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WATER QUALITY CONTROL OF THE ANDELSE MAAS BASIN, THE NETHERLANDS, BY IRON DOSING

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ABSTRACT

The Dune Water Works of The Hague pumps yearly about 45 million cubic meters of water from the Andelse Maas Basin to the dunes for infiltration purposes. The water in the Andelse Maas Basin is strongly influenced by the Meuse river. Phosphate concentrations are so high that algal growth causes difficulties in filters and dunes. For phosphate reduction purposes, iron is dosed into the basin. Several limnological variables are monitored based on weekly measurements. A mathematical model has been developed for the description of the eutrophication in the basin. The model is time and space dependent and based on the one-dimensional dispersion-advection equation. Two separate submodels are used, one for the simulation of flow conditions and one for the algae and nutrient kinetics. The ortho-phosphate reduction is modelled as a first order process. The eutrophication model has been calibrated, verified and used for a prediction of chlorophyll-a and ortho-phosphate concentrations for the case of the shut down of the iron dosing installation. The dosing of iron appears to be a very effective way for phosphate removal. Termination of the dosing would give unacceptable high phosphate and chlorophyll-a concentrations. Present investigations are focussed upon the minimization of the amount of iron dosing.

KEYWORDS

Water quality, monitoring, internal storage, bioassay, eutrophication, phosphate removal, iron dosing, chlorophyll levels, dune infiltration, drinking water.

INTRODUCTION

The Andelse Maas Basin

The Andelse Maas Basin is about 12 km long, and 4.5 m deep. It has a volume of about 9 million cubic meters. The basin is connected with the river Meuse at one end and closed at the other end. Before the closure the Andelse Maas was a connection between the river Meuse and the river Waal. The tidal movement considerably influences the hydrodynamics of the basin. Several polders discharge their water into the basin. The water quality in the basin is strongly influenced by the water quality of the river Meuse, which is highly eutrophic.

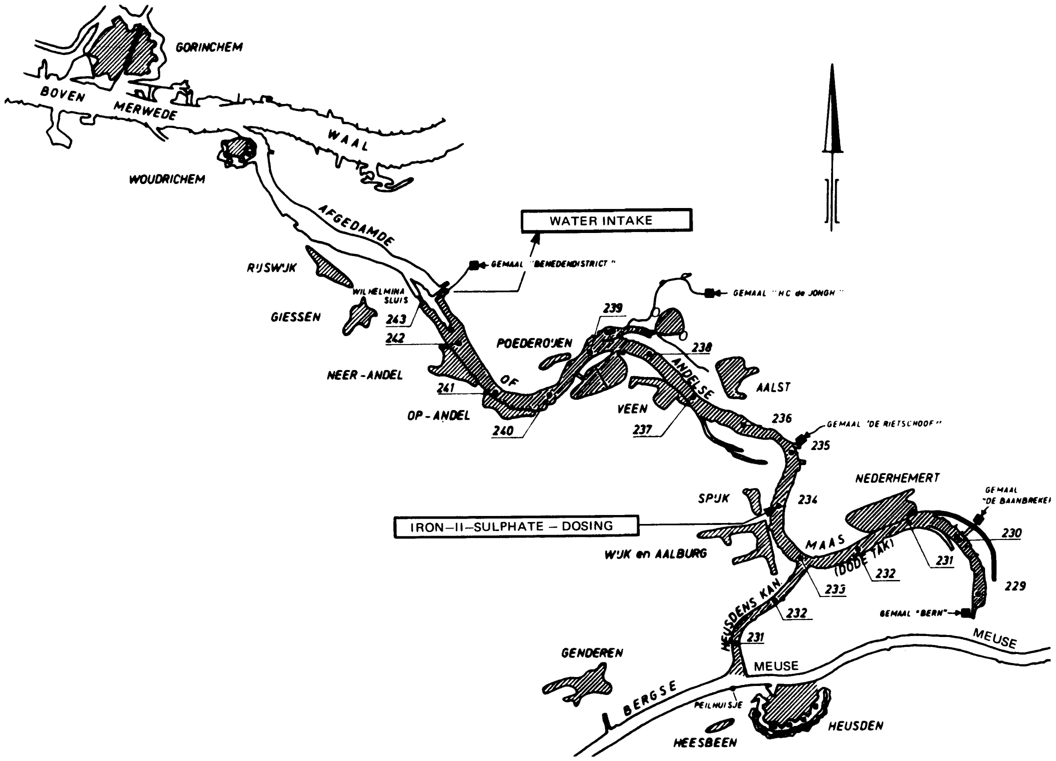

Fig. 1. The Andelse Maas Basin

The Drinking Water Supply

The Dune Water Works of The Hague uses the basin as a storage reservoir for drinking water supply of a population of about 900.000 people. For this purpose about 45 million cubic meters of water is pumped yearly from the Andelse Maas Basin into the dunes near The Hague for infiltration purposes. At Scheveningen the water is pumped into the distribution system after post-treatment. Because of the high phosphorus level of the river Meuse high chlorophyll-a levels could be expected in the Andelse Maas Basin. This could cause difficulties during several stages of the drinking water purification process. Therefore it was decided to reduce phosphorus levels by artificial precipitation with iron-II-sulphate. The iron-II-sulphate is dosed into the basin from a pipe at the bottom of the basin. Mixing is increased by infiltration of air under high pressure and by the tidal mechanism.

To study the influence of the iron dosing a limnological monitoring program was carried out from 1976.

Optimization of the Iron Dosing

The study aims primarily to minimize the amount of dosed iron in order to achieve certain prescribed phosphate levels in the basin. As a research tool a descriptive and predictive mathematical model for the phytoplankton biomass and ortho-phosphate level in the basin as a function of time and space was developed. Boundary values for the model are the quality of the river Meuse and the quality of the discharged polder water. Iron dosing was implemented in the model in such a way that it was possible to study the relation between phosphate levels and the amount of dosed iron.

THE PHOSPHATE CONTENT REDUCTION

To counteract the consequences of eutrophication in the presence of nutrient loadings physical and/or chemical measures must be taken to reduce algal growth to acceptable levels. For the shallow Andelse Maas Basin the chemical method is used. This method consists of the addition of precipitants at a location near the incoming water side of the Basin, whereby the phosphorus is retained in the sediments. Experience in The Netherlands has shown that the use of iron-II-sulphate gives better effects than the application of trivalent iron or aluminium salts, if the retention time of the water is rather long, say 3 months. See Oskam (1983). However the choice of the reagent, divalent or trivalent, seems to depend on the characteristics of the basin itself and must be found in practice. For the Andelse Maas Basin the use of iron-II-sulphate has been chosen, mainly based on the moderate costs.

The Iron Dosing Installation

In two tanks (near Wijk and Aalburg) with a total volume of 70 cubic meters, iron-II-sulphate is dissolved. By means of a compressor and a pump, this salt is added to the water through a perforated pipe which lies on a raised part of the bottom.

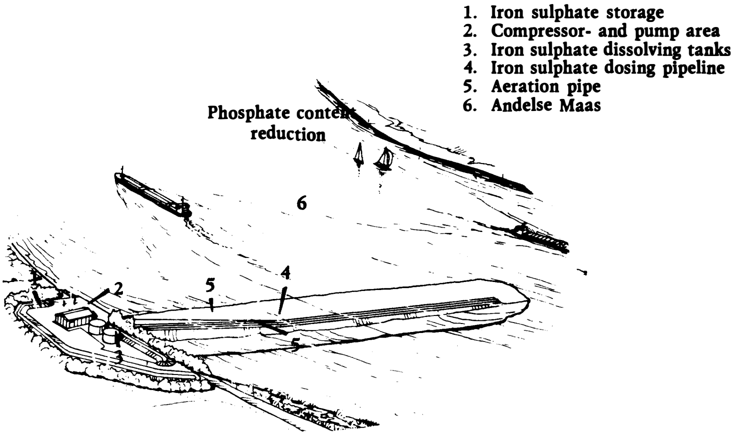

Fig. 2. The iron dosing installation

On both sides lie similar pipes for mixing the salt and aerating the water by air bubbling at high pressure. An increased mixing is obtained by the tidal mechanism. In fact each water particle passes the point of dosing several times.

The amount of iron dosage is estimated with bioassays and 'jartest' experiments. The potential upper limit of biomass of algae depends on the available amount of nutrients P, N and Si and the light intensity. By means of bioassays the quantity of algae which could be expected if the Andelse Maas was completely filled with untreated riverwater has been determined to remove phyto- and zooplankton and inoculated with the green alga *Scenedesmus quadricauda*. On controlled conditions (light and temperature) a biomass of algae of 570 g chlorophyll-a/l developed in water containing 0.49 mg/l ortho-P.

As well from the point of view of preparation of drinking water as from recreative interests no more chlorophyll-a is allowed than 25 to 50 µg per liter. By bioassays it was determined that such a level could be obtained by reducing the ortho-P content 80 to 90 percent. This reduction is possible, according to 'jartest' experiments, by dosing 5 to 10 mg/l iron-II-sulphate. The results of biomass assays however, are of limited value because in practice the amount of developed algae is strongly influenced by the grazing pressure of zooplankton, settling and non-optimal light conditions. Assuming that there is a residual flow of 3 m^3/s at the point of the iron dosing installation, since september 1976 about 8 tons iron-II-sulphate per day was dosed, in theory that means about 6 mg iron per liter. From the end of 1981 the amount of dosing was reduced to 4 tons iron-II-sulphate per day in order to obtain a better understanding of the real amount of iron dosing needed for sufficiently high algal control.

DESCRIPTION OF THE WATER QUALITY

To study the change of the water quality, the river Meuse water and the Andelse Maas Basin has been sampled weekly at seven locations. Phyto- and zooplankton are examined microscopically, quantitatively as well as qualitatively. Measured and analysed are: temperature, Secchi depth, pH, chlorophyll-a, silicon, phosphorus and nitrogen compounds, oxygen, iron, chemical oxygen demand and adenosine-triphosphate (ATP). In this paper however, only a few parameters which are used for the calibration and verification of the eutrophication model, are described.

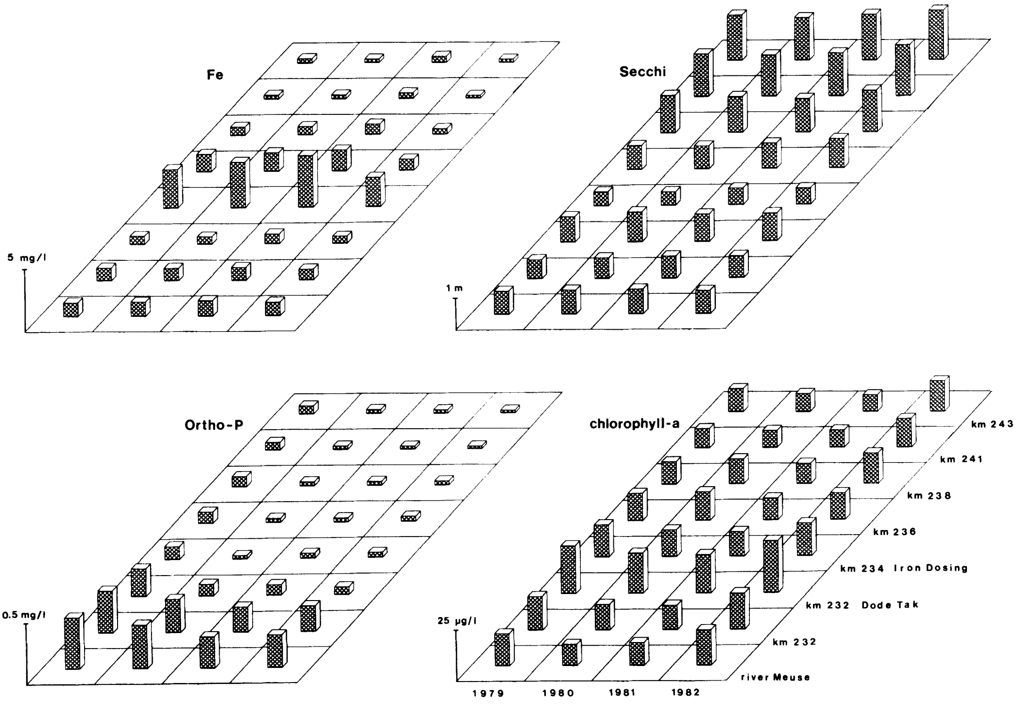

Fig. 3. Annual means of Iron, Secchi-depth, Ortho-P and Chlorophyll-a

Due to the tidal mixing an increased concentration of iron is measured both upstream and downstream of the iron dosing test installation. Rarely, however, at the point of the iron dosing, has the theoretically computed amount of iron been found. Probably this 'iron-loss' is explained by the dispersion mechanism. Coagulation, flocculation and sedimentation mainly occur between the point of dosing and some two km upstream. As a consequence of the iron flocculation, the transparency of the water decreases locally. Upstream of the iron dosing the Secchi depths increase considerably.

The most important decrease of ortho-P happens at the level of the 'dead arm' or segment 2 (see figure 1), again caused by the tidally dispersed iron. The concentration of ortho-phosphate never gives rise to the development of biomass of algae above the acceptable limit of 25 to 50 µg chlorophyll-a per liter. By halving the dosing to 4 tons iron-II-sulphate per day (1982), no significant increase in ortho-phosphate levels is observed. With regard to the preceeding years the annual means of chlorophyll-a are slightly increased.

THE EUTROPHICATION MODEL

The eutrophication model consists of two submodels. One submodel for the computation of the algal growth and one for the hydrodynamic computations. Furthermore the coupling of the submodels and the data flow is organized by the eutrophication model.

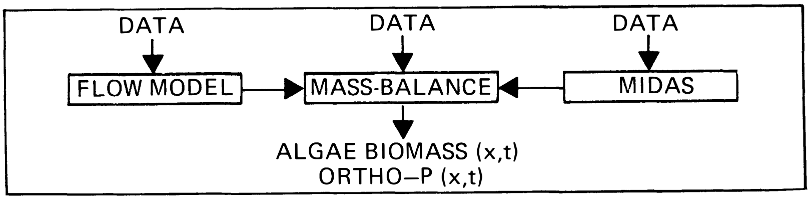

Fig. 4. Organization scheme of the eutrophication model

The organization of the Study

The study was divided into the following parts:

- data collection and analysis
- implementation of the MIDAS model
- implementation of a flow model and coupling
- calibration and verification
- simulation of scenarios

Data collection and analysis. For the model study the following data were necessary, partly for the calibration, verification and simulation purposes:

1. Geometric and hydrological data.
   Data concerning the shape of the river bed, the location of the polder pumping stations, the iron dosing station, the subdivision of the basin into computational elements, the discharges of the pumping stations, the mean levels of the river Meuse and averaged tidal elevations.
2. Limnological data.
   Forcing functions for the MIDAS model, such as surface light intensity, water temperature, Secchi-depth, the nutrients not included in the model and zooplankton concentrations. Data for calibration and verification, e.g. levels of the main algal groups and ortho-phosphate.
3. Upstream conditions.
   The biomass of the main algal groups and ortho-phosphate levels at the

junction of the river Meuse and the Andelse Maas Basin.

4. Loadings.
   The biomass of the main algal groups and ortho-phosphate levels in the discharged polder water.
5. Initial conditions.
   The biomass of the main algal groups and ortho-phosphate levels at the start of the computation.

Normally the time interval for the computations is one year, initial conditions are given for an initial time in the winter period. All time varying functions are given in the form of weekly observations. Intertidal fluctuations are averaged over a tidal period.

The MIDAS model. MIDAS is a mathematical model describing the interaction between phytoplankton and nutrients. MIDAS is an acronym meaning

- M ulticomponent
- I nternal storage
- D ynamic
- A lgae
- S imulation

The aim of the model is, in the first place, to deduce the dynamic description of relevant chemical and biological processes in a well-mixed body of water. In the second place the model aims to predict the effects of controlling the nutrient loads on the composition and quantity of the phytoplankton biomass.

The model concept is based upon the work of Biermann (1976). A unique feature of the model is that cell growth is considered to be a two-step process involving separate nutrient uptake and cell synthesis mechanisms.

If spatial effects or transport processes are important the model has to be applied for several segments. Each segment is considered as a well-mixed body of water. For the exchange of matter between the segments an appropriate flow module is included.

The biological and chemical state variables in MIDAS are:

- biomass of the functional algae groups
- internal phosphorus and nitrogen storages
- dissolved nutrient concentrations.

The selection of the functional algae groups in the model depends on the expected composition of the most important groups and on the availability of the parameters for these groups. Considering the available data and the aim of the study a limited number of state variables was incorporated for the Andelse Maas Basin study:

1. the biomass of diatoms
2. the biomass of green algae
3. internal P-storage in diatoms
4. internal N-storage in diatoms
5. internal P-storage in green algae
6. internal N-storage in green algae
7. dissolved ortho-phosphate

The selection of internal phosphorus and nitrogen storage in the algae groups is a direct consequence of the two-step model concept. The first step is the uptake of nutrients from the surrounding water. In this step an internal nutrient storage is built up. This process is often referred to as luxury consumption. The second step in the algae kinetics is the cell synthesis, which no longer depends on external nutrient concentrations but on internal dissolved nutrients.

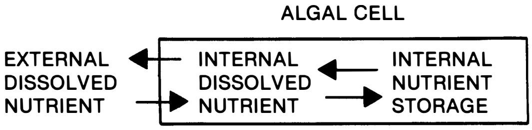

Fig. 5. Nutrient uptake in MIDAS

Ortho-phosphate is the only nutrient incorporated in this study. The reason for this choice is threefold:

1. There are data available,
2. ortho-phosphate is considered to be the most important limiting nutrient and
3. ortho-phosphate can be controlled easily by iron dosing.

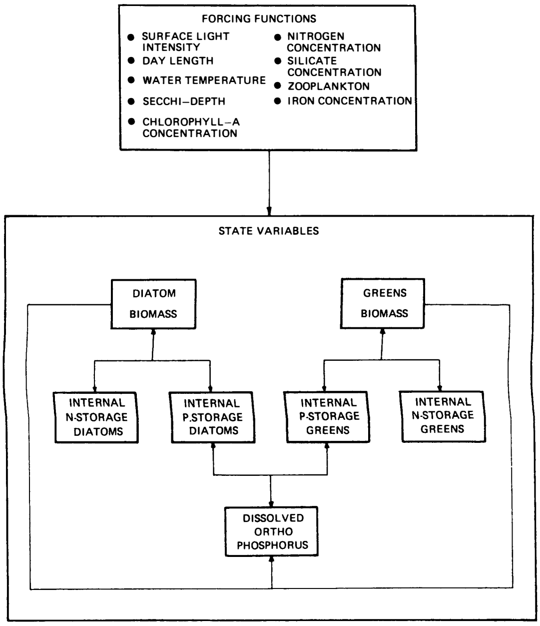

Fig. 6. Relations in MIDAS

For each state variable the model equations are written in the form of a mass-balance equation:

> rate of change of state variable = rate of change due to external point loading + rate of change due to interactions in the system volume.

For each functional algae group the rate of change of biomass is given by:

> rate of change of biomass = biomass * (specific growth rate - grazing rate zooplankton - algal death rate - sinking rate)

The specific growth rate equals the maximal specific growth rate multiplied by a reduction factor. This reduction factor is a function of non-optimal light and temperature conditions. Furthermore nutrient limitations by one of the internal nutrients can reduce the specific growth rate. For diatoms also the dissolved silicon concentration is taken into account. The grazing term depends on the measured zooplankton concentration, the temperature and the zooplankton grazing rates. Algal death rate is proportional to the water temperature. The sinking rate term contains a refinement: the sinking rate increases for slowly growing algae populations e.g. older populations have a higher sinking rate than fast growing populations.

The rate equation for the internal nutrient storage is:

> rate of change of internal nutrient storage = luxury consumption by algae - contribution to cell synthesis.

The luxury consumption depends on the difference between internal and external nutrient concentrations and can be reduced by non-optimal light and temperature conditions. The contribution to the cell synthesis is proportional with the internal nutrient concentration and the specific growth rate of the algae.

For dissolved ortho-phosphate the rate equation is:

> rate of change of dissolved ortho-phosphate = increase by death of algae - increase by mineralization of settled algae + increase by excretion of zooplankton - luxury consumption by algae - total effect interaction between water and sediment - iron dependent reduction term.

Part of the internal phosphate storage of algae groups is returned to the water body by algal death (autolysis). Also a fraction of the settled algae is returned to the water body by mineralization, as well as a fraction of the grazed algae by zooplankton which is returned to the dissolved ortho-phosphate pool by excretion. Finally ortho-phosphate is removed from the water body by means of the combined effect of settlement caused by decreasing flow velocities in an upstream direction, the exchange between water and sediment and the mineralization of other phosphate sources. This combined effect is modelled as a first-order reaction. The reduction of ortho-phosphate by dosing of iron is modelled as a first-order reaction. The reaction constant is determined by calibration in the segment where the iron dosing takes place. In the other segments of the basin the reaction constant is supposed to be negligible.

In this way 7 coupled ordinary differential equations must be solved. Two different time scales are involved in the system. A time scale of 6 hours for the phytoplankton growth and a much smaller time scale of about 20 minutes for the intracellular dissolved nutrients. This means that a system of stiff differential equations must be solved. This system is integrated numerically with a Gear method using self-adaptive step size. All input functions are smoothed with least square spline functions in order to guarantee convergence in the self-adaptive algorithm.

Implementation of a flow model and coupling. The concentration of algae and nutrients along the Andelse Maas Basin is time and space dependent. Therefore the basin was subdivided into a number of computational elements along the longitudinal axis of the basin. In each element the concentration is influenced by:

- advective transport due to the residual flow
- dispersive transport mainly due to tidal mixing
- loads
- biological and chemical processes.

A one-dimensional model of the flow in the basin was developed, for the advective transport. At 24 computational elements in the basin the flow was calculated by solving the continuity equation. The elements have a trapezoidal cross-section. By integration over the tidal period only the residual current has been considered. The water level in the basin is equal to the mean level of the river Meuse. The residual flow is induced by the rate of change of the mean level of the river Meuse and the discharges of the pumping stations.

For the mass-balance of algae and nutrients a number of the computational elements has been joined to form a new computational element. In this way the basin has been subdivided into 7 computational elements for the numerical solution of the mass-balance equation. The center of each of these computational elements coincides with the routine measuring sites of the Dune Water Works of The Hague. The length of the elements varies between 1 km and 4 km.

The effect of tidal mixing has been modelled by dispersive transport. The transport between the computational elements is proportional to the concentration gradients and the absolute values of the local horizontal tidal velocities. As the basin is open at the side of the river Meuse and closed at the water intake station, tidal velocities and thus dispersion decreases in the upstream direction of the basin.

In each computational element the time-varying numerical solution is calculated by superposition of the solution of the MIDAS model for the biological and chemical processes and the contributions of advective and dispersive transport together with loads and withdrawals from the pumping stations.

Calibration and Verification. Because of its complexity the calibration of the eutrophication model was performed in two steps. First chlorophyll-a was calibrated for one segment only. Calibration period for this segment was the year 1978. Growth rate, sinking rate and death rate of the functional algae groups were calibrated and kept fixed for the rest of the investigations.

Ortho-phosphate was calibrated in a very special period, namely September till December 1979. The reason for the choice of this period was that the iron dosing installation was out of operation for three weeks. This gave an excellent opportunity to calibrate the rate constant for the precipitation of ortho-phosphate within the segment where the dosing station is located. Another advantage of this period was the low biomass level, so there was no strong interaction between chlorophyll-a and ortho-phosphate. Also the constant factor for the dispersion coefficient was calibrated in this period.

During verification, the model performance was checked for an independent data set. For this study the whole year 1978 was used as a verification period for all the segments in the basin. Model results and observations compared very reasonably.

OPTIMIZATION OF THE IRON DOSING

The description of the iron dosing installation and the choice of the flux of dosed iron are given in an earlier section of this paper. Up till now two different constant fluxes of iron have been used: 8 tons/day from 1976 to the end of 1981 and 4 tons/day from the end of 1981 to November 1983. An experiment without iron dosing at all takes place in a period from November 10th 1983. The length of that experiment will be in the order of some weeks, dependent on the hydrological circumstances. After that period another experiment with a still further decreased iron dosing of 2 tons/day will be carried out.

For environmental and for economical reasons a minimization of the yearly fluxes of dosed iron should be achieved. The constraints in this optimization process are the ortho-phosphate and chlorophyll-a levels obtained. A long term goal of the

Andelse Maas study is the minimization of the iron dosing as a function of meteorological and hydrological circumstances, given a certain water quality of the river Meuse and the polder water pumped into the basin.

As a first step the relation between a constant flux of dosed iron and the resulting ortho-phosphate and chlorophyll-a levels have been investigated by calibration with the eutrophication model.

Given a first-order ortho-phosphate reduction equation:

$$\frac{dP}{dt} = -rP$$

where P = concentration of ortho-P in the segment with iron dosing
t = time
r = ortho-phosphate reduction factor,

by calibration the following values have been found for the Andelse Maas Basin:

TABLE 1 Relation between Iron Flux and Ortho-P Reduction

Iron dosing (tons/day)	Ortho-P reduction constant r (per day)
8	4.50
4	2.25

For the segments without iron dosing the value of r is set equal to zero. For the year 1982 computations with r-values corresponding with no iron dosing at all, 4 tons of iron per day and 8 tons of iron per day have been carried out. The results are compared with each other and with the observations. The observations are values corresponding with the actual iron dosing in 1982, which was a constant value of 4 tons of iron per day.

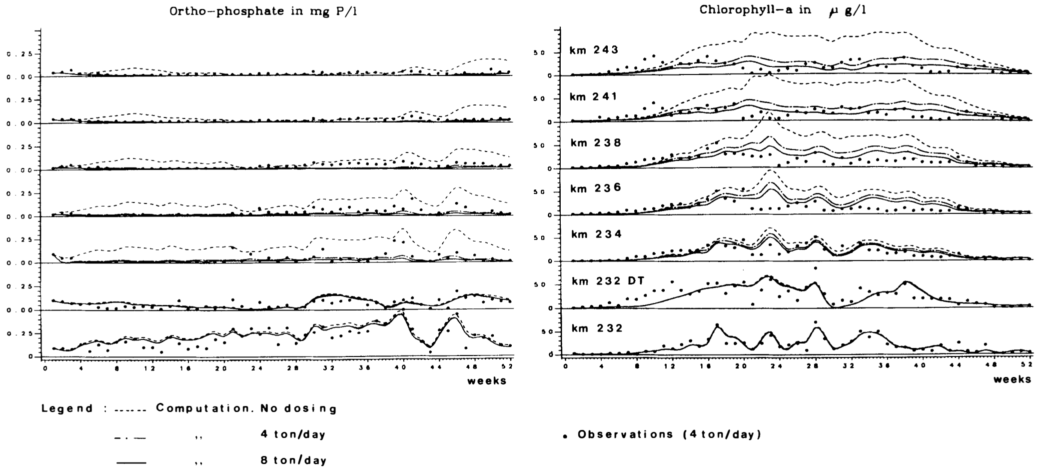

Fig. 7. 1982 Simulation of chlorophyll-a and ortho-P for different iron dosing fluxes.

The consequences of the shut down of the iron dosing installation are spectacular. In the growing season maximum levels of about 100 micrograms of chlorophyll-a per liter could be reached. Besides, outside the growing season ortho-phosphate levels could reach concentrations which are almost equal to the original river Meuse water.

The simulation also shows slightly increased chlorophyll-a levels if the iron dosing had been 8 tons/day in 1982 instead of the 4 tons/day which was actually used. The calibration for a dosing of 2 tons of iron per day will take place during early 1984.

Also the eutrophication model has been used to predict the behaviour of the ortho-phosphate levels for some hypothetical cases, e.g. the development of the water quality in the basin for a constant river Meuse level and no polder discharges (a dry period). The only remaining factor for advective transport is the discharge for the Dune Water Works of The Hague. In that case due to advective transport and tidal dispersion it appears that at the water inlet the maximal rate of change for the ortho-phosphate levels is about 0.01 mg/l per day if the iron dosing installation, at a distance of about 9 km, is shut down or reactivated. This computation also shows that it takes at least some weeks before a catastrophe on the river Meuse considerably influences the water quality at the water intake site.

Present investigations are focussed upon a more profound understanding of the relation between iron dosing and the effects on ortho-phosphate and nutrient levels (dose-effect relationship) and further time-dependent minimization of the amount of iron dosing needed for sufficiently high phosphate reduction and algal control.

DISCUSSION

To counteract the consequences of eutrophication in the presence of high phosphorus levels of the river Meuse, an artificial precipitation of phosphorus in the Andelse Maas Basin is used with iron-II-sulphate. In practice this appears to be a very effective way to control algal growth to acceptable levels, this in contrast to the summer of 1976 when dosing was not yet in full operation. At that time in the water of the intake pumping station, the chlorophyll-a concentration reached the value of 125 µg per liter. In this period the frequency of the washing process of the rapid sandfilters had to be doubled. This was also necessary during a few weeks in the summer of 1980, while the water of the inlet station had a Secchi disc visibility of more than three meters. In that case however, the shortened filter run was caused by strongly increased zooplankton populations.

A mathematical model has been developed to describe and predict phytoplankton biomass and ortho-phosphate levels as a function of space and time. Boundary values for the model were the quality of the river Meuse and the quality of the discharged polder water. Iron dosing was implemented in the model in such a way that it was possible to quantify the influences of iron dosing on the quality of the water being pumped to the dunes near The Hague.

It was of the utmost importance to know what would happen to chlorophyll-a and ortho-phosphate levels in the basin if the process of iron dosing was completely terminated for a considerable period. For this investigation the year 1982 was recalculated as a case study without iron dosing. Termination of the dosing will result in unacceptable high phosphorus concentrations. In winter, concentrations are to be expected of more than 0.50 mg ortho-P per liter, in water pumped to the infiltration reservoirs in the dunes. Chlorophyll-a also reaches unacceptably high levels in the growing season, maximum concentrations could be expected of about 120 µg chlorophyll-a per liter. Predictions of the model with dosing of 4 tons of iron per day compared favourably with the observations of chlorophyll-a and ortho-P in that year. Finally, model predictions for that year showed only slightly decreased chlorophyll-a levels for the case of dosing the full amount of eight tons of iron per day.

Based upon model predictions, the Dune Water Works of The Hague decided not to terminate the iron dosing because of the possibly high risks for drinking water preparation. Also it was decided to continue the experiments for the investigation of the relationship between the amount of dosed iron and the water quality in the basin for further optimization of the dosing strategy.

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