization of waste water, discharged into this river, could be some of the measures.

Additional research subjects and options for polder management

The investigations in the Echtener Veenpolder indicated that there was a contribution from processes in the polder itself. Probably these processes are surface runoff, (natural) leaching and resuspension. However, exact data are unknown. Moreover, the adsorption capacity of peaty soils and especially the role of agriculture might also need more attention.

Steenvoorden and De Heus (1988) suggested that leaching of phosphorus in peaty districts in The Netherlands is probably still on a natural level and that human activities like spreading manure and fertilizing have not had any influence on this process so far. Preliminary results of studies in other polders with agricultural activities in Friesland showed that leaching was on the same level as in nature reserves (Province of Friesland, unpublished results). However, in P balance studies leaching and the contribution of agriculture are often unknown and together they are estimated by quantification of all other contributions to the P balance. Jansen (1988a) concluded that in other regions in The Netherlands very high contributions of agriculture and leaching occurred (together 50%, peak levels up to 90%).

It is also hard to quantify the contribution of the surface runoff; it is probably highest in the winter period, particularly when the ground is frozen. Spreading of manure under these circumstances will lead to high TP concentrations in runoff water. Runoff from peaty soil might be high compared to sandy soil (Steenvoorden, 1988). The contribution of manure runoff to surface water P balances is estimated at 1% by Feenstra and Van der Most (1986).

Also, attention should be paid to local leaching and the adsorption capacities of soils (Van der Zee, 1988). In peaty districts in The Netherlands the average P surplus on the overall balance (including import of cattle food, fertilizers, etc) is 30 kg $P.ha^{-1}.yr^{-1}$, with peak levels up to 45 kg $P.ha^{-1}.yr^{-1}$ (Terwan, 1988). This is very high as compared to measured outputs (maximum calculated value 4.13 kg $P.ha^{-1}.yr^{-1}$), indicating that a massive storage of P has accumulated in the soil over the years. For a detailed insight into the polder P contribution, not only overall polder P balances and surface water balances are needed, but also P balances of individual farms.

As the impact of the indirect loading is very high (i.e. water from polders east of the research area, discharged through the Broeresloot and Pier Christiaansloot), research on point sources and management in this watershed is recommended. Furthermore, the influence of phosphorus from polders on algal growth, succession and species in the lakes might need more attention.

Another important theme in further polder research is the quantification of dynamic balances. The complex hydrology in, for example the Echtener Veenpolder and the polder Rottige Meente (Chapter 4 and Jansen, 1988b, respectively) and consequently the changing character of the several contributions of the water balance do not lead to an optimal water regime. For instance, simultaneous pumping and inflow of water may occur in practice although this would not be necessary for a proper water table regulation. Altogether the polder investigations need a more integrated analysis, with emphasis on both water quality and water quantity aspects.

Because of the high population density and high productivity standard in The Netherlands, environmental and agricultural policy have contradictory interests (Van Bakel, 1988; Terwan, 1988; Steenvoorden and Bouma, 1987). Nevertheless, the question is what could be done in theory, to diminish the P-loads from polders? Here, some options are given, although it should be emphasized that more knowledge of the effects is needed. Most of these measures are being studied and field experiments are in progress in some areas in The Netherlands. The options are:

a) Improvement of quantity control as well as of quality control. This should lead to an optimum regime of the timing of inflow and pumping in combination with storage control (see b). Furthermore, simulation of these processes can be of value for management.

b) An optimized water level and reservoir management inside the polders, in combination with inlet and pumping of water with relatively low TP concentrations (see a). The increase in water storage capacity could be achieved by inundation of low lying lots (which occurred in the 19th century when there was less sophisticated man-made hydrology). In addition measure e) could be of value.

c) Inflow of water close to the pumping stations, as in the nature reserve Rottige Meente should be avoided (Jansen, 1988b). For example resuspension of P-rich sediments in the interconnecting ditches could be avoided by this measure.

d) The isolation of areas or lots with local seepage and reasonably good ground water quality should be considered, in order to protect these zones.

e) The construction of helophyte filters (reed, rush) which could act as a buffer for phosphorus (Van der Aart, 1985). This implies the removal of the biomass in which the phosphorus is trapped.

f) Transport of all water from housing and farms to water treatment plants with dephosphorization units.

g) Reduction of fertilizer and manure quantities.

h) Reduction of phosphorus quantities in cattle food (Rijtema, 1986).

i) Lowering of the cattle density.

j) Lowering of the water table in the ditches and consequently the ground water table (Dorenbosch, 1983). On the one hand this process could lead to lower P-runoff rates (Steenvoorden and Bouma, 1987; Wind, 1986) but on the other hand an increase in P accumulation in soil will occur, and possibly deterioration of the ground water quality, because of a more intensive manuring regime and/or the shrinking of soil due to mineralization (Pankow et al, 1985; Terwan 1988; Broers, 1987). Consequently short term and long term effects should be weighed against each other.

h) Phosphorus precipitation by adding iron in the water that is discharged from the polder.

This thesis clearly showed that large reductions of external loads are necessary for restoration of the eutrophicated canal-lake system. The modelling approach taken in this thesis has prompted a proper data gathering, and served as a guideline for the investigations that were necessary to obtain a firm insight into the role of (external) loads, in view of the natural variability in data. Studying other processes and techniques, for instance biomanipulation, might lead to additional information on the role of phosphorus in the aquatic ecosystem.

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CURRICULUM VITAE

Harry van Huet werd op 8 augustus 1953 geboren te Ulft. Na één jaar MULO aldaar bezocht hij gedurende 1966-1971 het Ludgercollege te Doetinchem, resulterend in het diploma HBS-b. Hij studeerde gedurende de jaren 1971-1978 en 1982-1983 chemische technologie aan de toenmalige Technische Hogeschool Twente. Het baccalaureaatsdiploma werd in 1976 behaald met als afstudeertitel: "De relatie tussen fotosynthese-activiteit en pH en zuurstofconcentratie in oppervlaktewater". Tijdens de doctoraalfase volgde hij de afstudeerspecialisatie Technisch Milieubeheer en haalde hij onderwijsbevoegdheden in de scheikunde, natuurkunde en de wiskunde. Het doctoraalonderzoek werd gedeeltelijk verricht bij het toenmalige Instituut voor Cultuurtechniek en Waterhuishouding te Wageningen. Het doctoraal afstudeerrapport had als titel: "Kwantificering en modellering van de stikstofhuishouding in bodem en grondwater na bemesting". In februari 1984 volgde een aanstelling als chemisch hydroloog op het Tjeukemeerlaboratorium van het Limnologisch Instituut te Oosterzee (Koninklijke Nederlandse Academie van Wetenschappen). Het onderzoek dat leidde tot dit proefschrift werd in 1989 afgerond. Hij werkt sinds oktober 1990 als post-doc medewerker bij de Vakgroep Milieukunde, Faculteit der Natuurwetenschappen van de Katholieke Universiteit Nijmegen.