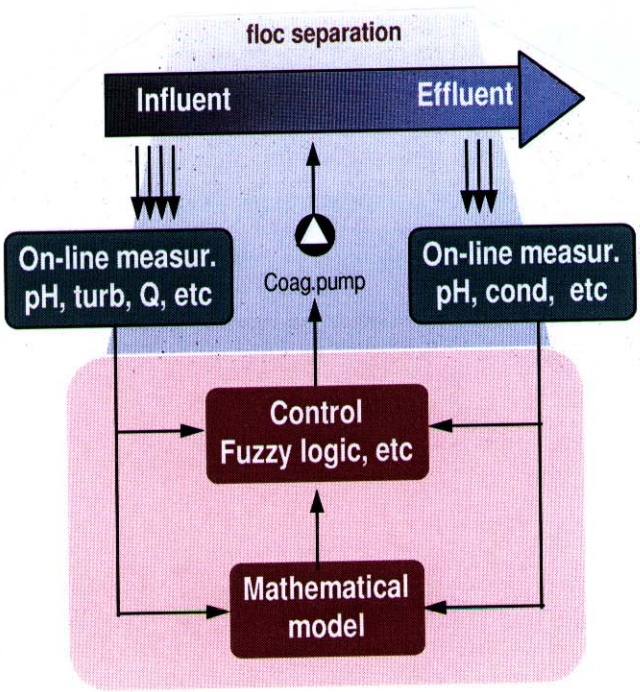
REPORT SNO 3713-97

Chemical Wastewater Treatment

A Concept for Optimal Dosing of Coagulants



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Abstract

A concept for optimisation of the coagulant dosing for domestic wastewater treatment is presented and evaluated. The concept is based on the real-time estimation of the optimal coagulant dosage using on on-line water quality measurements of the raw water. A preliminary project was established in 1992 and was completed in 1993. Laboratory- and pilot scale evaluation of the concept was followed. Finally, a consortium between NIVA, ANØ (Avløpssambandet Nordre Øyeren) and Alfa Laval Automation (earlier Satt Control AS) implemented full scale tests at a small scale treatment plant (Bårlidalen WWTP, Eidsvoll) and at a large/medium scale treatment plant (TAU WWTP, Tønsberg). A dosing concept based only on one or two influent parameters like flow and turbidity are not efficient, although they could be interesting for small WWTPs. At Bårlidalen WWTP, such a concept could save over 8% of the chemical costs. Dosing concepts based on more influent parameters enabling a comprehensive description of the influent are needed for larger WWTP. At small treatment plants such a system demonstrated savings up to 25% on chemical costs, while over 4-10% saving at larger WWTP are expected.

4 keywords, Norwegian	4 keywords, English
1. avløpsrensing	1. wastewater treatment
2. fellingskjemikalier	2. coagulants
3. optimalisering	3. optimisation
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Chemical Wastewater Treatment

A Concept for Optimal Dosing of Coagulants

Preface

Coagulation is one of the most popular wastewater treatment processes in the world. The efficiency and the economy of this process is primarily dependent on the optimal dosing of coagulants, which may cost 15-25 NOK/p.e. per year. However, the existing dosing concepts do not utilise the latest advantages in the coagulation theory, process technology, measurement technology, etc. This report briefly presents the results from a project which had a goal to develop and evaluate an efficient dosing method.

The project is mainly financed by the Norwegian Institute for Water Research (NIVA) and the State Pollution Control Authority (SFT) of Norway. The Alfa Laval Automation AS has supported the project with hardware and programming. The Wastewater Competence Centre at Nordre Øyeren (ANØ) and Kemira Chemicals of Norway has supported the full-scale experiments. Without the kind assistance from the wastewater treatment plant personnel at Eidsvoll, Tønsberg, Lillestrøm and Lillhammer this project would have not been possible to realise. The assistance from Arne Veidel, Morten Willbergh, Johan Ahlfors (NIVA), Ingar Næss (ANØ) and Øyvind Berntsen (ALA) is appreciated.

The author gratefully acknowledges the continuos encouragement from Gunnar Fr. Aasgaard (NIVA, ANØ) and Roland Olsson (ALA), and all other persons involved in this project.

Oslo, 30th August, 1997

Harsha Ratnaweera, dr.ing.

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Sammendrag

NIVA har igangsatt et FoU-prosjekt for utvikling av et styringssystem for kjemikaliedosering - KJEMISTYR basert på on-line måling av vannkvalitetsparametre. Målgruppen er kjemiske og kjemisk/biologiske avløpsrenseanlegg.

Ved dagens avløpsrenseanlegg doseres koagulanter i alt overveiende grad etter enkle kriterier, som konstante verdier dag/natt eller proporsjonalt med anleggets hydrauliske belastning, evt. overstyrt av pH. Unntaksvis benyttes vannkvalitet (turbiditet) eller erfaringsdata (karakteristiske belatningsvariasjoner over døgn, uke og år) som grunnlag for kjemikaliedoseringen.

Ved å styre kjemikaliedoseringen etter on-line registrering av relevante vannkvalitetsparametre vil en rekke fordeler oppnås. De viktigste er :

- Reduserte driftskostnader som følge av:
  - lavere forbruk av koagulanter og andre kjemikalier
  - lavere slambehandlingskostnader (mindre slam)
  - lavere analysekostnader
  - billigere drift av etterfølgende rensetrinn

- Miljøgevinster
  - høyere midlere renseeffekt
  - reduserte følgeskader av uforutsette belastningsendringer
  - mer miljøvennlig slam

Eksempler på aktuelle parametre for on-line registrering er turbiditet, pH, orto-P, temperatur, ledningsevne, fnokkegenskaper og vannmengde. Labskala forsøk utført i NIVA og pilotskala forsøk er utført i renseanleggene RA-2 ved Lillestrøm og R2 i Lillehammer. Fullskala forsøk er utført i Bårlidalen RA (Eidsvoll) og i TAU (Tønsberg). Resultatene viser at små renseanlegg kan spare kjemikaliekostnader opptil 25%. Selv et enkelt doseringskonsept kan redusere kostnadene til fellingskjemikalier på små renseanlegg med over 8%. For større renseanlegg må man ha mer avanserte doseringskonsepter som presentert og kan forvente en besparelse 4-10%.

Sluttproduktet KJEMISTYR vil bestå av en enkel styringsenhet (modifisert datalogger) og en programdiskett. Utstyret vil kunne bli innstallert som et selvstendig, komplett styringssystem for kjemikaliedoseringen, eller bli integrert i anleggets driftssystem.

En markedsundersøkelse utført av SattControl A/S viser at det er et godt forretningsmessig grunnlag for KJEMISTYR. Denne konklusjonen er basert på en vurdering av potensialet innen kommunale avløpsrenseanlegg i Norge, Sverige, Danmark, Finland, Tyskland, Sveits, Frankrike, Spania og Be-Ne-Lux landene.

Det gjennomførte prosjektet har bekreftet det teknologiske grunnlaget for produktidéen. Drøftelser er gjennomført med flere industribedrifter med sikte på samarbeid i det videre FoU-arbeid og produktlansering/markedsføring.

1. Introduction

Chemical coagulation is one of the major wastewater treatment processes today. The process is proven to be an efficient and robust method for particle and phosphate removal from the domestic wastewater, while the chemical costs and the management of the resulting sludge phase are identified as major constraints. The popularity of the process vary from country to country, and Norway is being identified as the country with the highest degree of chemical treatment of domestic wastewater. At present, over 70% of wastewater in Norway is treated in chemical- and biological/chemical treatment plants.

A survey among 72 Norwegian chemical treatment plants reveals that the average dosage is 183±70 g/m^3 for ALG and AVR and 252±61 g/m^3 for iron chloride (Ødegaard, 1991). In other words, there is a variation of annual chemical costs approximately between 15 and 25 NOK/p.e. The plant size, configuration and the wastewater composition is major factors for this variation. An additional important factor is the applied coagulant dosage, since even an overdose up to 50% of the optimal dosage, often will not affect treatment efficiency but will drastically affect the treatment costs.

Therefore, a project was established at NIVA to study and evaluate a system for optimisation of the coagulant dosing for domestic wastewater treatment. The concept was based on the real-time estimation of the optimal coagulant dosage based on on-line water quality measurements of the raw water.

A preliminary project was established in 1992 and was completed in 1993 with a laboratory scale evaluation of the concept. Following that, pilot scale experiments at two municipal wastewater treatment plants were carried out. For these phases, the Norwegian State Pollution Control Authority (SFT), the Ekspomil program of the Norwegian Research Council and NIVA has provided funding. Although it was the intention to verify the concept also in full-scale treatment plants, the project was temporally frozen due to financial and other resource constraints. However, in 1997 a consortium between NIVA, ANØ (Avløpssambandet Nordre Øyeren) and Alfa Laval Automation (earlier Satt Control AS) has managed to carry out full scale tests at a small scale (Bårlidalen WWTP, Eidsvoll) and at a large/medium scale (TAU WWTP, Tønsberg) plants with considerable help form the WWTP personnel. Kemira chemical has supplied the necessary dosing equipments for the full scale experiments.

This report briefly presents the concept and experimental results. The next stage will be the preparation of the unit for full-scale applications with collaboration of a producer/distributor.

2. Background

The importance of carrying out the coagulation process at optimum conditions increases with the requirements for the production of safe and clean water, with minimum side effects to the environment. The inefficient control of the coagulation process may result in high chemical costs, high sludge volumes, negative effects on consequent treatment processes, corrosion problems, health hazards etc. With the world-wide growth in the number of chemical water and wastewater treatment plants, the optimum coagulation conditions have become a considerable issue of economy, environment and health in water treatment.

For many years researchers have been investigating the optimisation of the coagulation process. The importance of physical/chemical parameters as the mixing of chemicals (Klute et al., 1990), the coagulation pH (Amirtharajah and O'Melia, 1991), the coagulant chemistry (Fettig et al., 1990, Ratnaweera, et al., 1992), the influence of flocculant aids (Ødegaard et al., 1992), etc. are well documented. The benefits of most of these conclusions are related to the dosing of coagulants in optimum amounts required by the influent quality and the required treatment efficiency (Ratnaweera, 1991).

The optimum coagulant dosage is primarily a function of the raw wastewater quality and the treatment requirement. The dosage is also dependent on the coagulant type and the treatment plant configuration. In practice, it is possible to consider that the treatment requirements, coagulant type and the plant configuration are constants for a given treatment plant. Then the optimum coagulant dosage varies only with the raw wastewater quality.

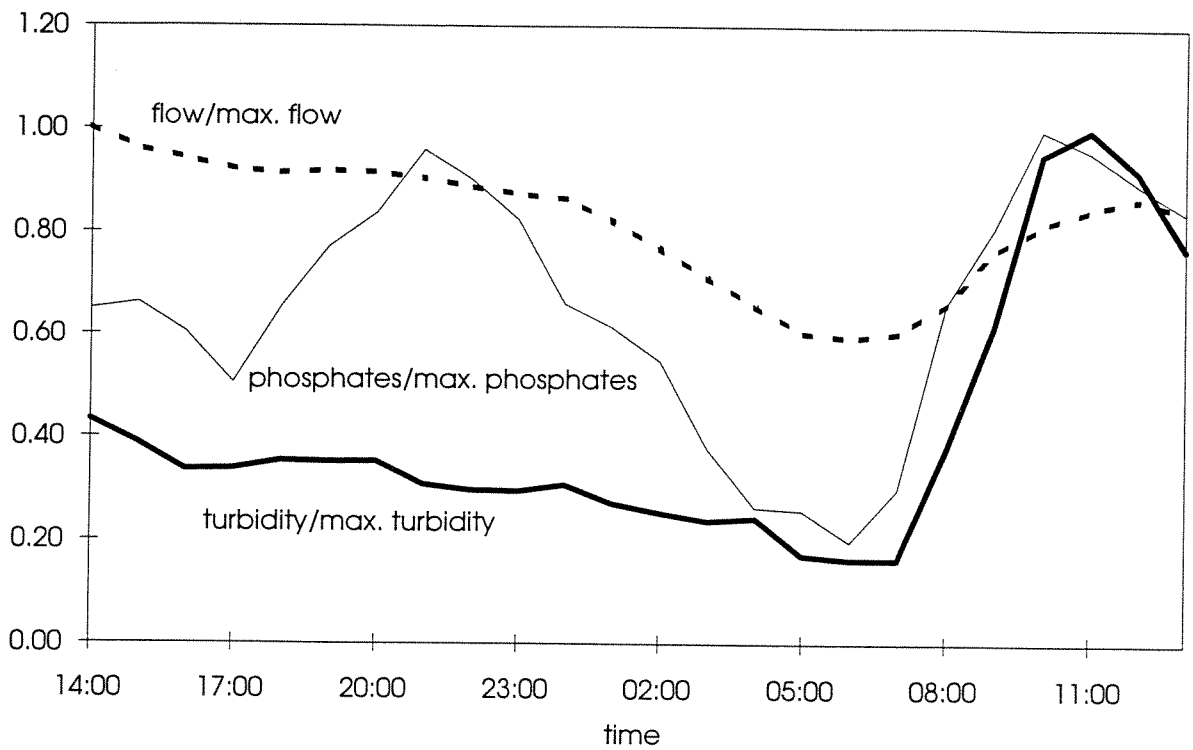


Figure 1. Variation of raw wastewater quality during a day: turbidity, phosphates and flow values in relation to the maximum daily values observed . (Lillestrøm RA-2 wastewater treatment plant).

The raw wastewater quality varies rapidly and considerably during the day. Fig. 1 illustrate the variations in turbidity and phosphates in raw wastewater during a day do not necessary follows the trends in wastewater flow variations. It may be possible to identify the patterns of wastewater quality variations during a day (hourly), week (working/non working days), and periods (summer holidays), etc. (Sagberg et. al., 1990). However, the frequent disturbances from industries and other natural or man-made sources influence these patterns and cause difficulties in the assumption of wastewater water quality without direct measurements.

An investigation on the available coagulant dosing control strategies reveals that most of the wastewater treatment plants have two important problems related to the optimal dosing: (1) many do not have the possibility to measure the influent water quality sufficiently quick and detailed; (2) there is a lack of a method to determine the optimum dosage for a given set of influent qualities.

Unlike many other industrial processes, the coagulant dosing is difficult to control using feed-back concepts, primarily due to the 2-6 hours of sedimentation times and the influent quality fluctuations during that period. The most widespread coagulant dosing strategies include the dosing proportional to flow and some times in combination with the over-run control of pH or conductivity in the coagulated water. Some of the large treatment plants practice dosing of coagulants based on experience curves/coefficients. On the other hand, there is no simple method to determine the optimum coagulant dosage even if the influent quality is well identified. This situation forces most of the treatment plants to run either with an overdose or an under dosage of coagulants, which results in many adverse effects.

Many treatment plants monitor only the flow, while some of them also monitor pH, conductivity and temperature of the influent. However, the turbidity and the phosphates, the two major components in the municipal wastewater treatment, are seldom measured in the influent. The developments in the water quality measuring technology (streaming current detectors, floc characteristic monitors, automatic phosphate analysers etc.) in the last few years indicate a promising future for real time evaluation of the wastewater quality to a sufficient level. For the optimum management of chemical treatment processes using all the important findings on the coagulation process optimisation, however, it is important to have a method for their on-line implementation based on the real time water quality measurements. The definition of a conceptual mathematical model for wastewater coagulation would have been an ideal solution for this purpose. However, the complex nature of municipal wastewater and the coagulation chemistry have obstructed to the development of a such comprehensive model. The few existing empirical models are addressing only one or two parameters and often complicated with many experimental coefficients.

3. The Concept

A quantitative understanding of the coagulation process is required for its mathematical description. Experimental results are available from many studies quantifying the coagulant requirement for single variable parameter (e.g.: turbidity, phosphate, etc.) for a given wastewater type. However, removal efficiencies are not the same for all pollutants at a given dosage for a given wastewater. For example, the prepolymerised aluminium coagulants should be dosed 10-20% more to achieve the same level of removal efficiency in phosphates as turbidity under identical conditions.

For the accurate calculation of the required coagulant dosage for a given condition, one has to study the coagulant consumption paths. An understanding of the mechanisms of coagulation process will the be an advantage. Many of these mechanisms are well understood and documented, and Ratnaweera, et. al. (1992) have presented the summarised coagulant consumption paths (Fig. 2).

Fig. 2 illustrates the various paths of coagulant consumption in municipal wastewater coagulation. The complexity of the wastewater coagulation process is well illustrated in Fig. 2. Two major conclusions are possible to derive from this figure: (1) Not only the particle and phosphate removal processes consume coagulants; (2) coagulation involves both stoichiometric (like adsorption-charge neutralisation) and non-stoichiometric (like sweep floc) mechanisms. For these reasons, it has not been possible to construct a simple and comprehensive conceptual mathematical model for coagulation.

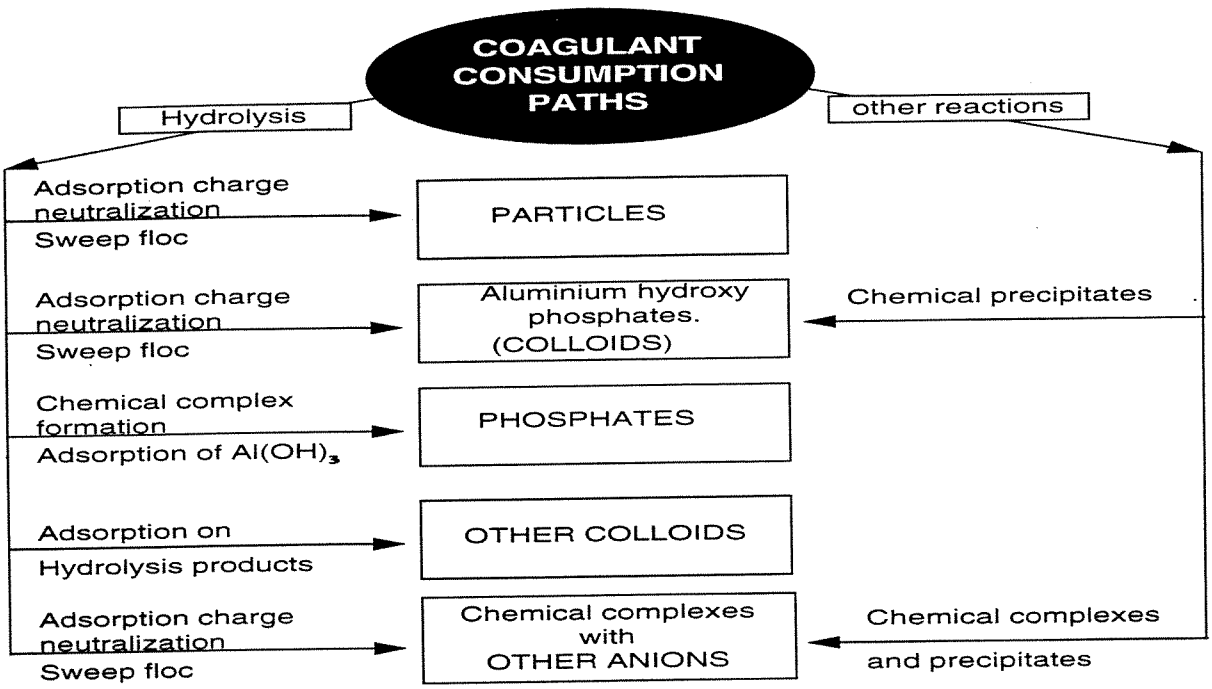


Figure 2. *Schematic illustration of coagulant consumption paths through different mechanisms in municipal wastewater (after Ratnaweera et. al., 1992).*

The only remaining way to calculate the required coagulant dosage on influent quality is the use of an empirical model. These approaches were often met with a scepticism due to the models' complexed and non-comprehensive nature. Many of these models are based only on one or two influent quality parameters, which is the reason for their failures as it was explained in the context of Fig. 1. In this report we will discuss a method to construct accurate empirical models overcoming these problems.

Any well-defined process is possible to describe mathematically. We can assume that the wastewater coagulation process is a well-defined process. For example, if we repeat identical coagulation experiments with identical samples and conditions, we should always get the identical effluent quality, sludge characteristics and amounts, despite the complexity of the process. Therefore, if we can describe each important sector of the coagulation process (influent-, effluent-, sludge-quality, coagulant type and plant configuration), it will be possible to describe the process mathematically. For the simplicity we will consider a coagulation process at one treatment plant using one coagulant type. We intend to develop an empirical model for coagulant dosage as a function of other parameters. Since the required coagulant dosage is not dependent on the sludge characteristics (while the inverse is true), we can exclude also that sector in the model.

The influent and effluent quality should be described sufficiently well that two influent samples with identical descriptions should result in identical effluents under the same conditions. If the description criteria are insufficient, for example only one parameter as influent turbidity is selected, this assumption is not valid, since two samples with identical turbidities will result in different effluent qualities if they have different phosphate contents. This is also the reason for the inefficiency of flow or turbidity proportional coagulant dosing. The description criteria may vary with the application as we have demonstrated later in the different experimental phases. For all experimental phases addressed in this report, we have excluded the specific description of flocculation and floc separation conditions, since for one and same conditions, they are indirectly represented in well-defined influent and effluent descriptions. Thus one may need to calibrate such a model for each plant, to account for the plant specific conditions like mixing and sedimentation environments.

Based on the above assumption, we can then construct an empirical model for determining the coagulant dosage as a function of influent and effluent quality. This is performed mathematically using multivariate statistical methods, which are further described later.

4. Experimental conditions and methods

4.1 Laboratory scale experiments

In order to study a wide and reproducible variation of influent quality, we decided to use a model wastewater during the laboratory scale experiments. The experiments were conducted using a set-up consisting of a raw water pump (2 l/min), an on-line coagulant dosing system (Klute, 1990), a semi automated 1 l jar-test system and analysis. A factorial experiment (Montgomery, 1984) was conducted according to the table 1(a) and 1 (b).

Table 1(a). Inorganic and organic constituents of the model wastewater, classified in to quality factorial levels

	Component	Concentration, mg/l		
		Level **L**	Level **M**	Level **H**
Particle content	Dry milk	150	300	600
	Potato starch	30	60	120
	Bentonite	40	80	160
	Humus	2.5	5	10
Alkalinity/Hardness	$CaCl_2 \cdot 2H_2O$	0		338
	$NaHCO_3$	60		400
	NaCl	400		0
	NH_4Cl	50		100
Phosphates	K_2HPO_4	25		50
pH	pH	6.8		7.5

Table 1(b) Variations in model wastewater quality constructed using combinations of quality and levels given in Table 1(a).

Water type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Particle content	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H
Phosphates	L	L	L	L	H	H	H	H	L	L	L	L	H	H	H	H	L	L	L	L	H	H	H	H
Alk./Hardness	L	L	H	H	L	L	H	H	L	L	H	H	L	L	H	H	L	L	H	H	L	L	H	H
pH	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H

The experimental design resulted in 24 water types representing many of the common wastewater types in Europe. The measured water quality parameters indicated variations of turbidity 75-420 NTU, ortho-phosphates 4.3-11.3 mg-P/l, alkalinity 1-5.5 mmole/l and pH 6.8-7.5.

The model wastewater was prepared in a 5 l beaker and further diluted to a 20 l suspension. The suspension was kept under slow mixing for two hours to achieve a certain degree of equilibrium. The coagulants were dosed continuously using an inline mixer (Klute, 1990) where a quick and efficient mixing was achieved. After a rapid mixing at 400 rpm for 1 min., a slow mixing at 50 rpm for 10 min. and sedimentation of 20 min. took place. Turbidity, pH, conductivity and the surface charge (using a Dosapro Milton Roy stream current monitor) was measured immediately while ortho-phosphates, COD and alkalinity was measured later. The results from one coagulant with 4-6 dosages for each model wastewater type are considered further.

4.2 Pilot scale experiments

The pilot scale experiments were conducted at Lillehammer WWTP and Lillestrøm WWTP (RA-2). A pilot scale experimental unit was constructed in Plexiglas. The unit consists with a dosing system, inline mixer, tube flocculation unit with 3 different diameters and a sedimentation reactor where the coagulated wastewater was pumped from the bottom. The flocs were further built up during the movement upwards and entrapped in a floc blanket which was continuously pumped out to maintain a constant volume of a blanket.

The treated wastewater was further removed via an overflow cell. The on line measuring instruments for turbidity, pH, conductivity and phosphates were connected to this cell. During selected periods an hourly samples were collected using an automatic sampler for manual analysis of COD.

Alfa Laval has produced and programmed a hardware unit for data accumulation and dosing signal generation. This unit was only used to receive data in the pilot mode as the pilot scale experiments were limited to data accumulation and model construction/calibration.

4.3 Full scale experiments

The criteria for the selection of the plants for full scale experiments were the presence of a primary coagulation stage, possibility to have two separate treatment lines and situated close to NIVA. Although Lillehammer and Lillestrøm treatment plants were meant to be used in full scale experiments, the frozen time of the project has changed the situation. Lillehammer WWTP has changed their treatment to post nitrification/denitrification stage with the introduction of nitrogen removal, and become a "not typical" coagulation plant in Norway. The Lillestrøm plant was at the time of full scale experiments expecting new requirements leading to process changes from the authorities (related to the new airport at Gardemoen and the nitrogen removal), thus was not available as an experimental site. However, we managed to identify two new locations for the full scale experiments. They were Eidsvoll (Bårlidalen WWTP) and at Tønsberg (TAU WWTP).

Bårlidalen WWTP is a small wastewater treatment plant with a design capacity to serve 15 000 p.e. The plant is using AVR as the coagulant. The plant consists of strainers, input of septic waste, sand traps and a primary sedimentation unit followed by a coagulation unit. The plant has four flocculation chambers and four sedimentation tanks. The coagulant AVR is dosed using a powder dosing unit with inline mixing with water. Solutions of AVR was required to prepare beforehand for the experimental dosing system. Three one cubic meter plastic tanks were used where in one tank the AVR suspension was under continuos mixing. After sufficient mixing the suspension was allowed to settle for at least two hours (to separate the 3% solid phase) and the supernatant was pumped to the dosing tank which was also equipped with a mixer. The concentration of AVR was measured using a density meter provided by the AVR producer.

TAU is a medium/large scale treatment plant with a design capacity of 60 000 p.e.. However, due to heavy periodic discharges from food processing factories the organic load exceeds the design capacity. The treatment plant has grit chambers, input of septic waste, sand traps, flocculation chambers and six sedimentation tanks. TAU is using ferric chloride as the coagulant. The plant has two dosing pumps to serve the two lines, in one line ferric chloride was dosed using the experimental dosing unit during the experiments.

The experimental dosing pump was supplied by Kemira Chemicals AS. It is a pump with a regulator which could control the pump from an external 4-20 mA signal. The maximum dosing was 170 l/h which was sufficient for the experimental lines. The pump also has the capacity to run and control without an external signal, which was an advantage during programming periods.

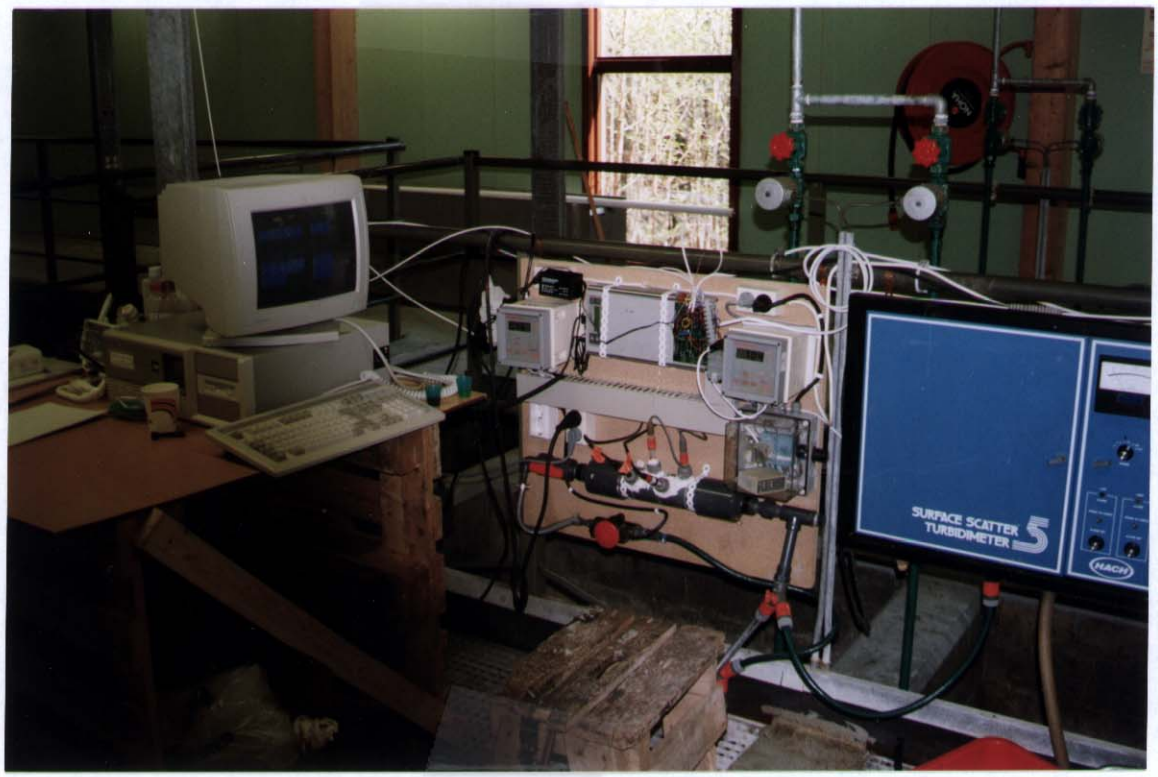


Figure 3. *On-line water quality monitoring system at Bårlidalen WWTP*

Figure 4. *Coagulant Dosing Control unit at Bårlidalen WWTP*

Alfa Laval Automation AS has programmed it's own unit type OP 65 to receive water quality measurements and to calculate the optimal dosage and to send an electrical signal to the dosing pump. A blank program with possibilities to receive coefficients was designed by NIVA and programmed by Alfa Laval Automation AS. The coefficients were possible to feed through the OP 65 screen directly. The OP 65 was the original hardware selected for the project in 1994, however the producer now in 1997 inform that new and more suitable hardware exists in the market. We have decided to use the original hardware for the test purposes and a more suitable hardware will be selected for further applications.

The influent and effluent quality were mostly monitored on-line. Turbidity, pH, conductivity, flow and temperature were measured in the influent and in both effluent lines continuously. Additionally, automatic samplers were placed to measure phosphates and organic matter in selected periods.

4.4 Procedures for model construction - Chemometry

In the field of chemometrics, statistical methods are used in planning experiments and data collection, and for interpretation of chemical data. The methods are general and can be used in any field where large amounts of numbers are to be collected and interpreted; biometrics, econometrics, psychometrics etc. Powerful software packages are available.

Chemometrics and use of advanced statistical methods in data exploration are powerful tools in extracting the relevant information from large data sets. Since chemical and physical instruments have developed rapidly over the last years, we often collect many variables (parameters) from many samples resulting in extensive data matrices. It is often difficult or impossible to get an overview over such magnitudes of data. By the use of e.g. principal component analysis (PCA), the structure of relationships between variables and samples in the data set can be studied. Often a few principal components can substitute many original variables without loss of important information. This yields a considerable data compression.

In multivariate calibration, regression techniques, e.g. principal component regression (PCR) and partial least squares regression (PLSR) are used to establish relationships between variables. An introduction to multivariate calibration and analysis is given by Beebe & Kowalski, 1987, whereas a thorough discussion of the subject is published by Martens & Næs, 1991.

In this investigation, PLSR has been applied to find relationships between coagulant dosage (D), influent variables (X_{in}), and effluent variables (X_{out}) as illustrated in the equation below:

$$D = f(X_{in}, X_{out})$$

There are several ways to assess the quality of the developed models. Predicted versus measured values should ideally give a straight line through the origin, with a slope=1. In practice, however, this is normally not the case, but the deviation of the individual data points from this ideal situation is a measure of the quality of the model. The correlation coefficient between predicted and measured values is one quality parameter, the slope another. RMSEP (Root Mean Square Error of Prediction) is a useful quality parameter. The difference between a predicted and measured value is squared, the sum of squares is calculated for all samples, and then the square root of this sum is found after dividing by the number of samples. Thus, the RMSEP is a measure of the average deviation between predicted and measured values.

A model should always be validated with samples not used in the calibration procedure. The best validation method is to use a test set. First a model is developed from a calibration set and then validated with a test set. If, however, a test set is not available or the original data set is too small or not suited to be split up into a calibration and a test set, cross validation can be used. In cross validation one repeats the calibration several times, each time treating a part of the whole calibration set as prediction samples. In the end all of the calibration objects have been treated as prediction samples. Calculating e.g. the RMSEP gives an indication of the prediction capability of the model.

5. Results and Discussions

5.1 Laboratory scale experiments

Using the results from the laboratory scale coagulation experiments we have attempted to construct an empirical model for the description of coagulant dosage (D) as a function of influent (X_{in}) and effluent (X_{out}) qualities: $D = f(X_{in},X_{out})$. The X_{in} was consisted with turbidity, pH, conductivity, ortho-phosphates, COD and Alkalinity of influent. The X_{out} was consisted with the same parameters as in X_{in}, excluding alkalinity. The model structure included single, square and cross variables (e.g. turb*pH) of the selected parameters. The model calibration and cross validation results are illustrated in Fig. 5(a) and 5(b), respectively.

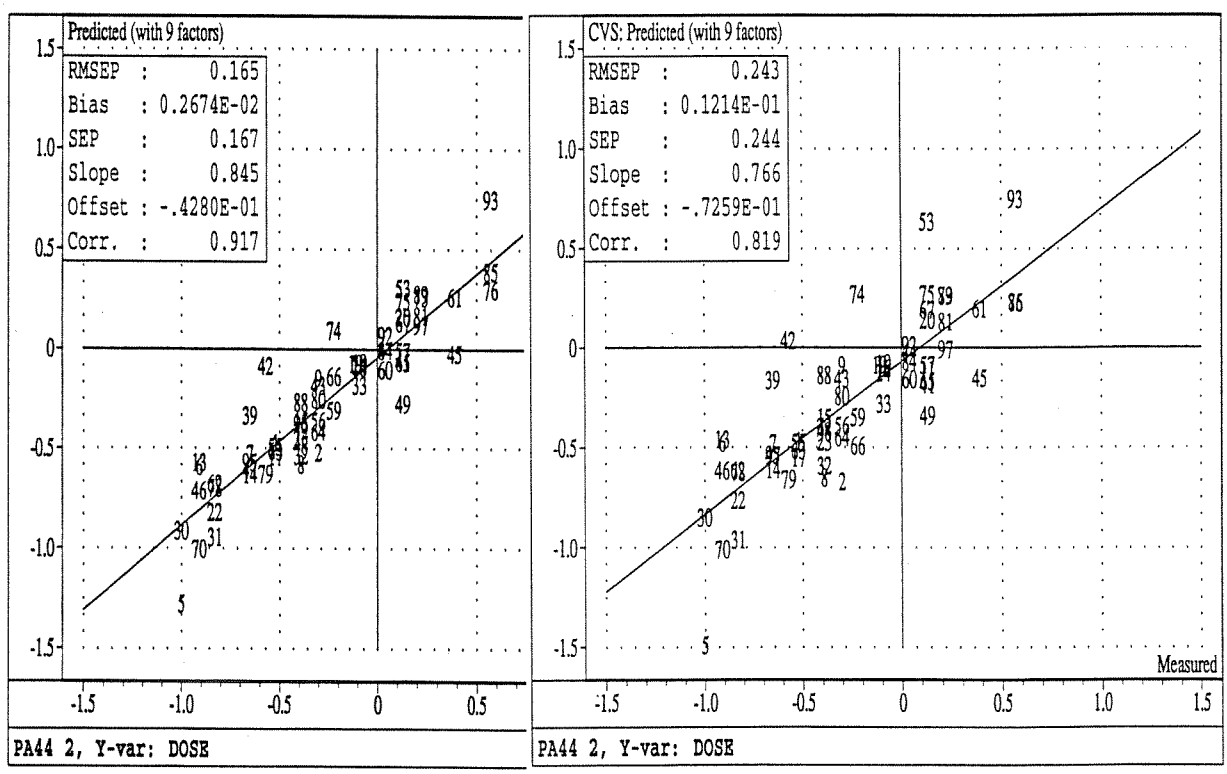


Figure 5. Predicted vs. measured values in the laboratory scale model with all parameters. (a) calibration model and (b) cross validation model. Values are given in coded dosages just to illustrate the model validity.

The calibration model resulted a correlation coefficient of 0.92 while in the cross validation model it was equal to 0.82. The two models resulted in RMSEP of 0.17 and 0.24 for coded dosages, which are equal to 1.9 and 2.8 mg/l for calibration and cross validation models, respectively. The obtained deviation values seem to be acceptable for this unrefined model and for the illustration of the concept. These deviations are possible to reduce considerably, when the wastewater variations are restricted (e.g. from one treatment plant) and with a larger test set.

Practically, using this model one can predict the necessary coagulant dosage for given influent and effluent data. The effluent data could be considered as given always, since that is equal to the

treatment requirement. Thus, the minimum dosage calculated using the model for any influent parameter set and the treatment requirement is the optimum coagulant dosage, and should be used for the steering of the dosing pump.

The model requires the definition of influent quality using 6 parameters. In practice, some of these parameters are complicated to monitor on-line, and the instrument costs will be unbearable to several medium and small size treatment plants. The multivariate calibration methods give us the possibility to calibrate models with less number of parameters for describing the effluent, even with only one parameter. However, this reduction in the number of parameters will result in the increase of uncertainty in the effluent description, which will reduce the model quality. For an example, the model may be simplified to $D = f(X_{in}, X_{out})$, where X_{in} = turbidity or flow (excluding phosphates, pH, alkalinity, conductivity and COD). Such a simplification will result in an empirical model that is similar to many existing steering strategies, which is inefficient as discussed earlier. Therefore, one has to evaluate the simplification level considering both the model accuracy and the investments on instruments.

In the next example, we have evaluated the effect on efficiency when a model is simplified by excluding only COD and phosphate measurements in the influent. X_{in}= turbidity, pH, alkalinity and conductivity. The results are given in Fig. 6.

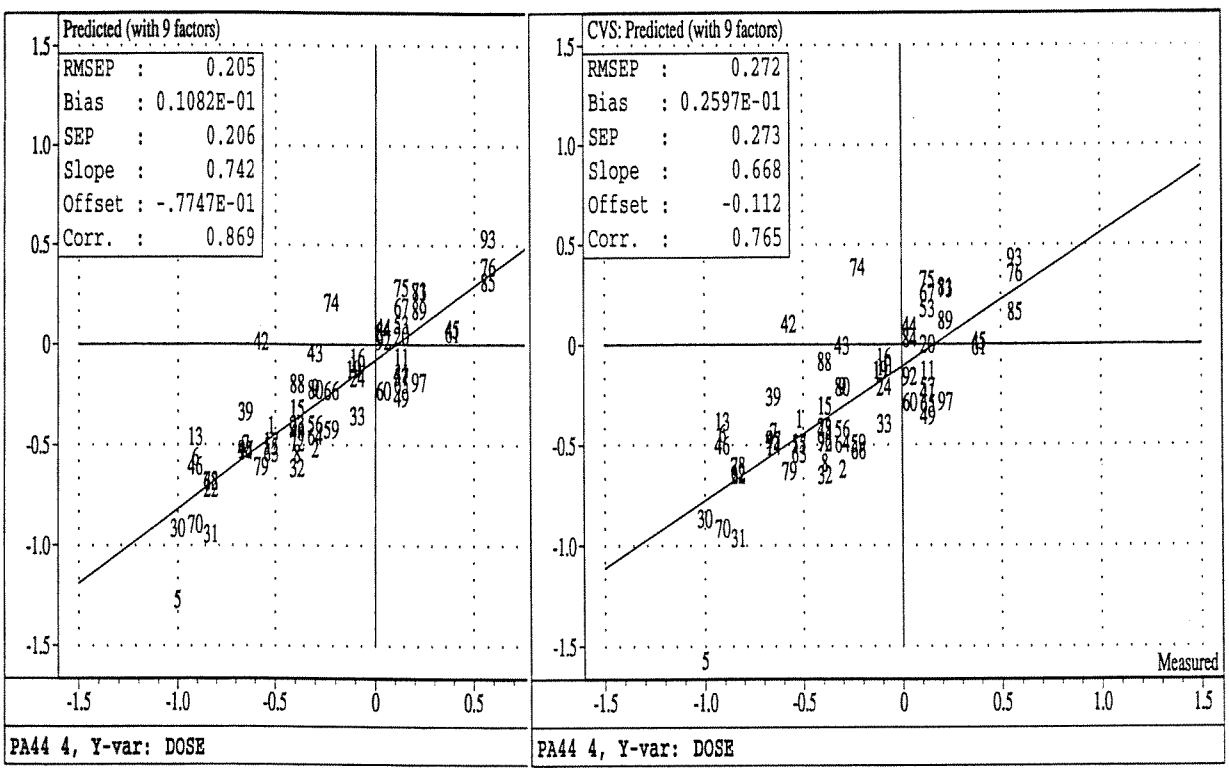


Figure 6. Predicted vs. measured values in the laboratory scale model excluding COD and phosphates as influent parameters. (a) calibration model and (b) cross validation model. Values are given in coded dosages just to illustrate the model validity.

The calibration and cross validation model results indicate about 5% lower correlation coefficients compared with the previous model (Fig. 5). This has cause an increase in the RMSEP of about 0.45 and 0.3 mg-Al/l in calibration and cross validation models, respectively.

An attempt to construct a model with X_{in} = Turbidity only indicate a 13-20% lower correlation coefficients and about 1 mg-Al/l increase in the RMSEP, compared to the initial model. This illustrates the inefficiency of steering systems only based on single parameter, which are widely used in practice today.

The pilot scale experiments at Lillestrøm and Lillehammer treatment plants resulted in RMSEP of 0.23 and 0.52 mg-Al/l with models where X_{in} = turbidity, pH, conductivity, ortho-phosphates and COD. This has confirmed the possibility to obtain more accurate models with wastewater from one treatment plant.

The correlation coefficients of models with very few (one or two) parameters as influent describes have found to be dramatically reducing when the effluent description is also reduced to one or two parameters (Ratnaweera et. al., 1994). The tendency of the well-defined effluent characteristics to indirectly define also the influent characteristics is suggested as a possible reason for this. This effect is negligible when the influent is well described and is increasing
significantly with the reduction in the number of parameters describing influent. Thus, the simple coagulant dosing control strategies based on a single influent parameter as in practice today ($D = f(flow_{in}, turbidity_{out})$) are found to give even poorer efficiencies, compared with the above discussed $D = f(turbidity_{in}, X_{out})$.

However, in practice, it is not possible to measure all the required influent parameters on-line. That will be an expensive solution, if not impossible. Now we have the choice to reduce the number of parameters used for the description of influent quality. However, we should be careful here so that each influent sample could be uniquely identified using the selected amount of parameters. Table 1 illustrates the calibration and cross validation values for different models with variable parameters in the influent description.

Table 2. Variation of calibration and cross validation parameters upon the reduction of influent quality parameters in laboratory-scale experiments. (OP, COD, TU, CO, PH, ALK are abbreviated for Otho phosphates, COD, turbidity, conductivity, pH and alkalinity of influent, respectively).

No	Model	Calibration		Cross validation	
		corr.	RMSEP	corr.	RMSEP
A_1	All influent and effluent parameters	0.92	0.17	0.82	0.24
B_1	As "A_1, excluding OPi and CODi	0.87	0.21	0.77	0.27
C_1	As "B_1", excluding TUi	0.85	0.22	0.75	0.28
D_1	As "B_1", excluding COi, PHi and ALKi	0.79	0.26	0.68	0.31

The reduction of the model prediction efficiency with the decrease in the number of parameters describing influent quality is well illustrated in Table 2. The reduction in model evaluation parameters, however, does not indicate the impossibility to use models with less parameters describing influent quality. It illustrates the increase in the error margin in required dosage prediction, which will in practice normally require a similar overdose to ensure the required effluent quality. Thus, the poorer the influent is described, the higher the error of prediction and consequently the higher the wastage of coagulants and the higher the other adverse effects. However, in this way, each plant can select its own level of the model considering the available instruments and expected savings contra new investments on instruments.

5.2 Pilot scale experiments

The pilot experiments conducted with municipal wastewater resulted in a RMSEP of 0.52 mg-Al/l and a correlation coefficient of 0.92 for the preliminary model based on the structure similar to model A_1 as above, but excluding ALKi and COo. These results again indicate the possibility of the concept realisation. The relatively high error in the model in comparison to traditional mathematical models in other processes is partially caused by experimental errors.

The observations from the full-scale experiments were modelled using a different approach. The model structure was similar to:

$$\text{Dosage} = f_2(\text{Q, SED, T, TUi, OPi, PHi, COi, TUe, PHe, COe})$$

where Q is flow; SED is sedimentation time, T is temperature TU is turbidity, OP is Ortho-phosphate, PH is pH, CO is conductivity, COD is biochemical oxygen demand, ALK is alkalinity and index "i" and "o" represent influent and effluent parameters, respectively. Figure 7 illustrates the model parameters.

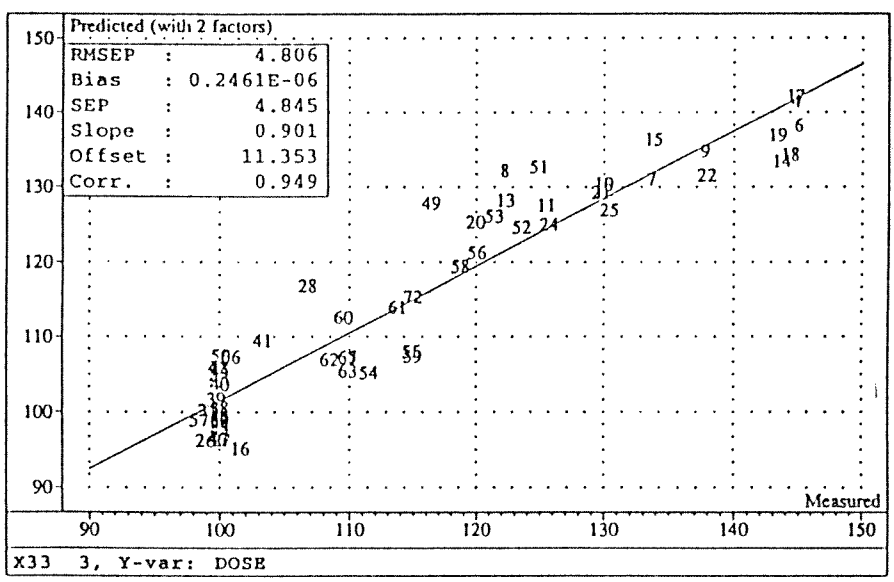


Figure 7. Predicted vs. measured values (coded dosages) in the pilot-scale model with all measured parameters.

The results indicate the possibility of the model to predict the dosage with an error of ± 4.8 units (± 0.44 mg-Al/l), and has a correlation coefficient of 0.95. Due to some practical reasons an error has occurred in the detection of the influent and effluent qualities from exactly the same wastewater portion. The maximum possible displacement is 30 minutes, and by using hourly average values we have minimised the possible error. However, this error seem to influence the model sensitivity. Our current studies are conducting without such errors and with the averages of 10 min data registration, which is expected to considerably increase the model efficiency.

We have conducted further analysis on the pilot-scale data, and the calibration and CVS parameters are presented in Table 3.

Table 3. Variation of calibration and cross validation parameters upon the reduction of influent quality parameters in full-scale experiments.

No	Model	Calibration		Cross validation	
		corr.	RMSEP	corr.	RMSEP
A_2	All influent and effluent parameters	0.95	4.8	0.93	5.8
B_2	As "A_2 excluding OPi	0.94	5.2	0.92	6.0
C_2	As "B_2", excluding TUi	0.93	5.6	0.91	6.4
D_2	As "B_2", excluding COi, PHi, T, SED, Q	0.92	6.0	0.89	7.1
E_2	As "B_2", excluding COi, PHi, T, SED, TUi	0.90	6.6	0.87	7.4

The results can be analysed similarly to table 2. The small differences in the model parameters with variable influent quality descriptions seem to be surprising at first sight. The information from each available parameter is used to construct the model. When we have only one or two parameters describing the influent quality, and a complete description of the effluent quality, the model may indirectly describe the influent quality to a certain degree by the effluent parameters. This may be the reason why model E_2, which is Dose = f_2(Q, effluent parameters), results in high apparent correlation coefficients.

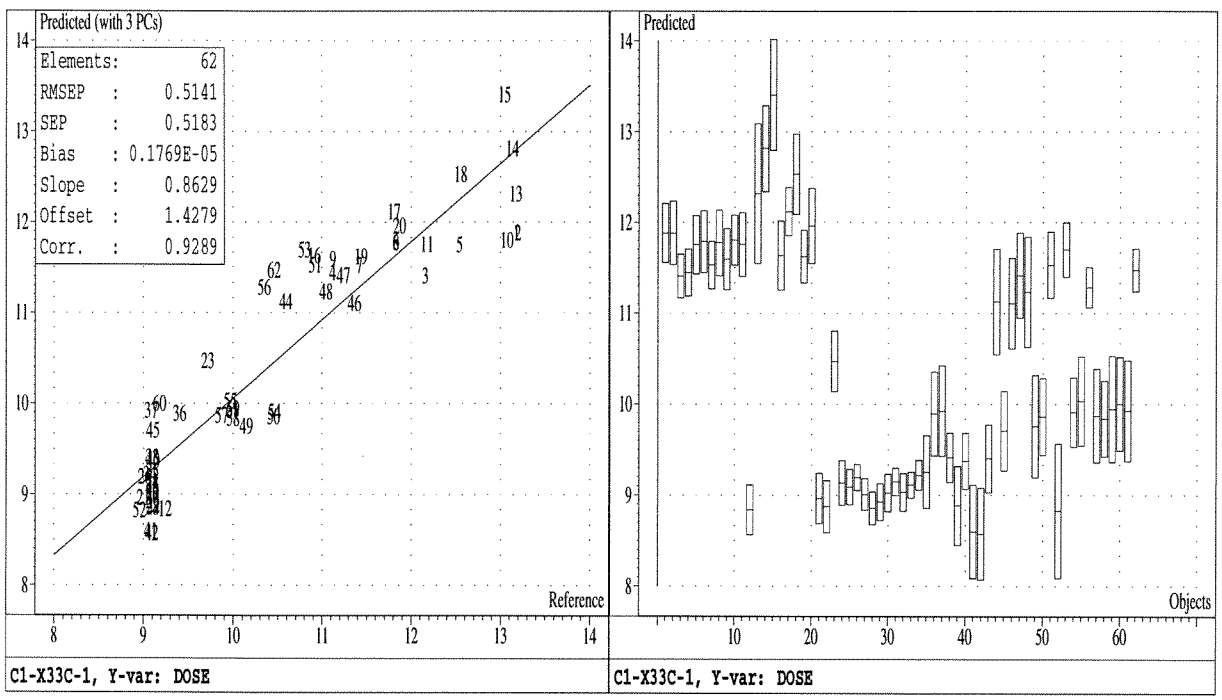


Figure 8. *Predicted vs. measured values (coded dosages) in the pilot-scale model with all influent parameters and one (turbidity) effluent parameter. left: correlation between predicted and measured dosages; right: prediction error with respective 95% confidence intervals.*

In order to avoid such overfitting phenomena, we have proposed another model structure, which avoids such unfavourable indirect evaluations.

Dosage = f_3(Q, SED, T, TUi, OPi, PHi, COi, TUe)
Dosage = f_3(Q, SED, T, TUi, OPi, PHi, COi, PHe)
Dosage = f_3(Q, SED, T, TUi, OPi, PHi, COi, COe)

The model coefficients for these models gave much more realistic values. The coefficients for the models with TUo as the only effluent parameter are illustrated in Fig. 8 and are also given in Table 4.

Table 4. Variation of calibration and cross validation parameters upon the reduction of influent quality parameters in full-scale experiments. Effluent quality is described using only TUo.

No	Model	Calibration		Cross validation	
		corr.	RMSEP	corr.	RMSEP
A_3	All influent and effluent parameters	0.93	5.7	0.90	6.7
B_3	As "A_3", excluding OPi	0.91	6.2	0.87	7.5
C_3	As "B_3", excluding TUi	0.90	6.5	0.86	7.8
D_3	As "B_3", excluding COi, PHi, T, SED, Q	0.65	11.6	0.61	12.1
E_3	As "B_3", excluding COi, PHi, T, SED, TUi	0.62	12.0	0.58	12.4

Both models D_3 and E_3 resulted in poor correlation which indicated the errors possible to cause with coagulant dosing controls using such applications.

Model D_3: Dosage = f_3(TUi,TUe)
Model E_3: Dosage = f_3(Q,TUe)

One of the most common coagulant dosing control methods is similar to the model E_3 (dosing of coagulants proportional to flow in order to reduce effluent turbidity), and the model results are illustrated in Fig. 9. The advantage of a proper dosing control system is clear, when comparing this model (E_3) with a model like A_3, B_3 or C_3.

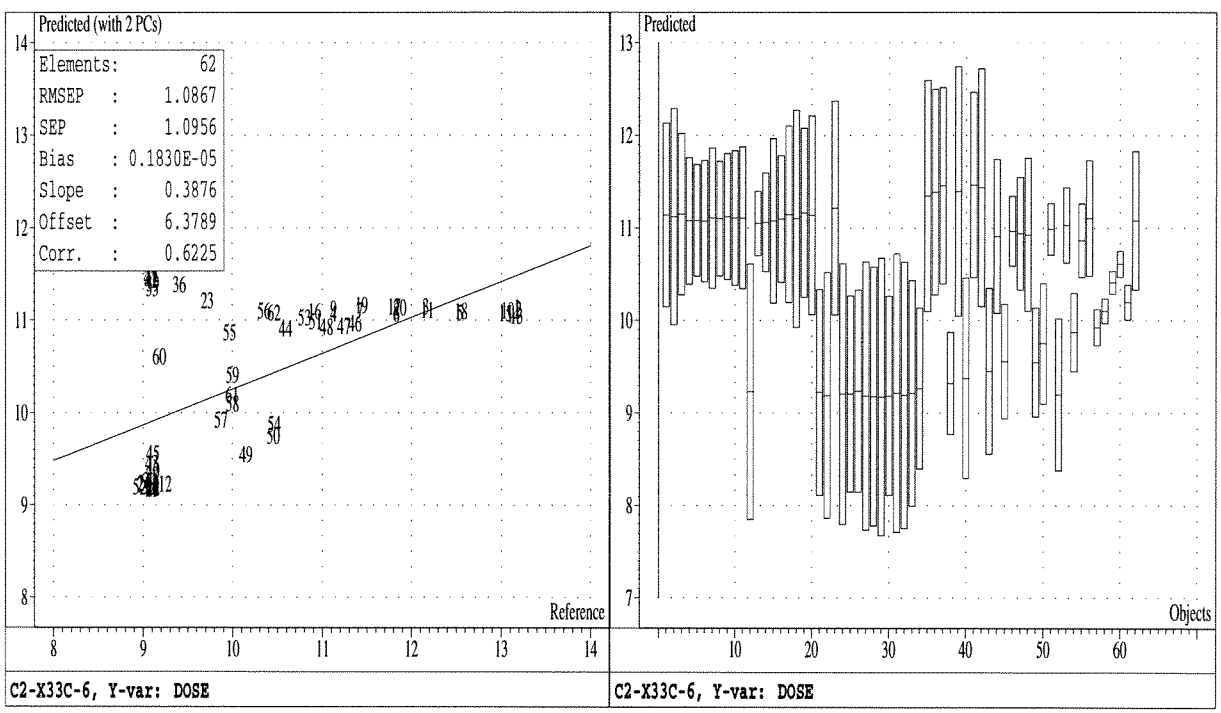


Figure 9. *Predicted vs. measured values (coded dosages) in the pilot-scale model with flow as the only influent parameters and one (turbidity) effluent parameter. left: correlation between predicted and measured dosages; right: prediction error with respective 95% confidence intervals. Note the differences in the error bars between Figs. 8 and 9.*

Models A_3, B_3, and C_3 seem to have a good description of the influent. And it is the influent quality which influences the coagulant requirement most (Ratnaweera, 1991).

None of these model structures are optimised yet and therefore, we may obtain even better models in future. Further, the optimisation of the coagulation process it self and the upgrading of the water quality data monitoring system which is the base for model construction, will indeed improve the models.

Due to the specific nature of each treatment plant's mixing, flocculation and sedimentation facilities, it will be necessary to make calibration models for each of them for the optimal use.

5.3 Full scale experiments

In full scale experiments, it was anticipated a 10% saving of coagulants at small WWTP and a 4% saving at medium/large scale WWTP while resulting in similar or better treatment efficiencies. These figures have been arbitrary defined for the system evaluation purpose.

The experience with various on-line instruments and their applications at wastewater treatment plants have slightly changed the concept. We have understood that even with fewer but robust on-line instrumentation we would be able to achieve substantial savings and such an approach will also increase the attractively of the concept. Therefore it was decided to evaluate fewer but more readily available on-line instruments.

The models were constructed using $D = f(X_{in}, X_{out})$, where X_{out} was limited to pH. The reason for excluding other effluent parameters is that only pH and conductivity reacts instantly to the dosage while other parameters like effluent turbidity takes 2- 4 hours to measure. However, the other effluent parameters were also indirectly considered in the model construction as we used only data series with satisfactory effluent results.

5.3.1 Bårlidalen WWTP

Bårlidalen WWTP has earlier evaluated to have a coagulant dosing dependent on the time of the day and the flow. This was however not adopted in practice due to the poor output during experiments. Experiments were conducted in three phases:

- passive data accumulation for preliminary model design
- data accumulation and active dosing control using a simplified algorithm
- data accumulation and active dosing control with an upgraded algorithm.

During the second experimental period a model based on flow and turbidity was used. However, upper and lower pH values were introduced and the dosing beyond these limits were accelerated or reduced as necessary, to keep the coagulated water pH within this range.

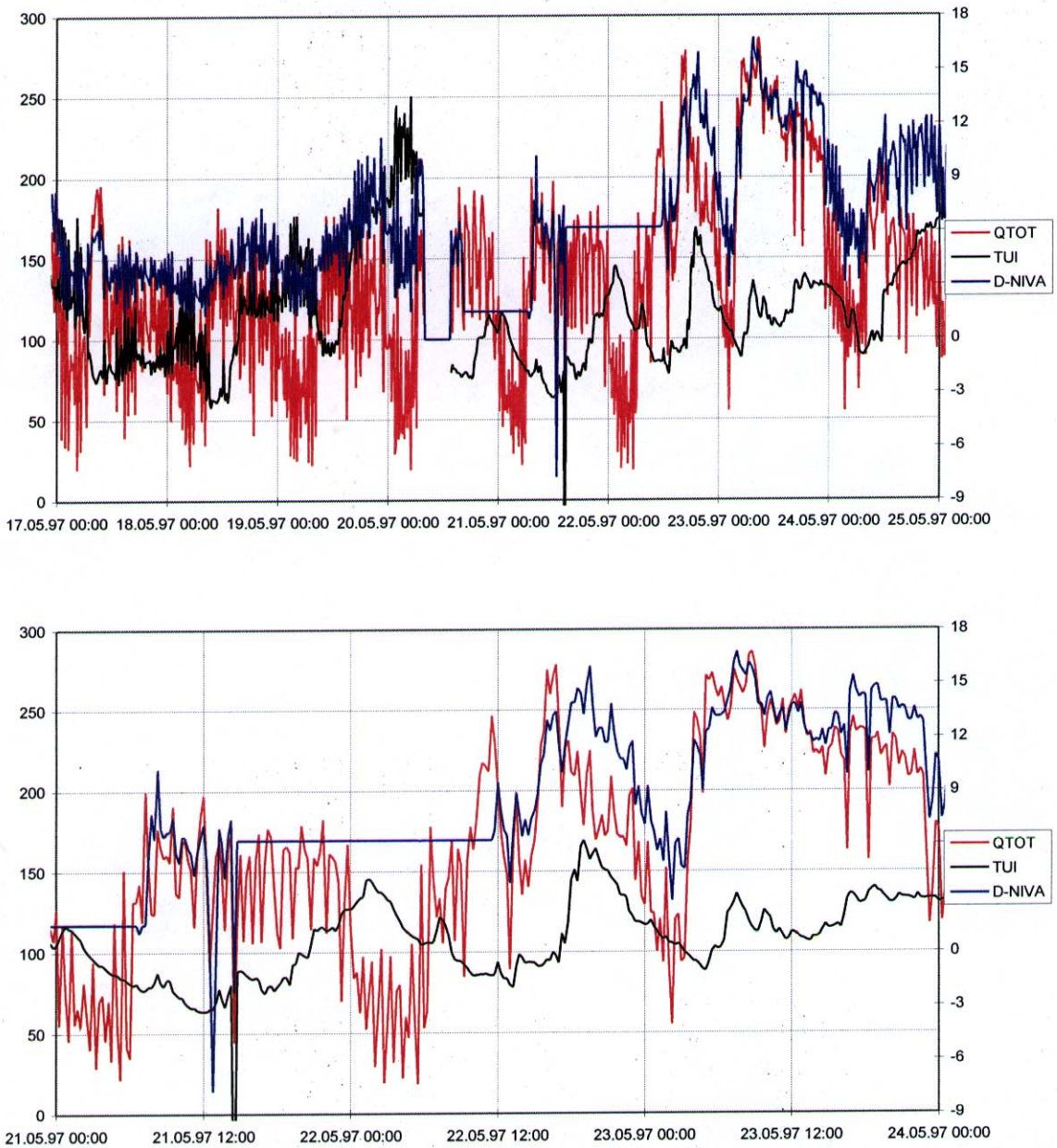


Figure 10. *Variation of influent flow, influent turbidity and dosing of coagulants using the model. The traditional dosing at the plant was set at a constant value of 10 kg/h. The upper figure indicates the results for 10 days and the lower figure shows a more detailed variation during a 3 days period. (left axis: QTOT= influent flow, m^3/h, TUI= influent turbidity, NTU; right axis: D-NIVA= Experimental dosing, kg-AVR/h).*

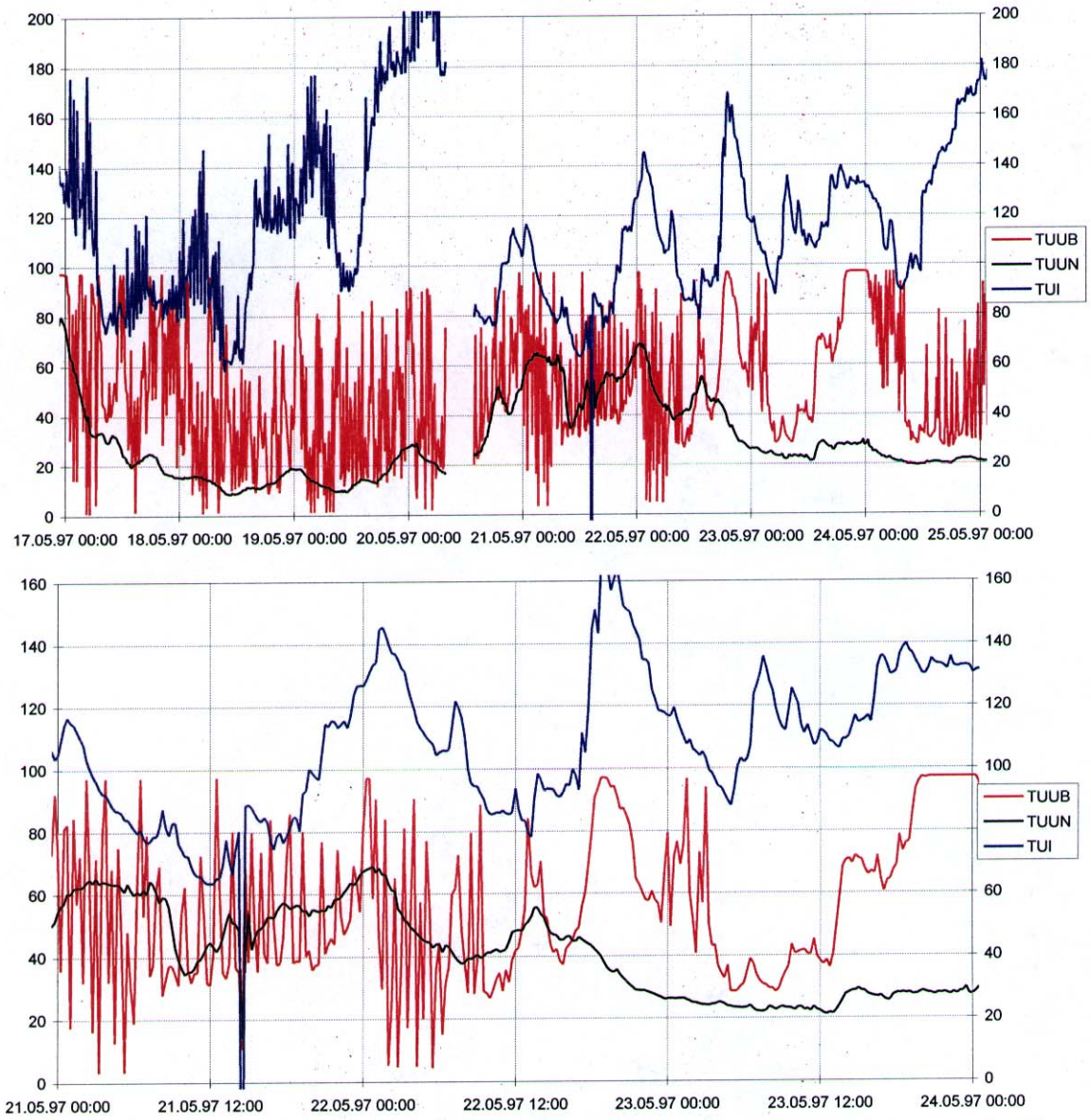


Figure 9. *Variation of influent turbidity and the effluent turbidity in the two lines (experimental and traditional). The traditional dosing at the plant was set at a constant value of 10 kg/h, while the experimental line dosing was based on a model D=f(Influent turbidity, flow). The upper figure indicates the results for 10 days and the lower figure shows a more detailed variation during a 3 days period. (left axis: TUUB, TUUN=effluent turbidity at traditional and experimental lines, respectively, right axis: TUI= Influent turbidity, NTU).*

The original dosing was kept at 10 kg/h while the experimental dosing vary with the flow and turbidity. The saving of coagulants during the last two days was an average of 8.8% even with a period of considerably high dosing compared to original dosing. This is a remarkable result.

During the final experimental period the following model was used:

Dose = a_1TUI+a_2Q+a_3Q.TUI+a_4Q.LEI+a_5Q.PHU+a_6
where TUI is influent turbidity, Q is flow, LEI is influent conductivity and PHU is pH after coagulant addition.

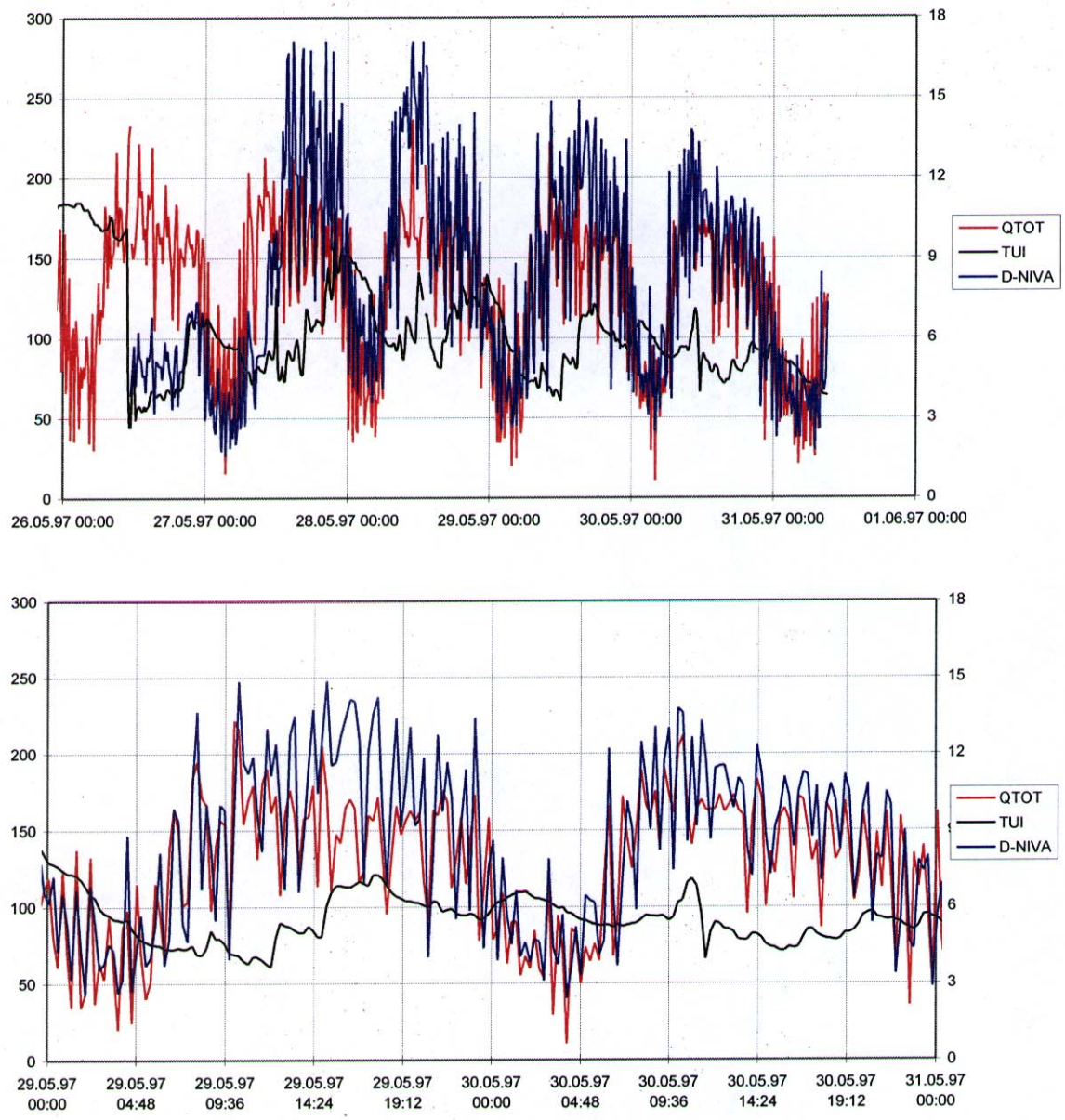


Figure 10. *Variation of influent flow, influent turbidity and dosing of coagulants using the model. The traditional dosing at the plant was set at a constant value of 10 kg/h. The upper figure indicates the results for 10 days and the lower figure shows a more detailed variation during a 3 days period. (left axis: QTOT=influent flow, m^3/h, TUI= influent turbidity, NTU; right axis: D-NIVA= Experimental dosing, kg-AVR/h).*

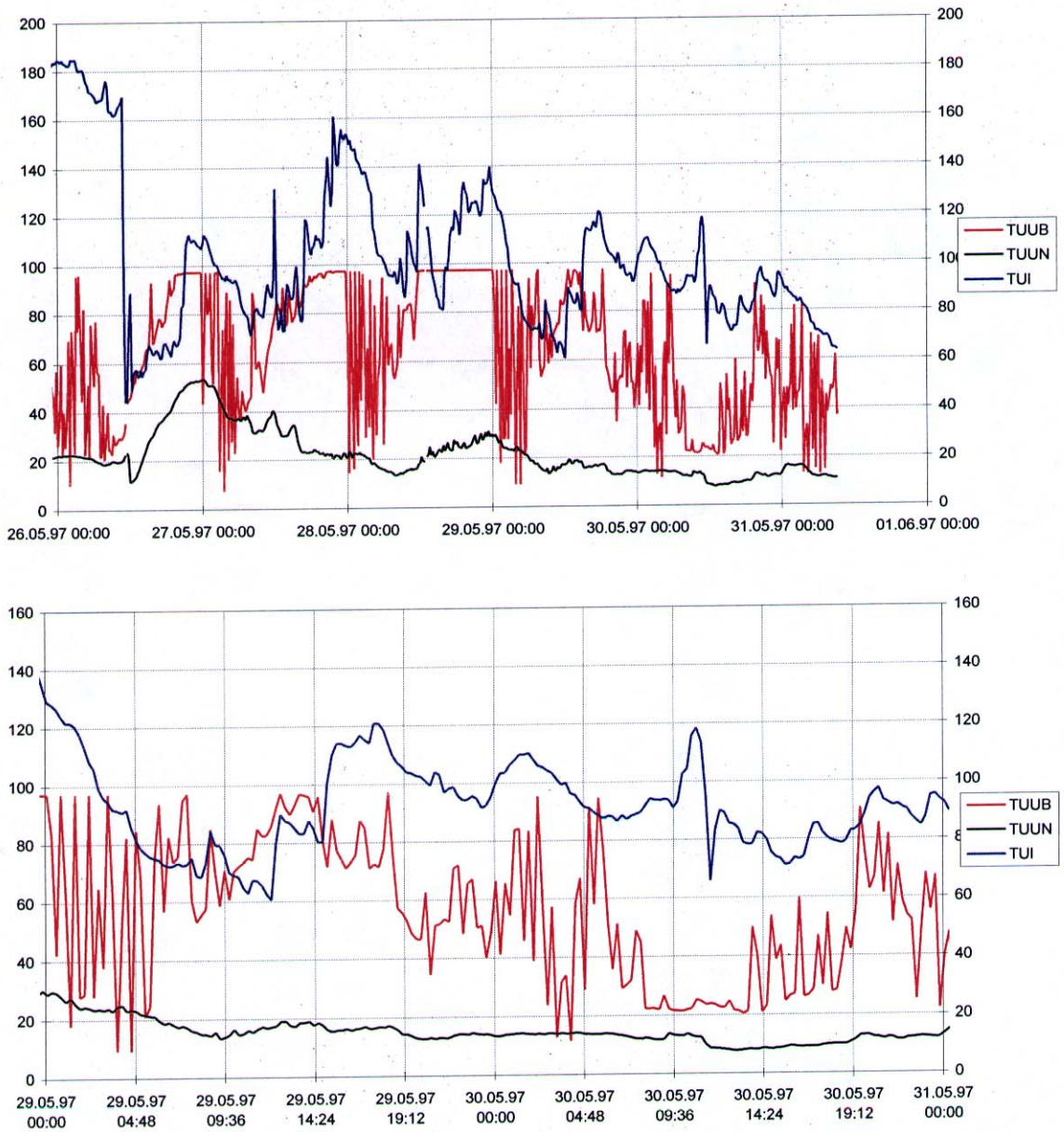


Figure 13. *Variation of influent turbidity and the effluent turbidity in the two lines (experimental and traditional). The traditional dosing at the plant was set at a constant value of 10 kg/h, while the experimental line dosing was based on a model D=f(Influent turbidity, flow, conductivity and pHe). The upper figure indicates the results for 10 days and the lower figure shows a more detailed variation during a 3 days period. (left axis: TUUB, TUUN=effluent turbidity at traditional and experimental lines, respectively, right axis: TUI= Influent turbidity, NTU).*

As it seen from the Figs. 12 and 13 the resulting turbidity in the experimental line using the final model was considerably better than the traditional dosing line. The chemical dosage savings varied between 16%-27% for the period shown in the figure. We have also tested the possibility of reducing even more, up to 40%, but then the treatment results were negatively affected.

5.3.2 Tønsberg WWTP (TAU)

TAU has a coagulant dosing concept based on flow proportional constants for each hour of the day with a pH overriding function. The flow proportional constants and the pH set points are changed according to the treatment results and past experiences by the senior plant personnel.

Our experiments were to be conducted in three phases:

- passive data accumulation for preliminary model design
- data accumulation and active dosing control using a simplified algorithm
- active dosing control with an upgraded algorithm (recommended for further studies)

Algorithms used in this section are similar to the ones used at the Bårlidalen WWTP.

During the first active dosing period, a model based on flow and turbidity was used. Upper and lower pH values were introduced and the dosing beyond these limits were accelerated or reduced as necessary, to keep the coagulated water pH within this range. However, the upper and lower dosing limitations were set in units of "l/h", rather than "l/m^3" which would have been a better solution.

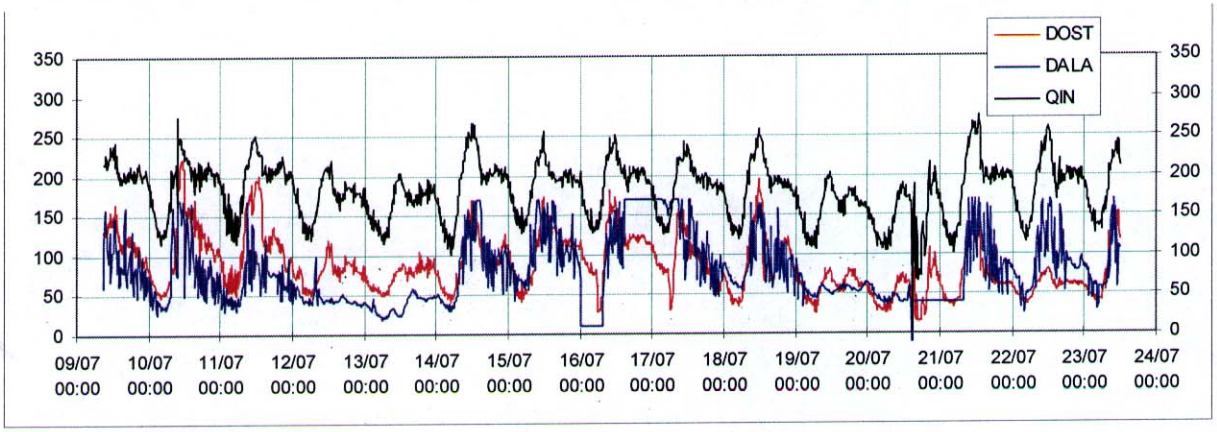


Figure 14. *Variation of influent flow (QIN, l/sec), traditional dosing (DOST, l/h) and experimental dosing (DALA, l/h) at TAU.*

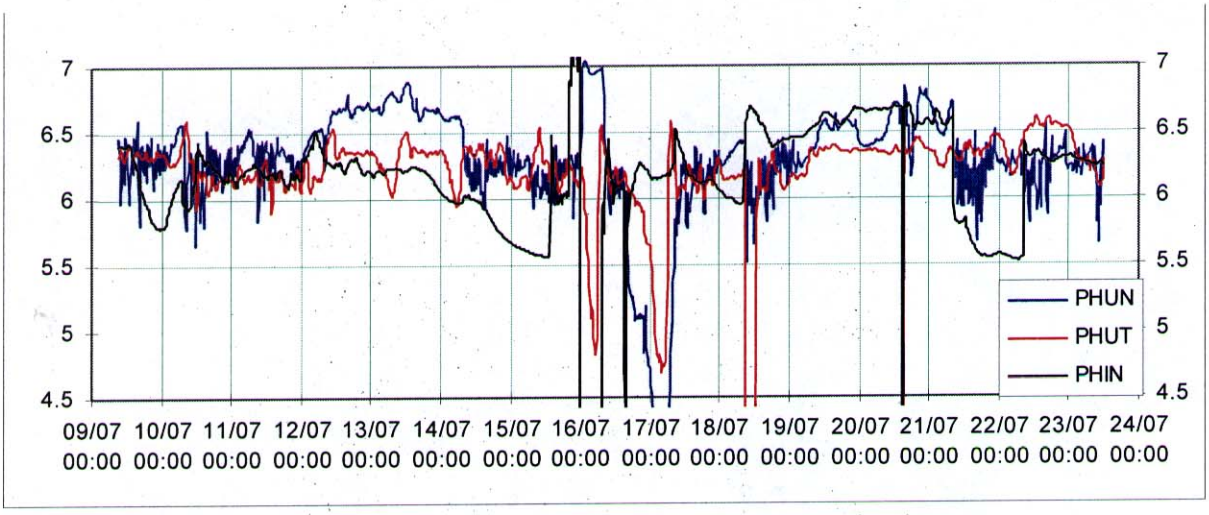


Figure 15. Variation of pH at TAU: Influent pH (PHIN), effluent in the traditional line (PHUT) and experimental line (PHUN). Note that the pH electrodes were out of order during several occasions. Compare also the high pH caused by too low dosing (and vice versa) in periods according to Fig. 14.

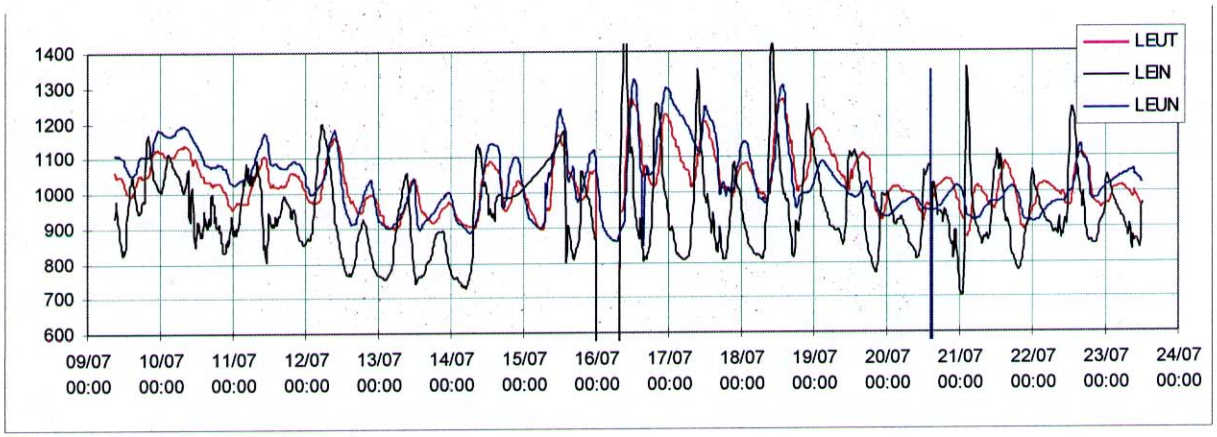


Figure 16. Variation of conductivity during the experimental period at TAU. Influent conductivity (LEIN), conductivity after dosing of coagulants at traditional (LEUT) and experimental lines (LEUN), all in µS/m.

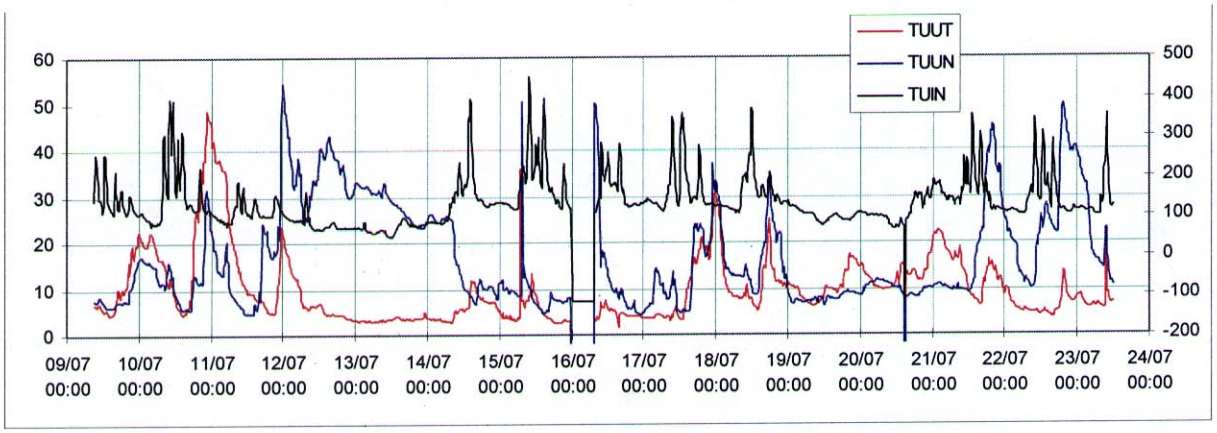


Figure 17. Resulting turbidity in the traditional (TUUT) and experimental (TUUN) lines are given in NTU referring to the left axis. The influent turbidity (TUIN) refers to the right axis.

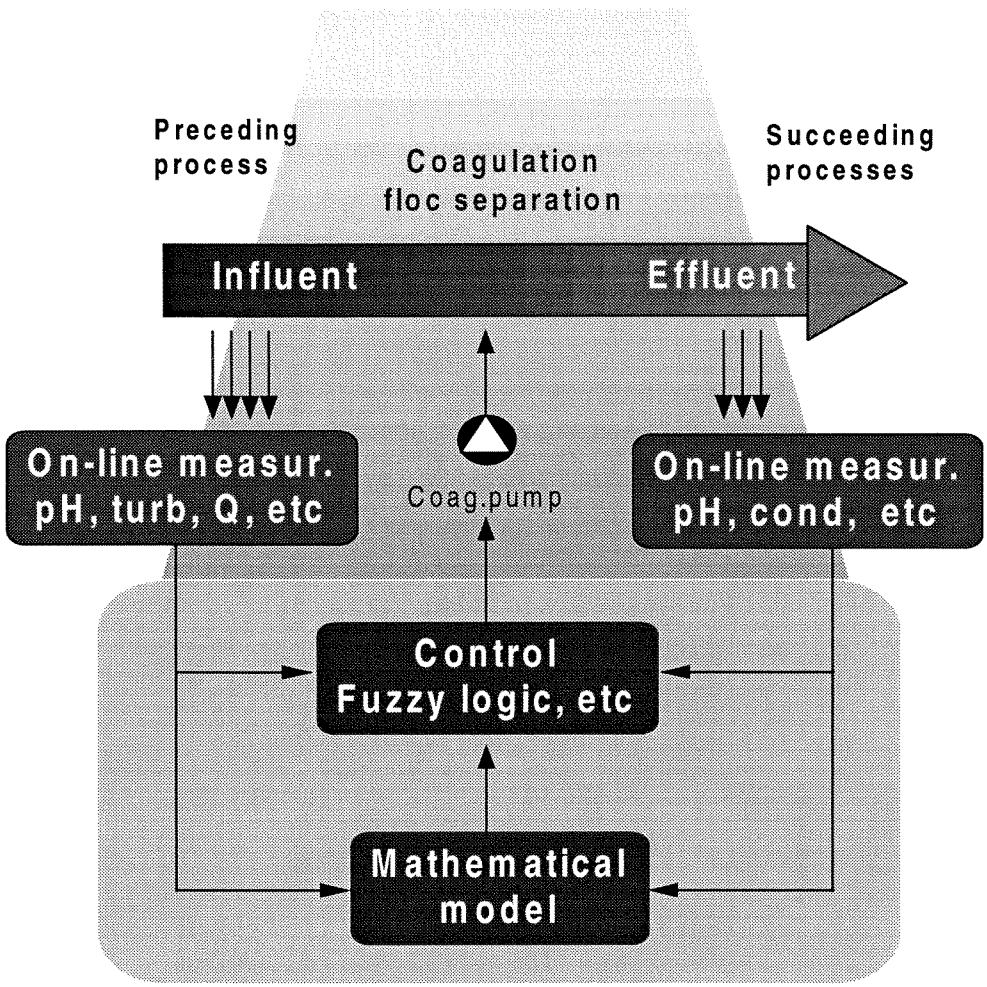
Table 5. Summary of coagulant consumption during the first active dosing period.

Date & Time	Traditional consumption, l/day	Experimental consumption, l/day
08/07/97 07:30	2096	2280
09/07/97 07:30	2078	2180
10/07/97 07:30	1900	1896
11/07/97 07:30	2128	1939
12/07/97 07:30	1776	1217
13/07/97 07:30	1776	1217
14/07/97 07:30	1776	1217
15/07/97 07:30	1806	2426
16/07/97 07:30	2124	2123
17/07/97 07:30	2184	3581
18/07/97 07:30	1623	2434
19/07/97 07:30	1484	1468
20/07/97 07:30	1484	1468
21/07/97 07:30	1484	1468

Considering the Figs. 14-17 and the Table 5 it is clear that a dosing concept like Dose = f(flow, turbidity) has not given any advantages compared with the existing dosing strategy at TAU. However, such a concept was able to give over 8% saving at Bårlidalen WWTP. This indicates that TAU's existing dosing concept is far better than that of Bårlidalen WWTP. However, the effluent turbidities vary significantly at TAU and there are periods where the experimental dosing has functioned equally good as the TAU's traditional method, while the experimental dosage was lower. These aspects should be studied further and anticipated to be resulting savings when a more comprehensive model will be used. This will be studied in a follow-up project.

6. Conclusions

- The existing coagulant strategies summarised and related disadvantages are described
- A concept for an optimal coagulant strategy is presented and demonstrated in laboratory-, pilot- and full-scale experiments.
- A dosing concept based only on one or two influent parameters like flow and turbidity are not efficient, although they could be interesting for small WWTP. At Bårlidalen WWTP, such a concept could save over 8% chemical costs. At large treatment plants these resulted in no significant improvement.
- Dosing concepts based on more influent parameters enabling a comprehensive description of the influent are needed for larger WWTP. At small treatment plants these may result in upto 25% savings of coagulants, while 4-10% saving are expected at larger WWTP are expected. The basis for a such a dosing model for a large WWTP is constructed and is recommended to study in a full scale experiment.
- The optimal dosing concept presented in this report could be schematically presented as following (a control function for the estimated optimal dosage should be incorporated in a commercial application as suggested to realise via an another model or fuzzy logic control):



7. References

- Following is a list of relevant literature (including the references to this report) which is useful for further studies.

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