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The monetary benefits of nutrient abatement in the Rhine basin for the water treatment plant of WRK at Andijk

Rob J. H. M. van der Veeren and Luuk C. Rietveld

ABSTRACT

Excessive nutrient loads in rivers and lakes have adverse effects on ecosystem functioning and human activities. The International Rhine Committee has tried to reverse this trend by formulating emission reduction objectives. One of the human activities that may benefit from this is water production that uses surface water as its main source. This paper explores whether reductions in nutrient loads in the Rhine basin result in changes in (the intensity of) treatment activities by the water treatment plant of the Water-transport-company Rhine-Kennemerland (WRK) at Andijk, the Netherlands. For this purpose, a regression analysis was performed on data from 1990–1995 to find a quantitative relationship between the water quality objective for the end product on the one hand, and water quality parameters in Lake IJssel and various treatment processes on the other hand.

In the years 1985–1995, phosphorus loads to Lake IJssel reduced by 50% as a result of significant abatement efforts in the Rhine river basin. As a result, chlorophyll-a concentrations decreased by less than 10%. Further phosphorus emission reductions in the Rhine river basin, for example 75% by the year 2000 as is the objective in the Rhine Action Programme, are expected to result in a 30% decrease in chlorophyll-a concentrations compared with the levels of 1985. These reductions in chlorophyll-a concentrations can be expected to have some impacts on the water treatment plant of WRK at Andijk. However, as they constitute less than 1% of production costs, the monetary benefits of these reductions are limited.

Key words | economic analyses, eutrophication, Rhine basin, water treatment

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INTRODUCTION

Excessive nutrient loads in rivers and lakes have adverse effects on ecosystem functioning and human activities. One of the human activities that may be affected is recreation. See van der Veeren (2000) for a study on the influence of eutrophication on this activity. Another human activity that may be seriously affected is drinking water production using surface water as its main source. This paper explores whether past changes in water quality resulted in changes in treatment activities by the water treatment plant of WRK at Andijk, the Netherlands.

The treatment plant of WRK at Andijk applies a pre-treatment to water to make it suitable for drinking water production for a large area in the (north-) western part of the Netherlands, and for industrial use by the steel factories of Corus (the former Hoogovens). The WRK plant takes water from Lake IJssel, which is located in the centre of the Netherlands, has a surface area of 1130 km^2, and an average depth of 4.3 m (Vrind *et al*. 1994). About 80% of the water in this lake originates from the Rhine. Therefore, water quality levels in this river are of utmost importance to the water treatment plant of WRK at Andijk.

High nutrient loads in the water taken in by the water treatment plant at Andijk may cause problems owing to algae development in the reservoirs; these algae may clog filters and thus hamper the treatment processes. To prevent this, nutrients can be removed from the intake water.

The main focus is on the removal of phosphorus, and not on nitrogen. This choice is based on the following (STOWA 1994; Wiujts and Koelman, unpublished data): first, when nitrogen limitation in water occurs, certain algae will use atmospheric nitrogen; second, phosphorus is already the limiting nutrient in many Dutch lakes; third, phosphorus removal is technically easier and less expensive than nitrogen removal.

Phosphorus concentrations in Lake IJssel increased from 1972 to 1980, when concentrations more or less stabilised. In 1987 the International Commission for the Protection of the Rhine launched the Rhine Action Programme, which stated a 50% emission reduction objective for many substances for the year 1995, compared with 1985 levels. For the year 2000, the emissions of most substances had to be reduced by 70–75% (RIZA 1990). As a result of international abatement efforts in the Rhine basin, initiated by this Rhine Action Programme, phosphorus loads in Dutch surface water were reduced by 50% in 1995 compared with the levels in 1985 (RIZA 1996). This resulted in a decrease in chlorophyll-a concentration in Lake IJssel of approximately 10% (Lammens and Hosper 1998). Further phosphorus emission reductions in the Rhine basin, for example 75% by the year 2000 as is the objective in the Rhine Action Programme, is expected to result in a 30% decrease in chlorophyll-a concentrations (Lammens and Hosper 1998).

The objective of this paper is to estimate the potential monetary consequences of changes in nutrient emissions in the Rhine basin on the water purification plant of WRK at Andijk. For this purpose, this paper applies regression analysis to determine whether and how the water treatment plant at Andijk could adjust its treatment processes as a result of changes in water quality in Lake IJssel in the period 1990–1995, all other things being equal. Then, the 10 and 30% decreases in chlorophyll-a concentration in lake IJssel in 1995 and 2000 compared with 1985 levels are included in the regression equation to estimate the impacts of nutrient abatement policies on the treatment processes applied by WRK at Andijk. These impacts are then monetised by multiplying the changes in the amount of chemicals used by their respective prices.

The structure of this paper is as follows. The next section gives a brief qualitative description of the treatment processes used at Andijk. Then, regression analysis is performed to find a quantitative relationship between required water quality levels of the end product on the one hand, and the water quality of lake IJssel and the various chemicals and processes applied by the treatment plant on the other hand. Based upon this regression equation the last section describes and discusses the potential benefits in both physical (e.g. reductions in required chemical use) and monetary terms.

A QUALITATIVE DESCRIPTION OF THE PRODUCTION PROCESS AT THE WATER TREATMENT PLANT 'PRINSES JULIANA' AT ANDIJK

In most of the western part of the Netherlands, groundwater cannot be used for drinking water purposes because of salinity problems, due to saltwater intrusion from the North Sea. Therefore, drinking water for a number of large cities, e.g. Amsterdam, Leyden, and The Hague, and the province of Northern Holland, is extracted from the dunes. Since 1957, water has been taken from other regions (e.g. Lake IJssel, Lek Canal, Meuse) to recharge the aquifers in the dunes. Continuous transport of water for infiltration and industrial use is one of the main responsibilities of the water transport company Rhine-Kennemerland (WRK), founded in 1952 by the municipal council of Amsterdam and the province of Northern Holland. This company takes care of extraction, pre-treatment, and transport of water and delivers this pre-treated water to industry (mainly used as process water by the steel factories of Corus) and water companies (Amsterdam and n.v. PWN, watercompany Northern Holland) (Anon n.d.). WRK has two water treatment plants: one in Nieuwegein, 'Ir Cornelis Biemond', with an annual capacity of 150 million m^3, which extracts water from the Lek Canal (Anon n.d.) and a second, 'Prinses Juliana' (capacity 110 million m^3 per annum), located at Andijk, which extracts water from Lake IJssel (Anon n.d.). The focus in this paper is on the latter plant.

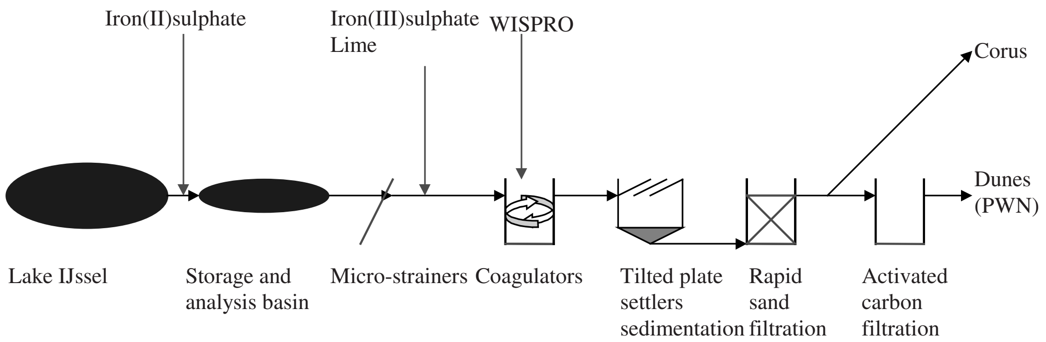

Figure 1 | A schematic representation of the processes in the water treatment plant 'Prinses Juliana' at Andijk.

The plant at Andijk was built in 1981. The plant covers an area of 85 ha, with a 45 ha basin, together with 25 ha of built-up area and a harbour for the transport of materials and chemicals (Anon n.d.).

A schematic representation of the treatment process at Andijk is presented in Figure 1. Note that the description applies to the period for which the data analysis was performed (1990–1995) and certain processes may no longer take place.

The treatment process starts in the basin. The purpose of this basin is threefold. First, the residence time of 40 days enables autopurification of the water coming into the basin. Second, iron(II)sulphate is added to reduce algal blooms that can occur in this basin, especially during the summer period. Iron(II)sulphate reacts with phosphorus, making the latter unavailable for algae. Since phosphorus is one of the most important nutrients for algae, reductions in availability of this nutrient reduces algal development. Third, the residence period enables the analysis of water quality, and makes it possible to stop water intake in cases of calamities.

The water goes through the intake channel to the intake pumping station. On the way, it passes micro-strainers of different sizes. In the intake pumping station the water is lifted to a height of 7.2 m (Anon n.d.). Thereafter, the water can go through the treatment processes by gravity. At this point the water still contains large amounts of suspended solids (about 10 mg l^{-1}). During the process, iron(III)sulphate, WISPRO (a floccing aid used when 'regular' flocculation is difficult to achieve), and lime (necessary to correct for the decrease in pH due to iron(III)sulphate dosing) are added and flocs are formed.

After the addition of chemicals the water goes through four flocculation compartments. The purpose of these compartments is to stimulate collisions between flocs and thus create larger flocs by means of energy input (mixing). After this, the water passes a tilted plate separator, which removes the flocs. The flocs slide down to a sludge-storage underneath the plate settlers. The sludge is automatically removed to separate sludge drying beds. In the process of floc removal most of the suspended materials are removed.

The remaining solids in the water are removed using up-flow rapid sand filters. After several days, these sand filters become clogged and need to be washed. The frequency of washing varies depending on water quality and the water flow.

After the coagulation process and the rapid sand filtration, the water goes into three filtrate reservoirs. One of these filtrate reservoirs is (since 1988) equipped with activated carbon filters, to remove bentazon and other pesticides, because these pollutants cannot be removed in the previous processes (this last step is only used for drinking water pre-treatment).

Finally, the water is pumped through two 56 km pipes (diameter 1.4 m) to Heemskerk (PWN), where a part of it is used for infiltration in the dunes. The transport pumping station forwards the other part of the water through a 6 km pipe (diameter 1.4 m) to the Corus steel factories in IJmuiden.

A QUANTITATIVE DESCRIPTION OF POTENTIAL IMPACTS OF NUTRIENT ABATEMENT POLICIES ON THE TREATMENT PROCESSES

Data

The dataset was provided by Wuijts and Koelman (unpublished) of WRK, and consisted of process data and water quality measurement data for the years 1990–1995. For the analysis data were used on the quality of the water taken in from Lake IJssel and on the quality of the end product. Data on the different processes consisted of the amounts of iron(II)sulphate applied in the basin and the amounts of iron(III)sulphate, WISPRO, and NaOCl added during the coagulation process. Also the flow of treated water and filter runtime were used. This 'filter runtime' describes the washing frequency of the filter bed used in the rapid sand filtration process. Usually WRK washes the filter bed once every three days. When water quality levels or flocculation processes improve, the development of suspended materials decreases, and these filters may be washed with longer intervals. This increases the filter runtime and reduces costs.

However, NaOCl was only incidentally used to remove pathogens and zebra mussels, which are not related to nutrients. Therefore this chemical was excluded from the analyses. Since lime dosing depends on iron(III)sulphate application (correlation more than 50%), it was decided to exclude the former from the regression analyses. However, changes in lime requirements as a result of adjustments in dosing of iron(III)sulphate are included in the cost calculations presented below.

Most of the data were gathered on a routine basis; some parameters daily, others weekly. Most parameters for which daily measurements were available did not show a large variation from one day to another. Therefore, these datasets could be reduced to correspond with the dates on which weekly measurements were taken. This resulted in a total number of 272 observations.

The objective of the water treatment plant at Andijk is to provide a reliable delivery of good quality water to consumers. The membrane filtration index (MFI) describes the quality of the end product of the treatment plant. This index is a measure of the presence of colloid and suspended materials, which can clog hyper-filtration (or reverse osmosis) membranes (Schippers and Verdouw 1979; Kostense 1982). Low values for this parameter correspond with a high quality end product. Figure 2 presents the trends in MFI for the years 1990–1995. In this period, the plant has increased the quality of its end product significantly (average MFI declined from 15.75 in 1990, to 3.14 in 1995). This was due to explicit steering on this variable.

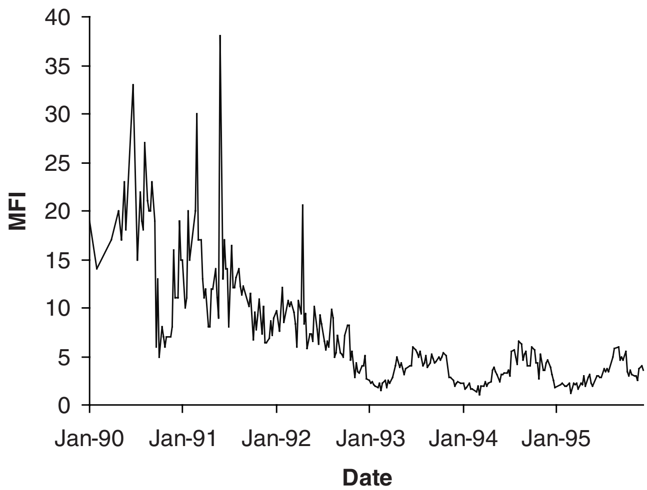

Figure 2 | MFI of the end product (1990–1995).

Table 1 | Iron(II)sulphate dosage in the Andijk basin in 1990–1995 (KIWA/WRK 1995)

Period	Dosing (mg Fe l^{-1})	Comments
1 January 1990–22 July 1992	None	
23 July 1992–15 September 1992	2	Acidified
16 September 1992–24 January 1993	4	Acidified
25 January 1993–August 1993	6	Acidified
August 1993–31 December 1995	6	Not acidified

In an attempt to improve the quality of the end product, the WRK plant experimented with iron(II)sulphate dosing in the basin during 1990–1995. This was done with limited variability in dosing during the year (see also Table 1 and KIWA/WRK 1995). As a result, both MFI

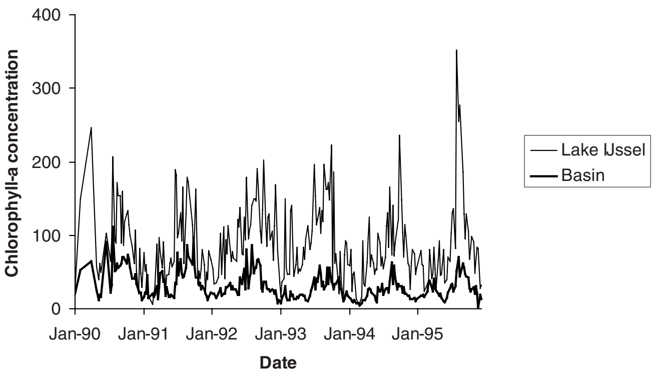

Figure 3 | Chlorophyll-a concentrations (1990–1995).

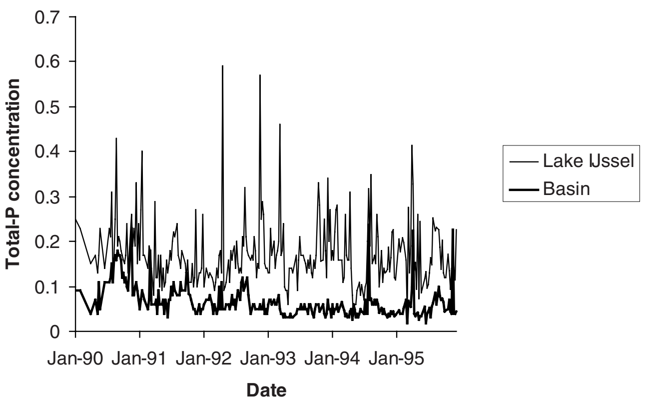

Figure 4 | Total-P concentrations (1990–1995).

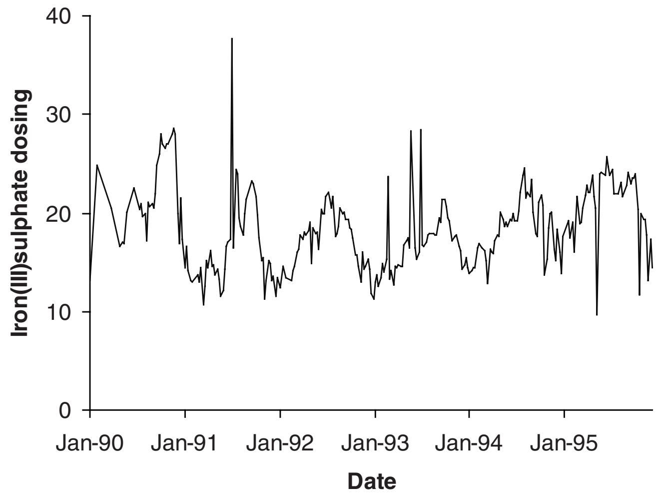

Figure 5 | Iron(III) dosing (1990–1995).

and the variance thereof reduced significantly (see also Figure 2). This increased the reliability of the delivery of good quality water. Figures 3 and 4 illustrate the changes over the years 1990–1995 for chlorophyll-a concentrations and total-P concentrations, both in the raw water and during the treatment process (in the basin). Figure 5 presents the iron(III)sulphate dosing over the same period.

A MATHEMATICAL REPRESENTATION OF THE TREATMENT PROCESSES

The treatment processes at the Andijk plant aim to achieve a certain quality level for the end product, given the water quality of Lake Ijssel as the starting product. This is described in Equation 1:

$$\text{Water quality end product} = f(\text{water quality starting product, treatment processes}) \quad (1)$$

In the previous section, MFI was introduced as a measurement for the quality of the end product. The water quality of the starting product can be described using a wide variety of parameters. Since the aim of this paper is to find a relationship between nutrient emission reduction policies and their potential impacts on water treatment processes, the main focus is on nutrient-related water quality parameters. Therefore, total-phosphate, chlorophyll-a, total-algae, and turbidity were used to describe the water quality of the starting product. The dosage of chemicals and the filter runtime were used to describe the various treatment processes. Temperature was included since algae development depends (partly) on the season.

MFI values show a wider variance when plotted on a logarithmic scale than on a linear scale, especially after October 1992. The amounts of chemicals used, the filter runtime, and the water quality parameters for Lake IJssel show a wide variance when plotted on a linear scale. Therefore a log-linear function was chosen.

The estimated equation was:

$$\begin{aligned}\log(\mathrm{MFI}) = {} & \mathrm{constant} + a_1\mathrm{total\text{-}P} + a_2\mathrm{chlorophyll\text{-}A} \\ & + a_3\mathrm{total\text{-}algae} + a_4\mathrm{turbidity} \\ & + a_5\mathrm{Fe(II)SO_4} + a_6\mathrm{Fe(III)SO_4} \\ & + a_7\mathrm{filter\ runtime} + a_8\mathrm{WISPRO} + a_9 Q \\ & + a_{10}\mathrm{temperature.}\end{aligned} \tag{2}$$

The amount of iron(II)sulphate dosage in the basin is represented by the term $Fe(II)SO_4$. $Fe(III)SO_4$ is the amount of iron(III)sulphate applied in the coagulation process. Q describes the flow of treated water. The other variables are self-explanatory: total-P, chlorophyll-A, total-algae, $Fe(II)SO_4$, $Fe(III)SO_4$, and WISPRO are all described in mg l^{-1}, MFI in second/litre^2, turbidity in FTU, Q in m^3 per day, filter runtime in hours, and temperature in °C.

Results

Equation 3 presents the coefficients and their respective t-values (in parentheses). Also the explanatory power of this equation is given. A straightforward application of Equation 2 on the data results in Equation 3:

$$\begin{aligned}Log(MFI) = {} & \underset{(13.79)}{1.06} + \underset{(0.98)}{0.14}TotP + \underset{(2.72)}{7.62*10^{-4}}\ ChlorophyllA \\ & + \underset{(0.72)}{1.25*10^{-8}}TotalAlgae - \underset{(-2.52)}{2.85*10^{-3}}Turbidity \\ & - \underset{(-25.39)}{9.08*10^{-2}}Fe(II)SO_4 - \underset{(-3.82)}{1.12*10^{-2}}Fe(III)SO_4 \\ & - \underset{(-0.77)}{3.70*10^{-4}}Filterruntime + \underset{(3.90)}{0.24}WISPRO \\ & - \underset{(-1.17)}{3.99*10^{-7}}Q + \underset{(5.64)}{1.38*10^{-2}}\,Temperature\end{aligned} \tag{3}$$

$R^2 = 0.78; R^2_{adj} = 0.77; n = 272$

High t-values, that is, absolute value>2, indicate that a particular coefficient contributes significantly to the explanatory power of a regression equation. If t-values are smaller than 2, including the particular variable increases R^2, without increasing R^2_{adj}. In regression analyses, the focus is on the latter measure for the explanatory power, since R^2_{adj} corrects for the inclusion of less relevant variables. For example, an equation with 20 variables may be capable of predicting 30 observations of a particular parameter exactly, thus giving a value of 1 for R^2. However, restricting the equation to only those variables that are significant, increases the efficiency of the equation, R^2_{adj}, without significantly reducing the explanatory power of the equation.

After removing insignificant variables, the following equation remains:

$$\begin{aligned}Log(MFI) = {} & \underset{(22.09)}{1.00} + \underset{(3.27)}{8.38*10^{-4}}ChlorophyllA - \underset{(-2.34)}{2.53*10^{-3}} \\ & Turbidity - \underset{(-26.46)}{8.99*10^{-2}}Fe(II)SO_4 - 1.14*10^{-2} \\ & \underset{(-3.95)}{Fe(III)SO_4} + \underset{(4.41)}{0.23}WISPRO + 1.34*10^{-2} \\ & \underset{(5.57)}{Temperature}\end{aligned} \tag{4}$$

$R^2 = 0.77; R^2_{adj} = 0.77; n = 272$

The coefficients for total algae and total phosphorus concentrations in Lake IJssel appeared to be insignificant at a 5% level. The same holds for the flow of treated water and the filter runtime. Including ortho-P instead of total-P gives the same result after removing insignificant variables.

Both chlorophyll-A concentrations and turbidity appear to be significant. Since algae may increase turbidity, some correlation might occur. This was tested but appeared to be insignificant (a regression of turbidity on total-P, chlorophyll-a, and total algae resulted in an explained variance of less than 0.15).

As a limited test on validity, a predictive test for stability was performed. For this test, 1990–1994 data were used to estimate the regression equation (see Appendix 1 for results). This equation was then used to obtain predictions for the 1995 data. The hypothesis to be tested is that the prediction errors have mean zero. The test statistic is (Maddala 1992):

$$F = \frac{(RSS - RSS_1)/n_2}{RSS_1/(n_1 - k - 1)} = \frac{(6.210 - 5.515)/43}{5.515/(229 - 7)} = 0.65 \tag{5}$$

which has an F-distribution with n_2 and $n_1 - k - 1$ degrees of freedom (d.f.), where k is the number of variables and RSS is the residual sum of squares from the regression based on $n_1 + n_2$ observations, which is the entire dataset

(1990–1995 data). The d.f. are $(n_1 + n_2) - (k + 1)$. RSS_1 is the residual sum of squares from the regression based on n_1 observations (the 1990–1994 dataset). When an uncertainty level of 5% is used, the test statistic should be higher than 1.39 to indicate instability (for d.f. 43 and 222 observations). The value found for the test statistic is well below this number. Therefore the hypotheses of stability cannot be rejected.

Appendix 2 presents the results of a linear model. The comparative relationships between the various process variables (iron(II)sulphate, iron(III)sulphate, and WISPRO) and temperature appear to be largely similar to the ones found for the log-linear model. However, none of the water quality variables appears to be significant. This insignificance of the water quality variables implies that changes in water quality in Lake IJssel have no effect on the water treatment plant at Andijk. This conclusion differs from that based on the log-linear model, which may be because of the moderate variability in water quality variables. The fact that, according to the linear model, water quality changes are not significant for the water treatment processes, is an indication that the impacts described below should be regarded as upper boundaries of the true impacts.

Discussion

A good quality end product corresponds with low values of MFI. A poor quality starting product (e.g. high chlorophyll-a concentrations in the intake water) results in a poor quality end product (high values of MFI). Thus the positive value found for the chlorophyll-a concentration variable is in line with prior expectations.

Algae development can be prevented by increasing the use of iron(II)sulphate in the basin. In this way less phosphate is available for the algae, which decreases the development of algae, and increases the quality of the end product. This explains the negative relationship between iron(II)sulphate and MFI. (Of course, this only applies within certain boundaries. Extreme overdosing will not have any additional effect. This applies not only to iron(II)sulphate dosage, but also to all chemical treatments described in this paper.)

Iron(III)sulphate dosage during the coagulation process stimulates floc formation. These flocs can then be easily removed. This increases the quality of the end product. Therefore the negative sign is according to prior expectations.

The sign for the WISPRO coefficient can either be positive or negative. A negative value is expected because increased use of this substance stimulates flocculation and thus enables the achievement of low values of MFI. On the other hand, WISPRO is applied when there are already problems with achieving water quality targets. Furthermore, there are some indications that excessive dosage of WISPRO may clog filters and increase MFI (Koelman, 1999, personal communication). The positive sign may be an indication that the latter is a more important explanation than the former.

The positive sign for the temperature variable corresponds with the fact that high temperatures stimulate algae development and thus increase MFI.

Finally, the high explanatory power of this equation (expressed by R^2) gives confidence that it can be used to analyse the potential impacts of nutrient abatement policies in the Rhine basin on this particular treatment plant in physical and monetary terms. This is done in the following section.

THE IMPACTS OF NUTRIENT ABATEMENT POLICIES IN THE RHINE BASIN ON THE TREATMENT PLANT AT ANDIJK

Four scenarios are used to illustrate the (potential) impacts. The first describes the situation in 1985, the base year for the Rhine Action Programme. The second describes the situation in 1995, when a 50% reduction in phosphorus loads resulted in a 10% reduction in chlorophyll-a concentrations (Vrind *et al*. 1994; see above). In the third scenario chlorophyll-a concentrations are reduced by 30% as a result of a 75% reduction in phosphorus loads (Vrind *et al*. 1994; see above). This represents the expected situation for the year 2000. The last scenario presented here is the most extreme one. It assumes a 50% reduction in chlorophyll-a concentrations due to even more stringent nutrient abatement policies than foreseen for the year 2000. Therefore, the last scenario is called 'beyond 2000'.

Having data on chlorophyll-a concentrations in lake IJssel for 1995, but not for 1985, it was assumed that these concentrations were 11% higher in 1985 than in 1995. Based on these 1985 concentrations, chlorophyll-a concentrations for the other scenarios were calculated according to the reductions described above. The chlorophyll-a concentrations for these four scenarios were used as input data for Equation 4.

Although the application of WISPRO appeared to be a significant variable in the regression, it is unlikely that the plant will adapt its use of this chemical according to nutrient-induced water quality changes (Koelman, 1999, personal communication). Therefore the focus is on potential changes in $Fe(II)SO_4$ and $Fe(III)SO_4$ dosing.

To calculate the potential monetary benefits of changes in chlorophyll-a concentrations one can simply use the marginal effect of changes in chlorophyll-a concentrations on the $Fe(II)SO_4$ and $Fe(III)SO_4$ dosing. This is represented by Equations 6 and 7 (all variables in mg l^{-1} ($=g\ m^{-3}$)):

$$Fe(II)SO_4 = \frac{8.38*10^{-4}}{8.99*10^{-2}} ChlorophyllA \tag{6}$$

$$Fe(III)SO_4 = \frac{8.38*10^{-4}}{1.14*10^{-2}} ChlorophyllA \tag{7}$$

These equations describe how either $Fe(II)SO_4$ or $Fe(III)SO_4$ dosing can be changed by the water treatment plant if chlorophyll-a concentrations in Lake IJsselmeer change by 1 mg l^{-1}.

The monetary benefits of changes in chlorophyll-a concentrations can be calculated by multiplication of the change in chemical dosing as described in the previous equation by the flow of water treated and the costs of the chemicals used. This is done in Equation 8:

$$Benefits = -P_{chemical} * \alpha_{chemical} * \Delta ChlorophyllA * Q \tag{8}$$

Where $P_{chemical}$ is the price of the chemical used (in euro g^{-1}), the chemical is either $Fe(II)SO_4$ or $Fe(III)SO_4$,

Table 2 | Costs and marginal dosing of iron(II)SO_4 and iron(III)SO_4

Chemical	$Fe(II)SO_4$	$Fe(III)SO_4$
α	9.32×10^{-3}	7.35×10^{-2}
Price (euro g^{-1}) (KIWA/WRK 1997)	0.07×10^{-3}	0.43×10^{-3} (0.41×10^{-3})

Note: If the annual ferro(III)sulphate dosage is increased the application of lime also has to be increased (see text). The annual costs decrease by approximately euro 22,500 if the annual ferro(III)sulphate dosage is reduced by 1.0 mg l^{-1}. This is equal to 3.6% of the costs for this chemical (Wuijts 1999, personal communication). The number in parentheses excludes additional lime application.

$\alpha_{chemical}$ is the marginal effect of changes in chlorophyll-a concentrations on the dosing (in (mg l^{-1})/(mg l^{-1})), Δ*Chlorophyll-A* is the average annual change in chlorophyll-a concentrations compared with the average concentration of 1985 (in mg $l^{-1} = g\ m^{-3}$), and Q is the annual flow of water treated by the treatment plant (in $m^3\ yr^{-1}$).

Since nutrient abatement results in reductions of chlorophyll-a concentrations, the sign of this variable will be negative, which corresponds with decreased chemical dosing. Obviously this should result in positive benefits. Therefore the right-hand side of Equation 8 starts with the minus sign.

The annual water quantity treated at Andijk is approximately 50 million m^3 (WRK 1996), and the average chlorophyll-a concentration in the period 1990–1995 was 90 mg l^{-1}. Using these data and the costs and marginal dosing of iron(II)SO_4 and iron(III)SO_4 presented in Table 2 the benefits of nutrient abatement policies can be calculated.

Another way to calculate the benefits is by taking the monthly averages presented in Figures 6 and 7, and multiplying them by the flow of water treated each month and summing them over the months. This gives the amounts of chemicals used per year. These annual amounts can be multiplied by the respective prices, resulting in annual costs. The difference in costs between the respective scenarios and those for 1985 gives the benefits of changes in chlorophyll-a concentrations.

Figures 6 and 7 in Appendix 3 show the impact of reduced chlorophyll-a concentrations on the average

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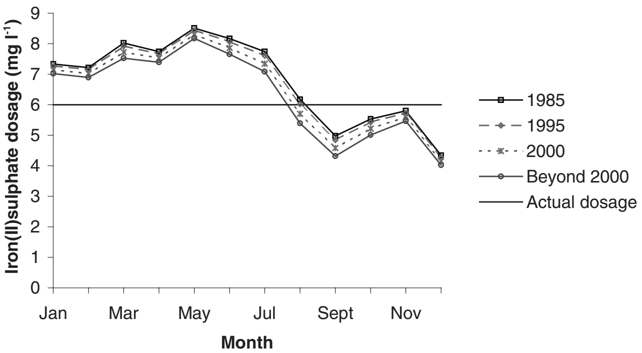

Figure 6 | Iron(II)sulphate dosage in the basin for different scenarios and actual dosage for 1995.

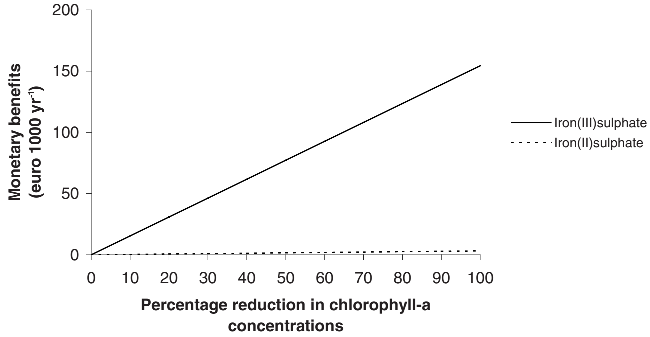

Figure 8 | Cost savings for the water treatment plant at Andijk when iron(II)sulphate and when iron(III)sulphate are used as steering variables, depending on reductions in chlorophyll-a concentrations in Lake IJssel compared with the situation in 1985.

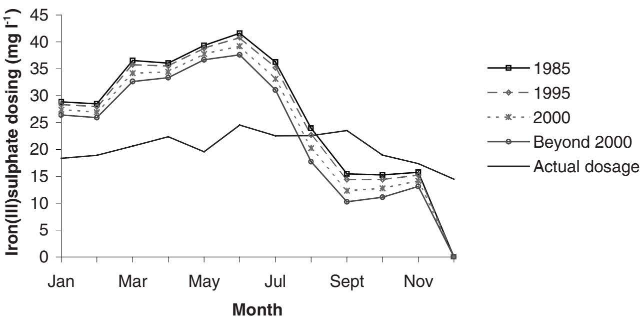

Figure 7 | Iron(III)sulphate dosage in the coagulation process for different scenarios and actual dosage for 1995.

monthly dosing of these two chemicals by the treatment plant when only one chemical is changed at a time. It appears that during a few months, the predicted doses are higher than those actually applied during the estimation period; for example, according to Figure 6 for a few months iron(II)sulphate doses are more than 7 mg l^{-1}, whereas during the regression period the actual doses did not exceed 6 mg l^{-1} (see also Table 1). The predicted doses are thus an extrapolation of actually observed behaviour outside ranges described by the data. Since it is not the purpose of the analysis presented in this paper to prescribe optimal behaviour that can actually be implemented, but to estimate the potential effects of changes in nutrient-related water quality variables, the interest lies more in relative than in absolute numbers. However, the fact that some doses fall outside the ranges described by actual data, has to be taken into consideration when looking at the results. The cost figures should not be taken as absolute values, but as indications of relative effects. The same applies to using average data for the years 1990–1995 instead of data for 1995. This would change the absolute values for the optimal dosing, but the differences in doses due to changes in chlorophyll-a concentrations remain similar.

If the water treatment plant at Andijk manipulated only one chemical at a time, changing iron(III)sulphate doses according to temperature and chlorophyll-a concentrations would result in the highest cost savings (see also Figure 8). However, the treatment plant is likely to change more than one process at a time as it takes into account more aspects than temperature and chlorophyll-a alone. According to Table 3, the 30% reduction in chlorophyll-a concentrations in Lake IJssel, expected for the year 2000, results in cost savings in the range of euro 956–46,328 per year, depending on which chemical is used. This equals 0.00002–0.0009 euro m^{-3}. Since the production costs are approximately 0.25 euro m^{-3} (WRK 1996), these benefits are less than 0.5% of the production costs.

Apparently, nutrient abatement policies in the Rhine basin as described in the Rhine Action Plan have only a limited effect on the total costs incurred by the water treatment plant of Andijk, if they have any impacts at all. The potential benefits of nutrient abatement in the Rhine basin as incurred by the Andijk plant clearly do not

Table 3 | The benefits of reductions in chemicals used in the three nutrient abatement scenarios (euro yr^{-1})

Variable chemical	Scenario	Reduction in chlorophyll-a concentration (%)	Cost savings (euro yr^{-1})
Iron(II)sulphate in the basin	1985	0	0
	1995	10	319
	2000	30	956
	beyond 2000	50	1,594
Iron(III)sulphate in the coagulation process	1985	0	0
	1995	10	15,442
	2000	30	46,328
	beyond 2000	50	77,208

compensate for the necessary monetary efforts, the costs of which are euro 700–1,000 million yr^{-1} (van der Veeren 1999; van der Veeren and Tol 2001).

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APPENDIX 1. EQUATIONS FOR 1990–1994 AND 1991–1995 DATA

The regression equation for the 1990–1994 data is, after removing insignificant variables, presented by Equation A.1.

$$
\begin{aligned}
Log(MFI) = {} & \underset{(18.16)}{0.96} + \underset{(2.91)}{9.03*10^{-4}} ChlorophyllA \underset{(-2.02)}{-2.62*10^{-3}} \\
& Turbidity \underset{(-22.90)}{-8.66*10^{-2}} Fe(II)SO_4 - 1.10*10^{-2} \\
& \underset{(-3.33)}{Fe(III)SO_4} + \underset{(5.24)}{0.32} WISPRO + 1.40*10^{-2} \\
& \underset{(5.40)}{Temperature}
\end{aligned}
\tag{A.1}
$$

$R^2 = 0.76; R^2_{adj} = 0.75; n = 229$

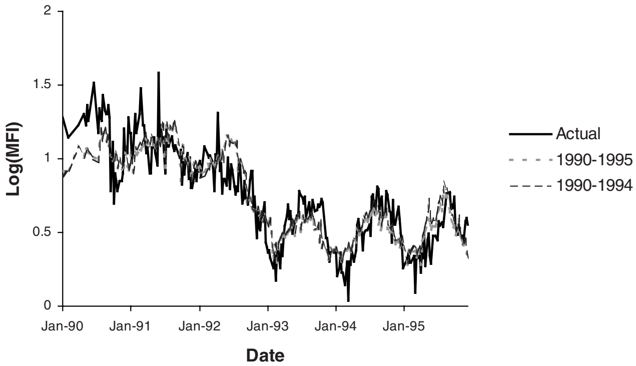

Figure A.1 | Actual and estimated log(MFI) values for the period 1990–1995.

Equation A.1 is not very much different from Equation 4, except for WISPRO dosing. In 1995 the dosing was comparable to that in 1990, which was higher than in 1991–1994. This seems to have some influence on the values found for this variable.

The result that Equation A.1 is not very much different from Equation 4 is visualised by Figure A.1. Line '1990–1995' presents the values for log(MFI) estimated using Equation 4, which is based on the entire dataset, and '1990–1994' presents the results of an application of Equation A.1. The similarity between Equations 4 and A.1 is reflected in the close correspondence between these two lines.

APPENDIX 2. RESULTS OF THE LINEAR MODEL

This appendix describes the results when MFI is used instead of log(MFI). Equation A.2 presents the application of Equation 2 on the data, similar to the estimation of Equation 3:

$$\begin{aligned} Log(MFI) = {} & \underset{(7.11)}{13.63} + \underset{(1.10)}{3.78}TotP + \underset{(1.01)}{7.05*10^{-3}}ChlorophyllA \\ & - \underset{(-6.17)}{2.68*10^{-6}}TotalAlgae - \underset{(-0.89)}{2.53*10^{-2}}Turbidity \\ & - \underset{(-16.76)}{1.50}Fe(II)SO_4 - \underset{(-3.29)}{0.24}Fe(III)SO_4 \\ & - \underset{(-0.73)}{8.72*10^{-3}}Filterruntime + \underset{(3.42)}{5.34}WISPRO \\ & - \underset{(-0.76)}{6.51*10^{-6}}Q + \underset{(3.26)}{0.20}Temperature \end{aligned} \qquad (A.2)$$

$R^2 = 0.59; R^2_{adj} = 0.58; n = 272$

After removing insignificant variables Equation A.3 remains:

$$\begin{aligned} Log(MFI) = {} & \underset{(11.56)}{12.74} - \underset{(-18.73)}{1.52}Fe(II)SO_4 - \underset{(-3.26)}{0.23}Fe(III)SO_4 \\ & + \underset{(4.01)}{5.18}WISPRO + \underset{(4.47)}{0.22}Temperature \end{aligned} \qquad (A.3)$$

$R^2 = 0.59; R^2_{adj} = 0.58; n = 272$

To see whether, although insignificant, chlorophyll-a concentrations would result in approximately the same impacts as described in the text, the equation was estimated using the same variables as in Equation A.4:

$$\begin{aligned} Log(MFI) = {} & \underset{(11.31)}{12.78} + \underset{(0.94)}{6.01*10^{-3}}ChlorophyllA - \underset{(-0.58)}{1.57*10^{-2}} \\ & Turbidity - \underset{(-17.79)}{1.51}Fe(II)SO_4 - \underset{(-3.23)}{0.23}Fe(III)SO_4 \\ & + \underset{(4.01)}{5.30}WISPRO + \underset{(3.03)}{0.18}Temperature \end{aligned} \qquad (A.4)$$

$R^2 = 0.59; R^2_{adj} = 0.58; n = 272$

The comparative relationships between chlorophyll-a and iron(II)sulphate and iron(III)sulphate are different from those described in the text. The comparative relationships between the process variables appear to be largely similar to those estimated in the log-linear model.

APPENDIX 3. ILLUSTRATION OF CHEMICAL DOSAGE FOR THE DIFFERENT SCENARIOS

Due to the relatively high dosing of both iron(II)sulphate and iron(III)sulphate for 1995, compared with the other years, both application rates are estimated lower than actual values (e.g. high iron(II)sulphate application is compensated by lower iron(III)sulphate application). This is partly compensated by relatively low MFI values and high WISPRO application (the latter especially in the summer) in 1995. The combination of these effects explains the overestimation of the application rates in the summer and the underestimation in the winter period.