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Use of Hybrid EA Models for the Prediction of Chlorophyll-a and Phytoplankton Functional Groups Abundance in Two Shallow Lakes

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ABSTRACT

Twenty-two years of water quality time-series of the two Dutch lakes Veluwemeer and Wolderwijd were subject to predictive modelling by hybrid evolutionary algorithms (HEA). The modeling aimed at forecasting changes of the phytoplankton community in response to the control of external nutrient loadings and fish abundances as consecutively implemented to both lakes since 1979. The water quality time-series of both lakes were structured for HEA modeling in order to reflect the following three different management periods by both training and validation datasets: no management (1976-1978), lake flushing and waste water treatment (1979 onwards) and lake flushing, waste water treatment and food web manipulation (1991-1993). This approach facilitated a comparative analysis for the two lakes and the three management periods. Firstly HEA achieved reasonably accurate results for 5-days-ahead forecasting of chlorophyll-a and phytoplankton functional groups. Secondly hybrid evolutionary algorithms (HEA) achieved similar good forecasting results but also provided model representations for chlorophyll-a and algae functional groups in the form of rule sets. HEA has been designed to evolve both the structure of rule sets as well as the parameter values imbedded in the rule sets by means of a genetic algorithm. With regards to the different approaches for eutrophication management, modelling results have shown that only the combination of external nutrient control with food web manipulation has changed the lakes from hypereutrophic to mesotrophic conditions as reflected by the change in the dominance of algae groups and chlorophyll-a concentrations. HEA provides rule sets for the explanation of these ecological changes. The rules revealed that phosphorus limitation by means of seasonal lake flushing and wastewater treatment with food-web manipulation diminished the abundance of the harmful blue-green algae but enhanced the abundance of harmless green algae and diatoms.

Keywords: hybrid evolutionary algorithms; rule sets; forecasting; eutrophication control; chlorophyll-a, blue-green algae, green algae, diatoms

INTRODUCTION

The analysis and forecasting of phytoplankton dynamics can be attempted for different scales from predicting chlorophyll-a to species abundance. Tracing the trajectories of community compositional responses to environmental changes such as eutrophication is recommended as one of the best ways to understand changes in system function (Powell, 1995). Analysing data for both periods of eutrophication without and with eutrophication control may reveal complex interrelationships that exist within the phytoplankton populations and community. The two long-term datasets of Lake Veluwemeer and Wolderwijd present a unique opportunity for forecasting eutrophication effects under managed and unmanaged conditions. It allows decision makers to assess the efficiency of lake restoration measures such as flushing and biomanipulation to achieve water quality and phytoplankton community composition and biomass objectives.

In the framework of the present study hybrid evolutionary algorithms (HEA) were applied to forecast chlorophyll-a and population dynamics of the blue-green algae, green algae and diatoms in the Dutch lakes Veluwemeer and Wolderwijd. Other time series forecasting methods include recurrent artificial neural networks, which have successfully been applied for modelling eutrophication processes in freshwater lakes and rivers (Jeong *et al*. 2001; Walter *et al*. 2001; Jeong *et al.* 2005; Recknagel, Kim and Welk 2005; Recknagel *et al*. 2005). HEA is a newly emerging technique that not only facilitates time series forecasting but also discovery of explanatory rules (Cao *et al*. 2005). HEA are applied to twenty-two years of water quality time-series of the two Dutch lakes in order to forecast changes in algal populations in response to control of external nutrient loadings and fish abundances as consecutively implemented to both lakes since 1979. The water quality time-series of both lakes are structured for the HEA modelling so that it is possible to reflect the following three different management periods by both training and validation datasets: no management (1976-1978), lake flushing and waste water treatment (1979 onwards) and lake flushing, waste water treatment and food web manipulation (1991-1993). This approach facilitates a comparative analysis for the two lakes and the three management periods. The results demonstrate firstly that HEA achieved reasonably accurate 5-days ahead forecasts of chlorophyll-a and abundances of blue-green and green algae and diatoms in both lakes. Secondly it is shown that HEA achieve similar good forecasting results but also provided model representations for both chloropyll-a and algae functional groups in the form of rule sets which can be causally interpreted. Thirdly it is revealed that phosphorus limitation induced by seasonal lake flushing and wastewater treatment in combination with food-web manipulation successfully diminished the abundance of the harmful blue-green algae *Oscillatoria* and enhanced the abundance of harmless green algae and diatoms in both lakes.

DATA AND METHODS

Lake Veluwemeer

Lake Veluwemeer was created in 1957 and is adjacent to Lake Wolderwijd (Fig. 1). Both lakes have similar geographical and hydrological conditions (Table 1). Originally Veluwemeer was a clear water lake with abundant macrophytes. From 1965 onwards the lake became increasingly turbid as a result of rising phosphorus loadings. As a result frequent blooms by *Oscillatoria agardhii* occurred in the mid 1970s. Phosphorus control by a sewage treatment plant and lake flushing in winter was implemented in 1979. Inflowing water with low concentrations of algae and phosphorus but high concentrations of calcium and nitrate was used for flushing. From 1985 onwards, summer flushing was also implemented. Commercial fishing was introduced to Lake Veluwemeer in the early 1990s, peaking in 1994 (Portielje & Rijsdijk 2003).

Lake Wolderwijd

Lake Wolderwijd was created in 1968 and ongoing eutrophication processes caused hypertrophic conditions in the 1970's and early 1980s with high abundances of blue-green algae. Between 1980 and 1983, large amounts of water from upstream lake Veluwemeer have occasionally been flushed through Lake Wolderwijd (van der Molen 1999). From November 1990 to July 1991 food web manipulation was carried out whereby 75% of bream was removed and young pike introduced. During that period the abundance of blue-green algae decreased by approximately 50%. From 1996 and 1997 the water quality declined again (Van der Molen, 1999).

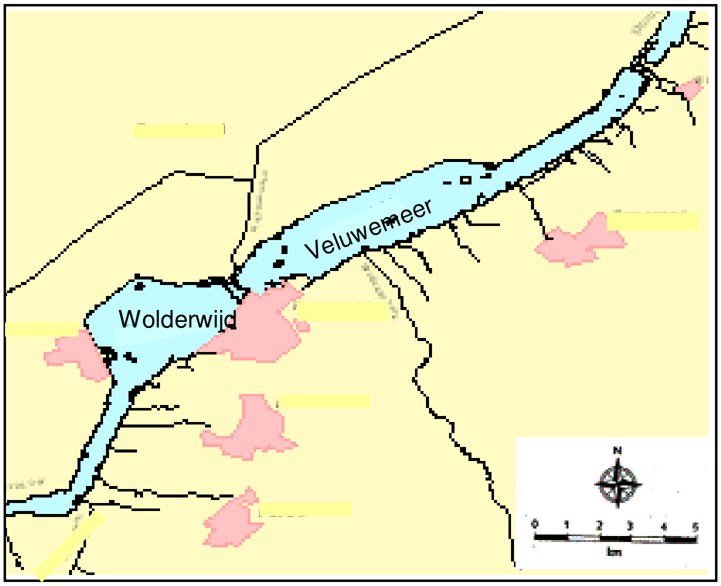


Figure 1: Locations of Lakes Veluwemeer and Wolderwijd in central Netherlands

TABLE 1: Atttributes of Lake Veluwemeer and Wolderwijd

Attributes	**Lake Veluwemeer**	**Lake Wolderwijd**
Latitude	52 ^{o} 23'	52 ^{o} 20'
Longitude (-0.2 m below sea level)	5 ^{o} 40'	5^{o} 35'
Area (Km^2)	32.4	26.7
Maximum Depth (m)	7.8	5.7
Mean Depth (m)	1.58	1.81
Precipitation (mm)	800	800
Geological Components	Sandy deposits	Sandy deposits

TABLE 2: Analyses of limnological variables of Lake Veluwemeer and Wolderwijd

	Lake Veluwemeer (1976-1993)	**Lake Wolderwijd (1976-1993)**
Limnological variables	Mean/Min/Max	Mean/Min/max
Dissolved Inorganic Nitrogen NO_3-N (mg/l)	0.80/0.001/5.77	0.24/0.001/7.24
Dissolved Inorganic Phosphaten PO_4-P (mg/l)	0.04/0.0001/0.42	0.01/0.0001/0.12
Silica Si (mg/l)	2.63/0.005/7.05	2.22/0.01/19.1
pH	8.5/7.3/10.5	8.5/7.1/9.7
Secchi Depth SD (m)	0.4/0.1/1.7	0.4/0.2/1.3
Temperature (^{o}C)	10.9/-1.7/25.1	11.1/0/23.9
Ammonium NH_4 (mg/l)	0.12/0.001/1.77	0.06/0.001/0.85
Chlorophyll-a (µg/l)	115/9/459	101/9/265

Blue-Green algae (mm^3/l)	84.2/0/390.6	113/0/390.6
Green Algae (mm^3/l)	4.7/0/37.1	4.2/0/34.6
Diatom (mm^3/l)	9.3/0/168.6	6.8/0/110.3

Lake Data

Data of the Lakes Veluwemeer and Wolderwijd were preprocessed by linear interpolation to create two consistent data sets. Table 2 lists the water quality variables for both lakes that were considered for the present study.

Hybrid Evolutionary Algorithms HEA

HEA has been designed to discover predictive rule set. It firstly evolves the structure of the rule sets by using genetic programming (GP) (Koza 1992, 1994; Banzhaf *et al*. 1997), and secondly optimises the random parameters in the rule set by using a general genetic algorithm (Yu *et al*. 1999). Rules discovered by HEA have the IF-THEN-ELSE structure and allow imbedding complex functions synthesised from various predefined arithmetic operators. The principal framework of HEA for the rule discovery in water quality time-series is represented in Fig. 2.

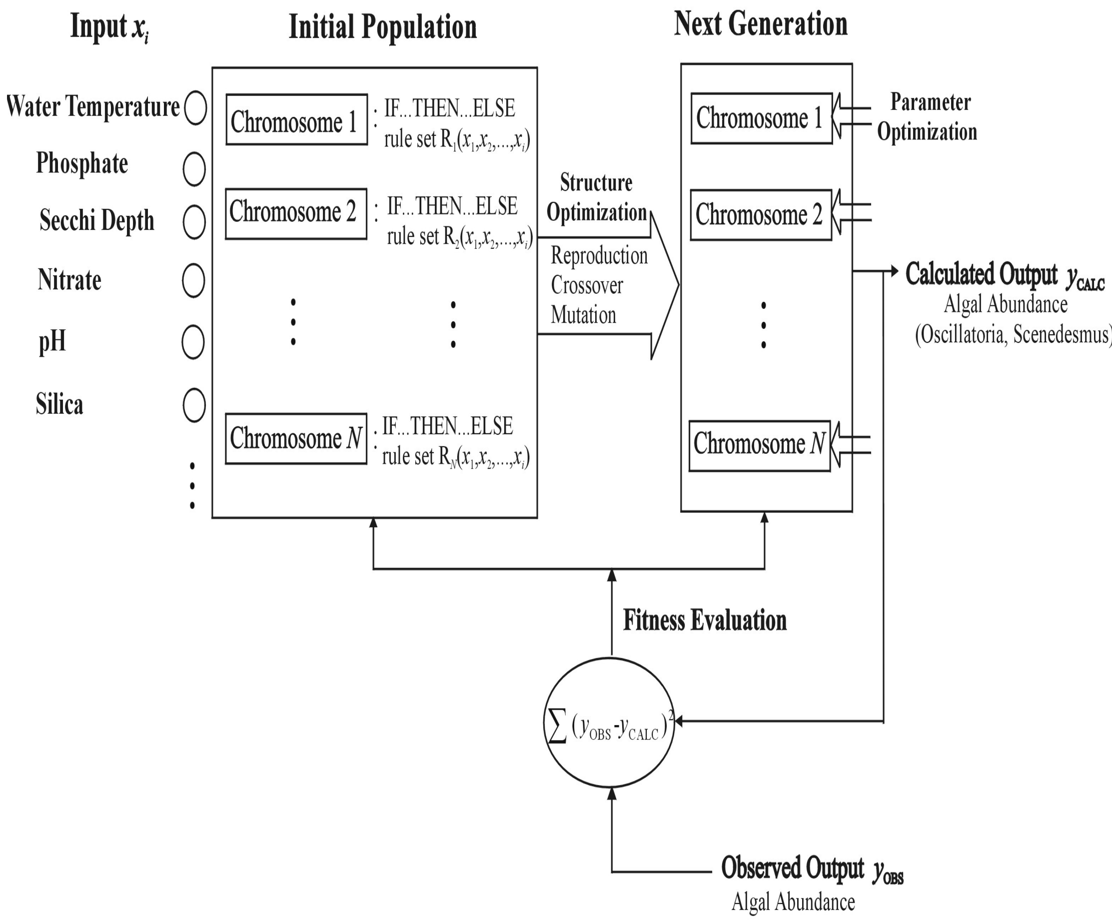


Figure 2: Conceptual diagram of HEA for the discovery of predictive rulesets in water quality time-series

Twenty-two years of merged water quality data of the two lakes from 1976 to 1993 were used for training the HEA models. The selection of training and testing years was based on data availability to include the years typical for distinct eutrophication management approaches. Testing was based on three years data that represented different management periods: 1978, 1985 and 1993. The output variables tested by the HEA models for both lakes are 5-days ahead forecasts of algae functional groups and chlorophyll-a concentration. To achieve this aim, the models were trained with input variables time lagged by 5 days. The remaining variables listed in Table 2 were considered as input variables.

100 runs were conducted independently for each data set. For simplicity, we set the maximal rule size to be 1 (single rule). All the experiments were performed on a Hydra supercomputer (IBM eServer 1350 Linux) with a peak speed of 1.2 TFlops by using the programming language C.

In order to validate the results of different rules, we define the fitness as the RMSE (Root Mean Square Error) as the training error and testing error:

where k is the number of training (testing data points) y_i and $\hat{y}_i$ are the ith observed value and the ith predicted value of the output variable.

$$\text{Fitness} = \sqrt{\frac{1}{k}\sum_{i=1}^{k}(\hat{y}_i - y_i)^2}$$

ith predicted value of the output variable.

RESULTS AND DISCUSSION

Forecasting of chlorophyll-a under different lake management conditions

HEA (Figure 3a) predicted the events of algal bloom well from the chlorophyll-a data sets.The results for HEA chlorophyll-a prediction forLake Veluwemeer and Wolderwijd (see Figure 3a) has shown very good fitting during the hypertrophic period of 1978 followed by mesotrophic conditions in 1985 and 1993 with good fitting (R^2 = 0.79) of the test data sets. The timing and magnitude of some high peaks in 1978 were correctly predicted. This model however, predicted one very high peak for Lake Veluwemeer in 1993, contrary to the mesotrophic conditions in that period. Another high peak in Lake Wolderwijd was missed in early 1993.

Responses in terms of lowered chlorophyll-a abundances are expected along trophic gradients in time. Lower chlorophyll-a abundances would also indicate the success of different lake management measures over long-term periods. The results from the HEA models have shown that the 5-days ahead forecast is able to predict short-term algal blooms in two managed Netherland shallow lakes. Most interestingly, it is able to distinguish between the two alternative stable states of turbid and clear water phases as postulated by Scheffer *et al.*, 1993; Scheffer, 1998; and Hosper, 1998.
The overall results from validation of the HEA models have identified 1978 as the turbid phase of Lake Veluwemeer and Lake Wolderwijd. This is due to the dominance of blue-green algae mainly *Oscillatoria agardhii,* leading to high trophic state and the depletion of dissolved nutrients (Mischke, 2003). Reasonably high magnitudes of chlorophyll-a abundance were

forecasted in Lake Veluwemeer and Wolderwijd ranging between 100 mg/m^3 in winter and 400 mg/ m^3 in summer, with slight differences in timing of the bloom events. This was in 1978 prior to the management measures carried out in 1979, when winter flushing and intensive phosphate reduction was implemented at a wastewater treatment plant. The flushing with polder water that was low in phosphorus and high in calcium and nitrate decreased the retention time of the dissolved compounds from 0.35 to 0.15 years (Jagtman *et al*., 1992).

With the implementation of intensive flushing, the results for 1985 clearly indicated a change in water quality from turbid to a clear-water phase for both lakes. Blue-green algae dominance is broken by a succession of dominance of diatoms and green algae (van der Molen *et al*., 1994). The predicted chlorophyll-a peaks are within the range of 100-150 mg/ m^3 which is slightly higher than the observed chlorophyll levels.

Similarly for 1993, the validation results have shown that the HEA models were able to forecast lower chlorophyll-a abundance during a period of biomanipulation with the right forecast regarding timing of chlorophyll-a peaks during summer.

Forecasting of algae functional groups under different lake management conditions

5-days Ahead Forecast of Blue-Green Algae

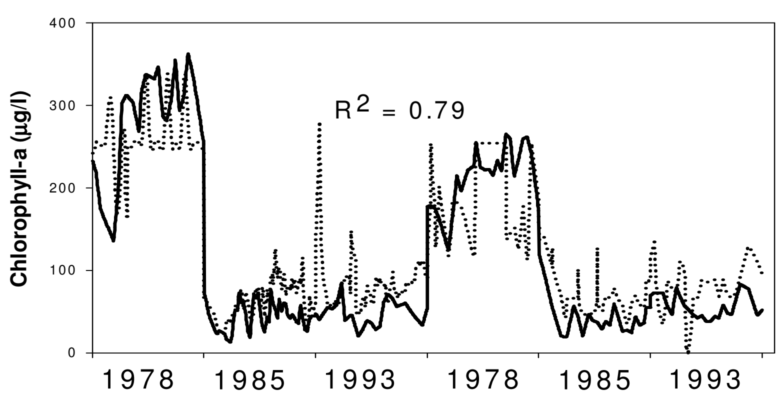
Figure 3b show the 5-days ahead prediction of blue-green algae for Lake Veluwemeer and Wolderwijd using HEA (R^2 = 0.48). The timing and magnitudes of the peaks in 1978 were predicted well.The first few peaks of the blue-green algae bloom were underestimated for both lakes Veluwemeer and Wolderwijd for HEA models in 1978. The ranges predicted for the blue-green algae biovolumes were lower than the measured values. The timing of some predicted peaks were earlier than the observed peaks. There was an unusually high peak of blue-green algae bloom observed in Lake Wolderwijd peaking at 400 mm^3/l, that was missed by both models. As predicted for 1985, blue-green algae are no longer dominant during this period of testing. The prediction was quite good although it predicted higher than the minimal growth that was shown by the measured data. There is an increase in the blue-green algae abundance in 1993 compared to 1985. The right timing of the blue-green algae peaks in 1993 was predicted but the models missed the magnitudes of some peaks in the algal bloom.

5-days Ahead Forecast of Green Algae

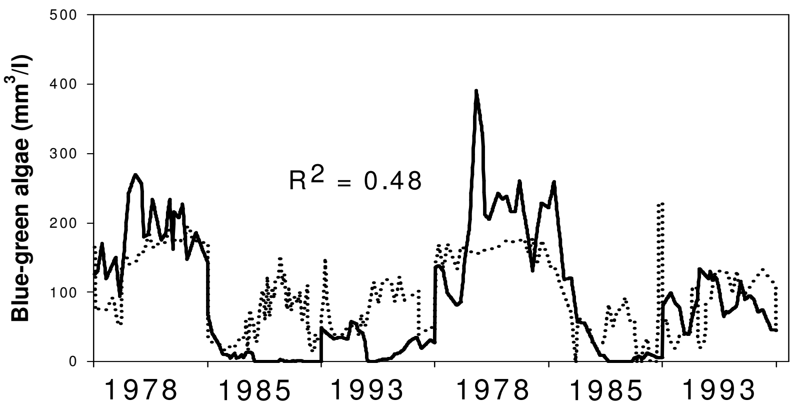
The results of merged models for the 5-days ahead green algae prediction are as shown in Figure 3c. Compared to blue-green algae, the forecasting results for green algae are less accurate with R^2=0.21. An increase in green algae abundance is predicted with peaks in spring and summer. Prediction of green algae peaks in 1993 were reasonable in terms of the timing although the magnitudes were lower than the observed peaks. A spring growth phase was predicted by HEA for Lake Wolderwijd that was not observed in the data sets. Overall, the magnitudes of green algae blooms were missed by both RANN and HEA models although the timing of the peaks were quite good.

5-days Ahead Forecast of Diatoms

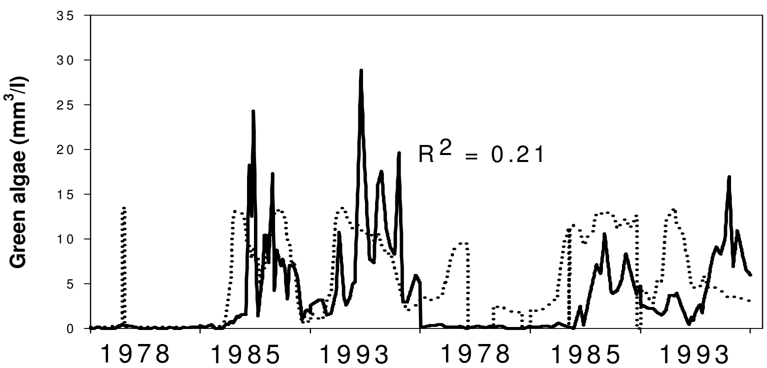
Results of the 5-days ahead diatom prediction are shown in Figure 3d. Overall, it can be seen that the model predicted the right timing for most of the diatom peaks. Winter was predicted to have more growth of diatoms although the peaks predicted are lower than the measured data sets for 1985 in Lake Veluwemeer. Apart from this, late summer diatom peaks were predicted in 1985, with the right timing but were lower in magnitude compared to the observed phenomenon. Diatom blooms of Lake Wolderwijd are not as frequent compared to Lake Veluwemeer for the three years tested. The HEA models performed well in predicting the winter diatom peaks in 1993 for Lake Wolderwijd.



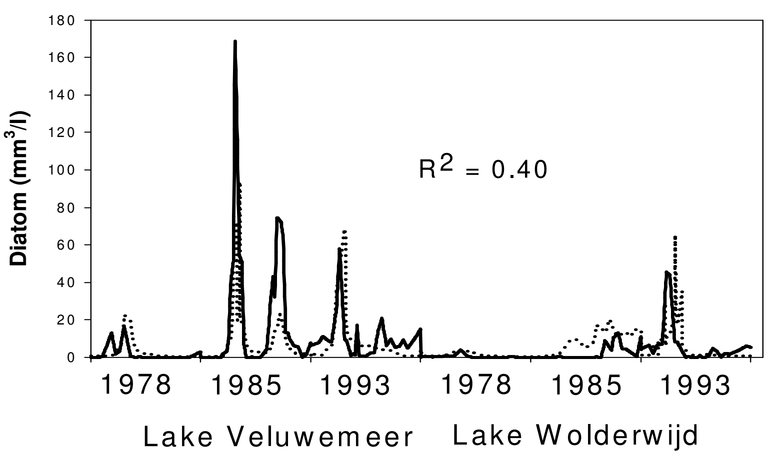
(a)



(b)



(c)



(d)

Fig 3 5-days ahead prediction of chlorophyll-a (a) and phytoplankton functional groups (b,c,d) of Lake Veluwemeer and Lake Wolderwijd using HEA trained with 22 years merged data and tested with 3 years data of 1978 (no management), 1985 (nutrient control) and 1993 (nutrient control and food web manipulation) for both lakes.

Successional patterns of algae functional groups under conditions related to turbid and clear-water phases

The hypothesis was that phosphate reduction and intensive flushing during winter may lead to the break-up of blue-green algae bloom resulting in clear-water, P-limited algal growth, reduced pH and therefore lower P release from the sediments. This should trigger the shift towards a clear-water state with increased abundance of diatom and green-algae.
The HEA models tested here with 7 input variables and chlorophyll-a as the output variable have indicated that it is possible to generalise trends of eutrophication in two adjacent lakes under pre and post-management conditions.

The rule sets discovered by HEA for the blue-green algae, green algae, diatom and chlorophyll-a in the two lakes are documented in Table 3 while the prediction results are in Figure 3. The rule sets 1 in Table 3 discovered for the 5-days-ahead prediction of chlorophyll-a in the two lakes are both largely determined by PO4-P , NO3-N, Secchi depths, and water temperature. By contrast rule sets 2 in Table 3 for blue-green algae showed that NO3-N, silica, pH and Secchi depths affect blue-green algae abundance. Rule sets 3 indicate that green algae are determined by PO4-P, Secchi depths and silica while diatoms are determined by NO3-N and silica from rule sets 4 in Table 3. These rule sets gave evidence that abundance of blue-green algae, green algae and diatoms are affected by nutrients such as phosphate, nitrate and silica as they are common in all the rule sets. The importance of Secchi depths in rule sets 1, 2 and 3 indicates the role of light-limiting factors in the succession between the phytoplankton functional groups. The available underwater light often limits growth of blue-green and green algae in eutrophic lakes when chlorophyll-a concentrations are high as a result of blue-green algae abundance in summer (Reynolds, 1984; Chorus and Bartram, 1999).

The 5-days ahead forecasts have also shown that blue-green algae were abundant in 1978 prior to phosphorus removal and flushing while green algae and diatoms were only abundant after this period. Similarly, the use of non-supervised ANN for patternising has shown that the years 1985 and 1993 for both lakes corresponded to the periods of P-limitation with increasing abundance of green algae and diatoms as a result of flushing and phosphate reduction measures (Recknagel *et al.*, 2006). During the periods of diminished blue-green algae and increased green algae and diatoms abundance (1985 and 1993), the rule sets discovered that their abundances can be explained by the additional variable silica. It is interesting to note that the limitation of the phytoplankton functional groups by silica revealed the complex nature of shallow lake dynamics involving multispecies competition and succession. Silica is important for the growth of diatoms to generate frustules. Our forecasting results for 5-days ahead chlorophyll-a and phytoplankton functional groups are consistent with our earlier forecasting results for individual algae species of *Oscillatoria* and *Scenedesmus* (Talib *et al.,* 2005) With these results we can therefore summarise that forecasting of blue-green and green algae are complex as they are interrelated to the growth and competition from other algal groups including diatoms. Although phosphorus reduction has been previously suggested as a key-factor for controlling the summer dominance of blue-green algal in the Lakes Veluwemeer and Wolderwijd (Reeders *et al*., 1998), results in this study have illustrated that a combination of ongoing phosphorus control and biomanipulation has achieved both, to further diminish blue-green algae abundance and shift an increasing abundance of diatoms and green algae. We suggest that the long-term successional patterns observed for the phytoplankton functional groups studied are related to a periodic shift between nutrients and light-limitation with decreasing trophic conditions. According to an alternate stable states (ASS) theory (Scheffer, 1989; Scheffer *et al*., 1993; Scheffer, 1998), the shift between clear and turbid states in a shallow lake follows a hysteresis due to the stabilising buffer mechanism operating in each state.

Segmentation of the THEN and ELSE branches and sensitivity results of the 5-days ahead HEA forecast of chlorophyll-a in Lake Veluwemeer and Wolderwijd (Figure 4), showed that different rules apply to turbid and clear-water phases of both lakes. In the turbid years, during the hyper-eutrophic periods before lake restoration measures were carried out (1978), the algal bloom wasdependent on the IF condition i.e. PO4-P concentration and the THEN branch that relates to the Secchi depth. With the break-up of algal bloom, i.e. during the eu-mesotrophic phases (1985 and 1993) the ELSE branches apply and are related to PO4-P concentration. The IF-THEN-ELSE rules hypothesize switches between the turbid versus clear-water phases in the long-term data sets of both lakes.

TABLE 3: Best rule sets for chlorophyll-a and phytoplankton functional groups for Merged Lake Models of Lake Veluwemeer-Wolderwijd.

Algal Population	**Best Rule Sets**	**Training Error**	**Testing Error**
Chlorophyll-a L.Veluwemeer L.Wolderwijd	**RULE SET 1:** IF (PO4 >= 0.03) THEN Chlorophyll-a = 50.71/SD ELSE Chlorophyll-a = $(43.64-NO_3*4.52-Temp)/SD$	43.38	48.57
Blue-green algae L.Veluwemeer L.Wolderwijd	**RULE SET 2:** IF (NO_3 <= 0.79) THEN Blue-green algae = Si*pH +462.50/exp(SD)-237.53 ELSE Blue-green algae = 14.79/SD+ ln(|SD|) +3.44	61.64	63.34
Green algae L.Veluwemeer L.Wolderwijd	**RULE SET 3:** IF ((PO_4+SD/ PO_4) <=6.28) THEN Green algae = SD ELSE Green algae = 171.92/exp(Si+SD) +11.35	10.87	5.12
Diatom L.Veluwemeer L.Wolderwijd	**RULE SET 4:** IF ((NO_3*(8.04/Si+84.63)) >124.55 THEN Diatom = 150.65/(NO_3+exp(Si)) ELSE Diatom = 27.31/(Si+exp(Si))	13.53	12.34

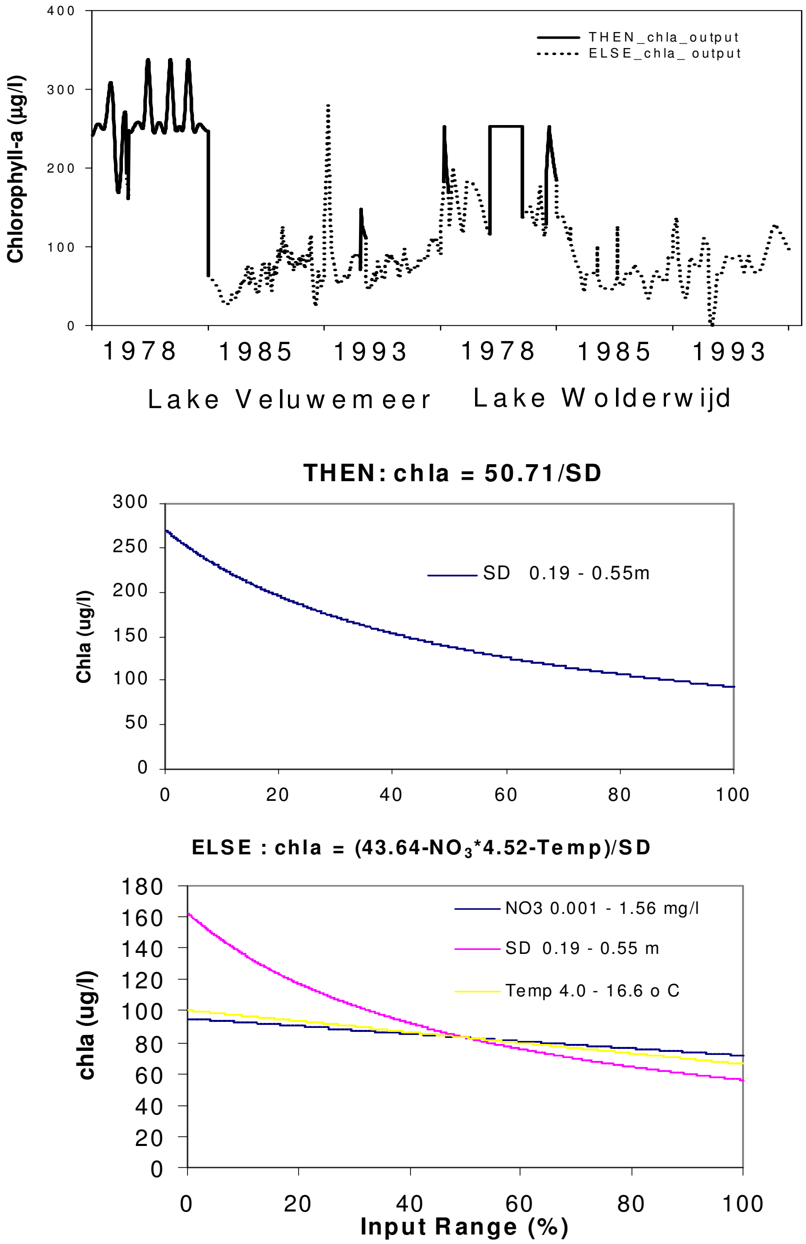


Figure 4: 5-days ahead forecasting and sensitivity analysis for chlorophyll-a with disturbance +/- 1 STDEV of input data for Lake Veluwemeer and Wolderwijd segmented by the THEN and ELSE branch of RULE SET 1 in Table 3.

CONCLUSIONS

The present study has demonstrated that distinct predictable patterns and complex explanatory rule-sets have been revealed for algae functional groups as they undergo competition and succession over temperature preferences and pH tolerance as well as over long-term changes in phosphate and underwater light limitations. The rule sets discovered that interactions between the supplies of phosphate, nitrate, silica and the effects of temperature and pH can explain the competition leading to a shift in succession between blue-green algae and green algae and diatoms in Lake Veluwemeer and Wolderwijd over a long-term period. From the assessment of long-term patterns in both lakes it can be concluded that the ongoing control measure on nutrient regimes towards phosphorus limitation by means of seasonal lake flushing and wastewater treatment up streams of Lake Veluwemeer since the early 1980s has achieved phosphorus limitation, weakened the abundance of blue green algae and elevated abundances of green algae and diatoms. The additional eutrophication control by food web manipulation in both lakes since the early 1990s may have contributed to this shift in algal succession. The IF-THEN-ELSE rules hypothesize switches between the turbid and clear-water phases based on the chlorophyll-a concentration for both lakes.

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