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ANALYSIS OF OPERATIONAL DATA COLLECTED AT THE ESKILSTUNA WASTEWATER TREATMENT PLANT

D. Lumley P. Balmer

PUBLIKATION 3:83 FORSKNINGSRAPPORT

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ISSN 0280-4026

Keywords: process analysis, operational data, Eskilstuna, operational stability, data retrieval system evaluation.

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PREFACE

This is a report for the Sewage Works Evaluation Project (SWEP) run by the Swedish Water and Wastewater Works Association and the Swedish National Environmental Protection Board. The report will be published as a SWEP-report in the National Environmental Protection Board:s PM-series.

The financial support for this study from the SWEP-project is gratefully acknowledged.

Göteborg, April 1983

D Lumley P Balmér

SUMMARY

If wastewater treatment plant effluent variability should be modelled it is desirable to have relationships between process variables and performance. To be realistic such relationships should preferably be developed from full scale plant operation.

The Sewage Works Evaluation Project (SWEP) generates a large amount of data from a limited number of treatment plants. The intention of this study was to test the possibility to develop relationships for process performance from this data.

Several process relationships are described and nine are tested using data from the Eskilstuna sewage treatment plant.

In general the relationships found from the Eskilstuna data were very weak. It was disappointing that the available data appeared so uncorrelated even when applied to process relationships with well documented theoretical bases.

The reasons for the weak correlations are discussed and it is proposed that further analysis of the Eskilstuna data is more likely to succed with simpler models using major parameters as flow and temperature etc., than using refined statistical methods on more detailed models.

Experiences from this study indicates that the sampling program and its practical execution should be reexamined, and that the daily operations should be better documented in the daily log book. The Swedish Water and Air Pollution Research Institute´s (IVL) Fysik Kemi (FYKE) information handling system could be improved as it restricts the investigator to simpler statistical programs and is quite toilsome when larger, more complex models are tested.

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1. INTRODUCTION

When the performance of wastewater treatment plants is evaluated the performance is commonly expressed as some type of average concentration or massflow. This is not sufficient as it does not give any information on the variability of effluent quality. During the last decade it has been common to express treatment plant performance by a time distribution e.g. frequency of effluent quality vs time. The performance of many treatment plants is modelled by log-normal distributions of effluent quality vs time.

This way of expressing effluent variability is satisfactory for each individual treatment plant in general terms. It does not, however, explain the variability, the causes of which are numerous. An attempt to systemize the causes of effluent variability has been made by Balmér (1981).

Environmental administrations require data on average effluent quality and effluent variability for the large number of wastewater treatment process alternatives that are available.

In principle there are two different approaches to collecting this data.

One approach is to collect effluent variability data from a sufficient number of treatment plants with the process alternatives of interest. Then it will be possible to calculate some kind of average performance and average performance variability for each process alternative. This information may be of value for nation-wide policy decisions but will be of little value when process alternatives for the individual plant are discussed.

The other appproach is to develop a model for effluent variability. Such a model should probably contain a stochastic element and an element that expresses the performance of each treatment process as a function of process variables such as flow, wastewater temperature, etc. In such a model mechanical failures could be included, if such factors as "mean time between failures" and "mean time to repair" were known. These could, for example, be transformed to percent of time with a process out of operation or percent of time for remaining units operating in parallel under increased loading.

Information on process performance as a function of process variables could be sought after in the literature. Numerous controlled experiments have been performed at the laboratory and pilot plant scale. However, it is believed that it is impossible to create a model of effluent variability that accounts for all factors. Controlled experiments tend to eliminate uncontrolled variables and are thus believed to produce "too good" data.

From this point of view it would be desirable to collect data from full scale plants that make it possible to express performance as a function of process variables.

This approach is often difficult to apply as most treatment plants do not sufficiently document operating conditions and process performance. In the Sewage Works Evaluation Project (SWEP) a number of treatment plants are carefully monitored over a long time period. In addition the data is easily available on a computer retrieval system. It was hoped that the data collected in this project could make it possible to generate algorithms decribing process performance as a function of process variables.

The study documented in this report should be seen as a test on the possibility to use SWEP-data for such a purpose.

2. POSSIBLE RELATIONSHIPS

In this section possible relationships between process variables and process performance are presented and discussed. The basis of discussion is the "Standard Swedish treatment plant" consisting of presettling, activated sludge and post precipitation of phosphorus. The description of possible relationships is not complete. Those relationships which have been further investigated are referenced.

2.1 Influent Wastewater

The population in a catchment area is believed to generate a constant amount of pollutants per day. Some systematic deviations between different days of the week may exist. This implies that:

- Mass flow (concentration * flow) of influent waste water should be constant

- Concentration of influent wastewater is inversly proportional to wastewater flow

The assumptions above are simplifications as they assume that infiltration and inflow have neglible pollutant concentrations. This may not be true for some components in wastewater e.g. COD and nitrogen. In such cases (if the concentration of infiltrations and inflow pollutants is assumed constant) there should be a linear relationship between influent massflow and the infiltration and inflow (Section 3.2)

The flow to a treatment plant connected to a mainly separated sewer system is composed of:

1. "true" wastewater water consumption
2. infiltration of ground water
3. inflow and enhanced infiltration in connection with precipitation

Infiltration is believed to be dependant on the ground water table and it could be worthwhile to try to relate a ground water table model to infiltration. Seasonal variations exist.

Inflow and enhanced infiltration in connection with precipitation depend on such factors as rain duration, rain intensity and antecedent dry period. Also in this case there could be seasonal variations. This is tested in Section 3.1.

2.2 Presettling

The assumption of a constant production of pollutants makes it reasonable as an initial approach to also assume a constant distribution of settling velocities of wastewater particulates.

This implies that presettling performance should be a function of wastewater flow. As raw wastewater particulates have high settling velocities it could also be assumed that performance dependence on flow should be small as long as surface overflow rates are less than, say, 2 m/h (Section 3.3).

There are several complications. Particulates settle in the sewer collection system under low flow and are resuspended under high flow conditions. This means that particulate massflow to a plant may be governed by flow and the antecedent low flow period.

It could also be assumed that a large proportion of the resuspended particulates have high settling velocities.

Wastewater temperature influences water viscosity and thus settling velocity. It is easy to correct for this. Wastewater temperature may have other effects. The colloidial non-settable particulates in wastewater flocculate slowly and are transformed to settable particulates. This process is probably temperature dependant and should result in better summertime performance especially at low hydraulic loads.

Solids recirculation often complicates the evaluation of primary settling performance.

Instead of testing the above assumption as suspended solids or COD-removals one could look at the primary solids production. However, at most plants this is complicated by solids recirculation from subsequent treatment steps and from the sludge treatment operations.

2.3 Activated Sludge Treatment

Microbial kinetics is the natural starting point for any relationship between activated sludge performance and process variables.

From microbial kinetics we can conclude that there should be a relationship between the mean cell residence time (MCRT) and secondary effluent concentration of biodegradable components. The MCRT is the inverse of the specific growth rate. The growth rate is temperature dependant and any model must take this into account.

Data from existing plants has shown that effluent soluble BOD-concentration is generally below 10 mg/l. This indicates that soluble BOD is removed quickly from the liquid phase. Thus it is likely that the soluble BOD-concentration is virtually independant of the MCRT when MCRT´s exceed 2-3 days.

Growth rates for nitrogen oxidizing bacteria are considerably smaller.

Hence, a relation between the degree of oxidation of nitrogenous compounds and MCRT could be expected. (Section 3.5)
As the performance of all secondary treatment units is a combination of biological activity and separation efficiency all attempts to evaluate the "biological" performance must be based on the analysis of dissolved components.

The secondary effluent also contains non-biodegradable organics. The COD analysis is a parameter for both biodegradable and non-biodegradable organics. This is believed to be the main reason for the rather poor correlations between BOD and COD often presented.

The effluent COD is assumed to consist of one part that is non-biodegradable, i.e. a part of the influent organics that is believed to be a constant proportion of the influent organics. The other part of the effluent organics may be metabolites from the microbial degradation. This part is probably proportional to the amount of organics degraded - thus also roughly proportional to the influent organics and maybe also dependant on the MCRT (Section 3.6).

The total performance of an activated sludge process is to a large extent dependant on secondary settling. The secondary clarifier must separate the solids from the liquid phase but also concentrate the solids in order to maintain a desired mixed liquor concentration.

The thickening function can according to White (1976) be described by the flow rate, return sludge flow rate, sludge volume and sludge volume index (SSVI), (Section 3.4).

The relationship of separation of solids to conventional settling theory by a temperature corrected surface overflow rate can also be investigated.

It has also been proposed that secondary clarifier performance is related to the flow per unit width ($m^3/h \cdot m$).

Abwassertechnische Verein in Germany has proposed that the acceptable surface overflow rate for secondary clarifiers is a function of the mixed liquor sludge volume.

The above relationships are only valid for settleable solids. In activated sludge mixed liquor the settleable solids dominate but a small portion is non-settleable or have very low settling velocities. These solids appear as a type of background value and complicate the evaluation of secondary effluent suspended solids data. Various assumptions can be made. If it is assumed that the fine solids are generated from the coarse solids it could be further assumed that the generation rate is a function of the MCRT and temperature.

The thickening properties expressed by the sludge volume index are of importance. Many efforts have been made to relate SVI to process variables. Previous attempts indicate that it could be valuable to investigate the correlation of SVI or SSVI to the MCRT and degree of longitudinal dispersion in the aeration tanks.

2.4 Chemical Precipitation

In chemical precipitation soluble phosphates are precipitated. Particulates, coarse as well as colloidal, are enmeshed in the precipitate and removed at the same time.

Total phosphorus concentration in the effluent is thus a function of, primarily, the precipitation efficiency and secondarily, the efficiency of the separation unit and the concentration of phosporus in the precipitate (the flocs). It is assumed that all flocs are of homogeneous composition.

All soluble phosphorus in secondary effluent is inorganic. The tertiary effluent soluble phosphorus is a function of the precipitation pH and the molar ratio of precipitant and influent phosphate of the precipitation stage.

The effluent suspended solids (and also suspended phosphorus) are according to settling theory dependent on a temperature corrected surface overflow rate and floc settling properties.

Floc settling properties in their turn are believed to depend on pH, coagulant dose, enmeshed solids and flocculating conditions.

The effluent particulate phosphorous is also proportional to the phosphorus concentration of the flocs. This is proportional to precipitated and enmeshed phosphorus and inversely proportional to the sum of phosphate and hydroxide precipitates and enmeshed solids.

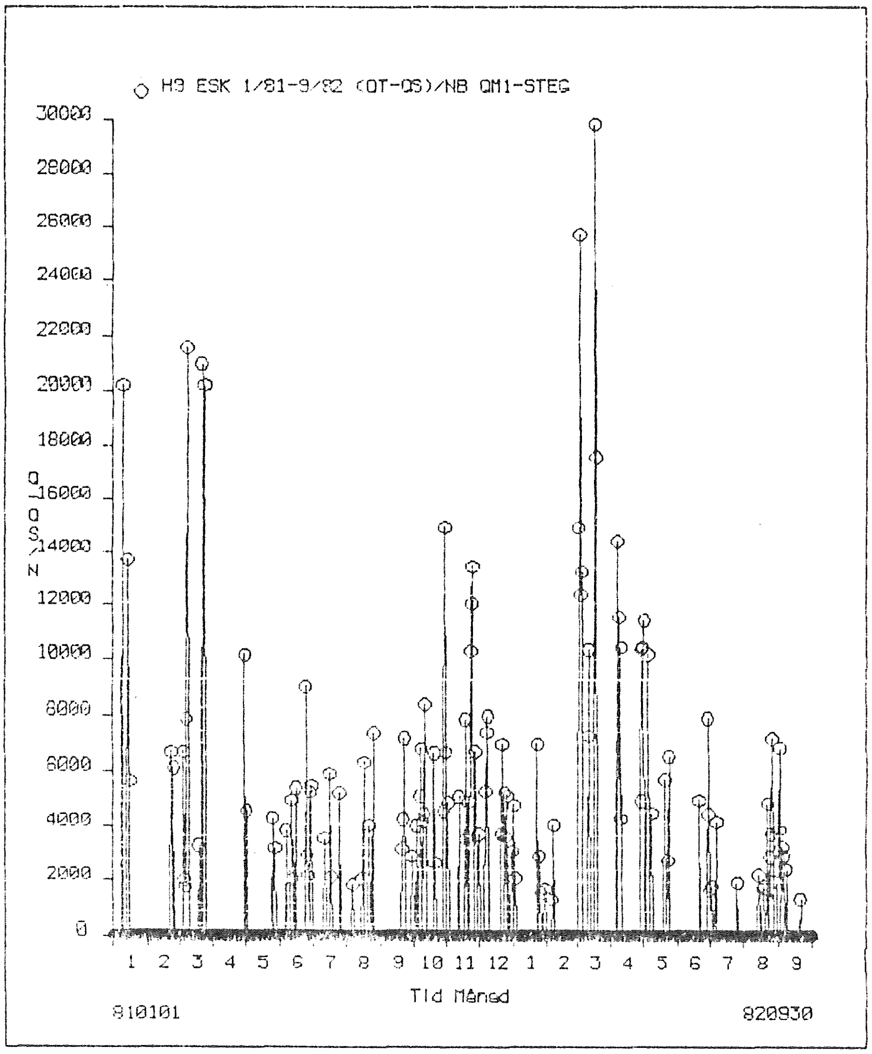
Influent alkalinity, pH, coagulant dose and effluent pH and alkalinity can be related by chemical equilibrium calculations. Thus alkalinity reduction and precipitation pH can be expressed as a function of the influent parameters or vice versa (Section 3.8 and 3.9).

The removal of particulate organics (and all other components in particulate form) in the precipitation stage can probably be calculated from the assumption that all particulates are enmeshed in the precipitate and that the degree of removal is then a function of effluent suspended solids to total precipitate including enmeshed solids.

When precipitate (sludge) from the precipitation stage is recirculated to preceeding stages some phosphorus removal is expected. It is reasonable to assume that this removal is proportional to the unused coagulant, that is, the dose expressed as (molar ratio - 1) (Section 3.7).

Figure 3.1 Infiltration vs Time

Infiltration expressed as (Q_{ink} - Q_s) in m^3/d per mm precipitation vs time for the period 810101 to 820930.



3.2 COD Loading

Influent COD-mass to a sewage treatment plant should consist of a relatively constant portion from domestic wastewaters (daily variations are probable). In addition there is a variable portion from infiltration waters. If the COD concentration of infiltration water is assumed constant, the following relationship should hold:

$$Q_{ink} * COD_{ink} = Q_s * COD_s + (Q_{ink}-Q_s)*COD_{INF}$$

where Q_{ink} = influent flow (m^3/d)
COD_{ink} = influent COD (kg/m^3)
Q_s = domestic wastewater flow assumed equal to water consumtion (m^3/d)
COD_s = COD of domestic wastewater (kg/m^3)
COD_{INF} = COD of infiltration water (kg/m^3)

Plotting ($Q_{ink} * COD_{ink}$) against ($Q_{ink} - Q_s$) should result in a linear relationship with slope COD_{INF} and intercept $Q_s * COD_s$, the domestic COD loading. With system overloading, the deviation may increase due to overflow bypassing.

Results

The data has been divided into two time groups, before and after June 1981 due to operational changes in sludge digester decanting. The pre-June ´81 period (Figure 3.2a) has a weak regression relationship with slope 0,257, intercept 6 381 and correlation 0,552. The later period (Figure 3.2b) has a still weaker regression relationship with slope 0,066, intercept 10 011 and correlation 0,227. An estimate of the COD loading from domestic wastewaters is

$$80\,000p * 150 \frac{g\ COD}{cap.day} = 12\,000\ kg/d.$$

The main cluster is also around this value.

Figure 3.2a COD-Loading in Infiltrate Water - Early Period

Influent COD loading in kg/d vs infiltrate flow in m^3/d for the period 810101 to 810630.

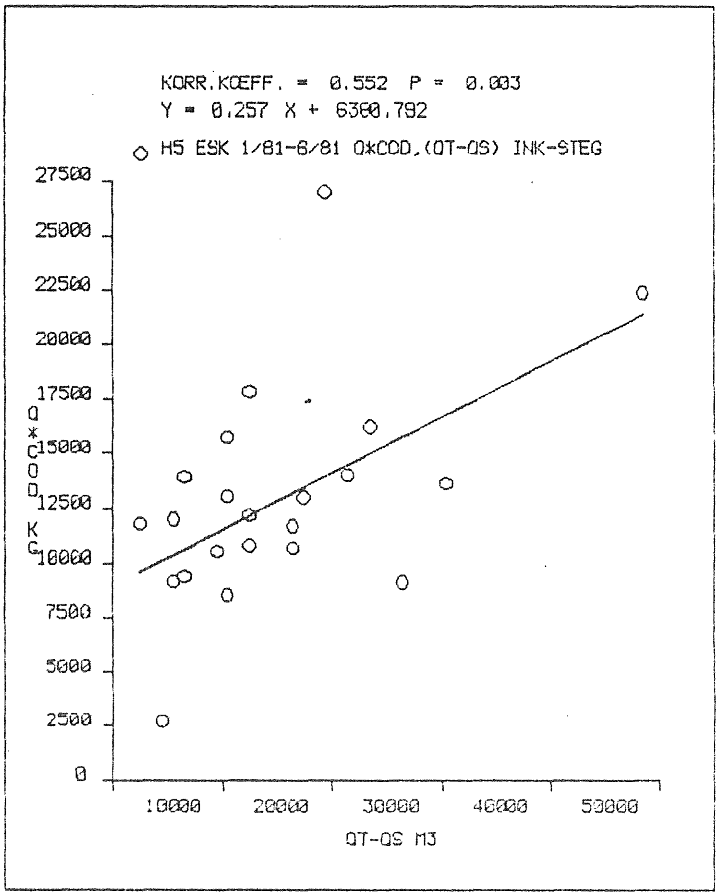
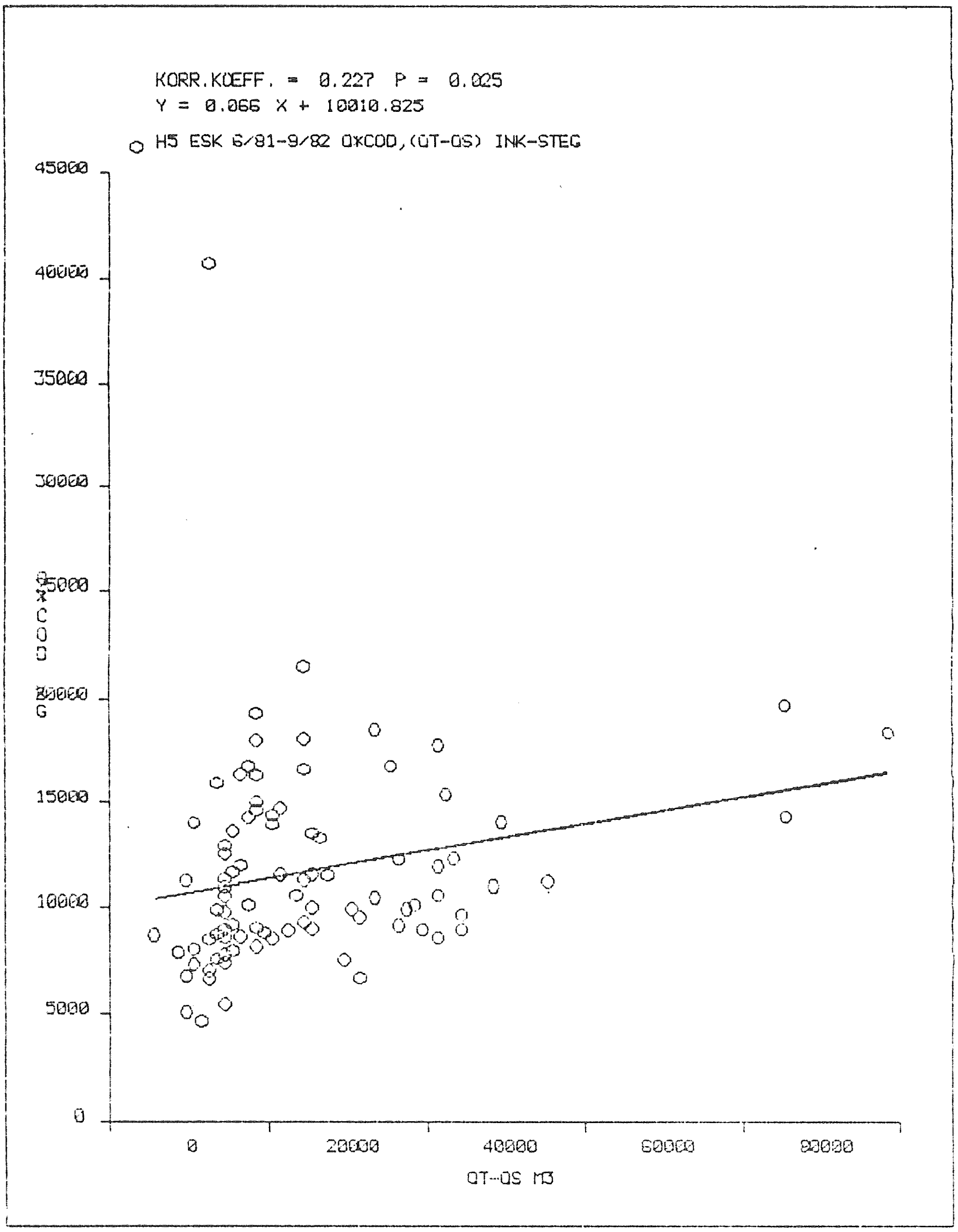


Figure 3.2b COD-Loading in Infiltrate Water - Later Period

Influent COD loading in kg/d vs infiltrate inflow in m^3/d for the period 810701 to 820930.



It is remarkable that the influent COD-load varies from 5 000 to 40 000 kg/d. Even with outliers eliminated the spread in influent loading is quite remarkable and should be further investigated.

3.3 Separation of Suspended Material in Primary Settlers

It is reasonable to assume that a relatively constant portion of the suspended solids in wastewater is settleable. Experience shows also that a major portion of settleable solids have high settling rates and thus that it is reasonable to assume that the influent flowrate has only a small effect on separation. This is not applicable in cases where sludge recirculation is found. The performance of the primary clarifier can be evaluated by plotting SS_{mek}/SS_{ink} and COD_{mek}/COD_{ink} against the flowrate.

Results

As in section 3.2, the data was divided into pre and post June 1981 groups. (Figures 3.3a,b and Figures 3.3c,d resp.) The general trends are summarized in Table 3.3. Those SS values lying over 1,0 indicate washout of the primary clarifier or erroneous data.

At low flows the suspended solids removal seems to be evenly scattered between 60 and 90% with the main cluser at about 75%. The large variation at low flows in suspended solids removal may be disappointing but may be explained by the difficulty in obtaining representative raw wastewater samples. Still the many days with 90%-removals are surprising.

At high flows there is a trend towards decreased removal. The scatter is too large for any attempt to quantify a relation between removal and flow.

The COD removals are as could be expected lower at low flows, i.e. around 50 % removal. The above comments are also relevant here.

Figure 3.3a Primary SS Removal vs Flow - Early Period

Ratio SS_{mek} / SS_{ink} vs flow in m^3/d for the period 810101 to 810630.

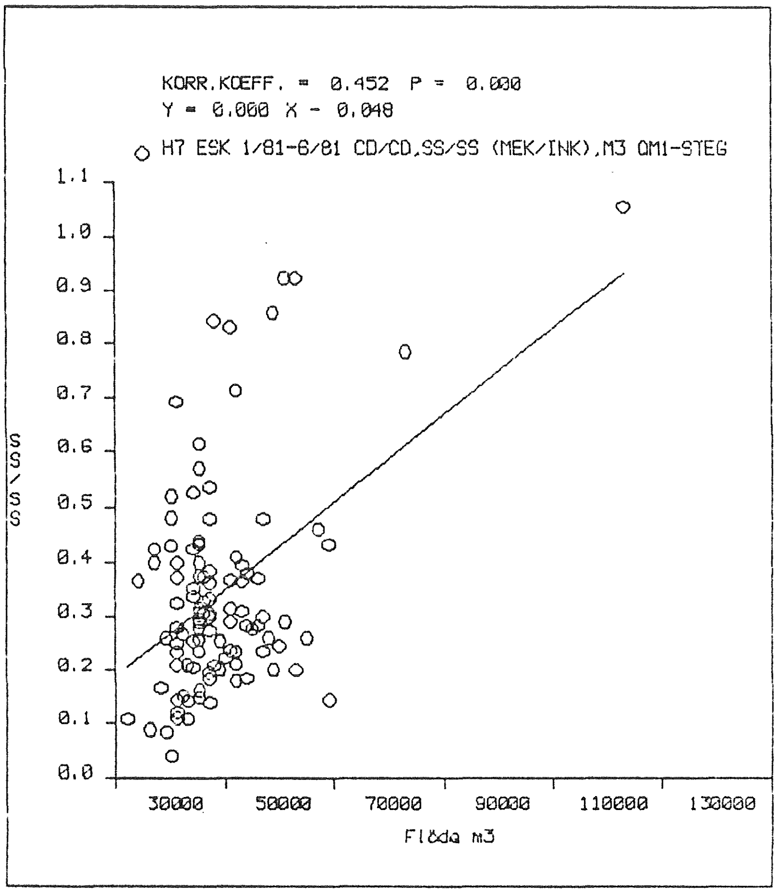


Figure 3.3b Primary SS Removal vs Flow - Later Period

Ratio SS_{mek} / SS_{ink} vs flow in m^3/d for the period 810701 to 820930.

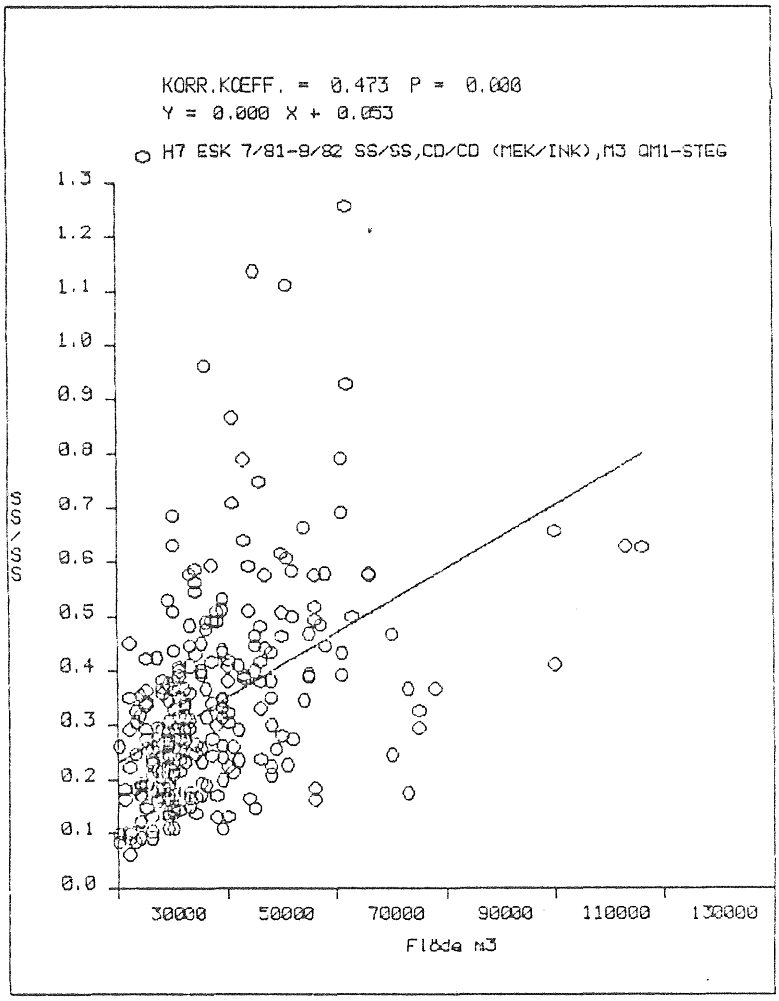


Figure 3.3c Primary COD Removal vs Flow - Early Period

Ratio COD_{mek} / COD_{ink} vs flow in m^3/d for the period 810101 to 810630.

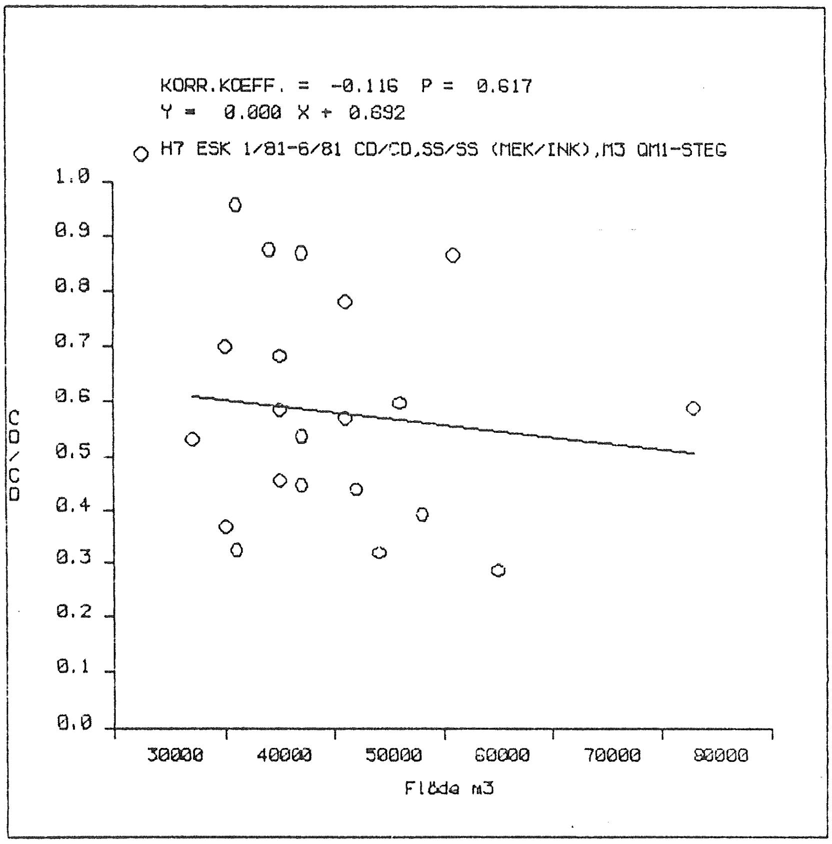
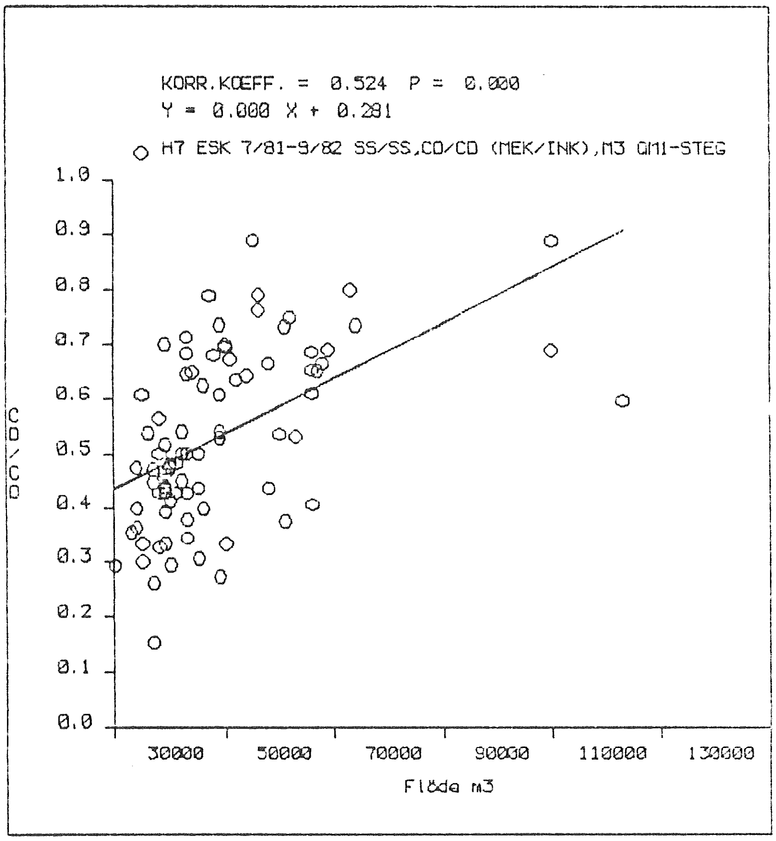


Figure 3.3d Primary COD Removal vs Flow - Later Period

Ratio COD_{mek} / COD_{ink} vs flow in m^3/d for the period 810701 to 820930.



Trends over time are examined in plots of SS_{mek}/SS_{ink} and COD_{mek}/COD_{ink} against time (Figures 3.3e,f). As can be expected, performance is generally poorer under the winter months. The large variation in SS and COD reduction at normal flows is surprising. The data could be corrected for temperature effects on viscosity and thus settling rates. It will hardly eliminate the large scatter.

Table 3.3 Summary of Primary Clarifier Performance.

Period	1/81 - 6/81	7/81 - 9/82
SS Removal:		
range of removal values	0,1-0,9	0,1-1,2
main cluster of removal values	0,25	0,25
correlation with flow	0,45	0,47
COD Removal		
range of removal values	0,3-0,9	0,3-0,9
main cluster of removal values	0,6	0,5
correlation with flow	-0,12	0,52

3.4 Suspended Solids in Activated Sludge Plant Effluent

In the 1970´s, many investigators reported that the function of activated sludge clarifier´s depended mainly on thickening. If a clarifiers thickening capacity is exceeded, the likelihood of increased suspended solids in the effluent is highly increased. White (1976) applied conventional thickening theory to the activated sludge clarifier and found that the allowable solids loading in kg $SS/m^2 \cdot h$ can be expressed as a function of the sludge volume index, mixed liquor suspended solids (MLSS), and the return activated sludge flow per unit surface area. The ratio of applied to predicted critical solids loading is

Figure 3.3e Primary SS Removal vs Time

Ratio SS_{mek} / SS_{ink} vs time for the period 810101 to 820930

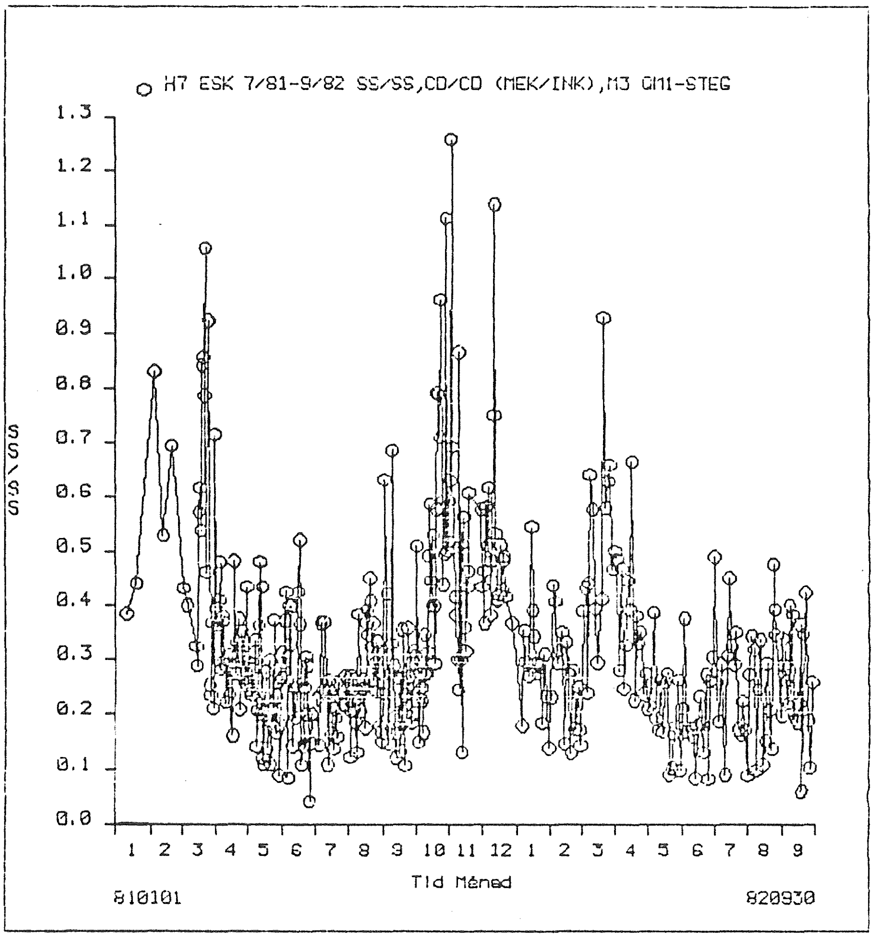
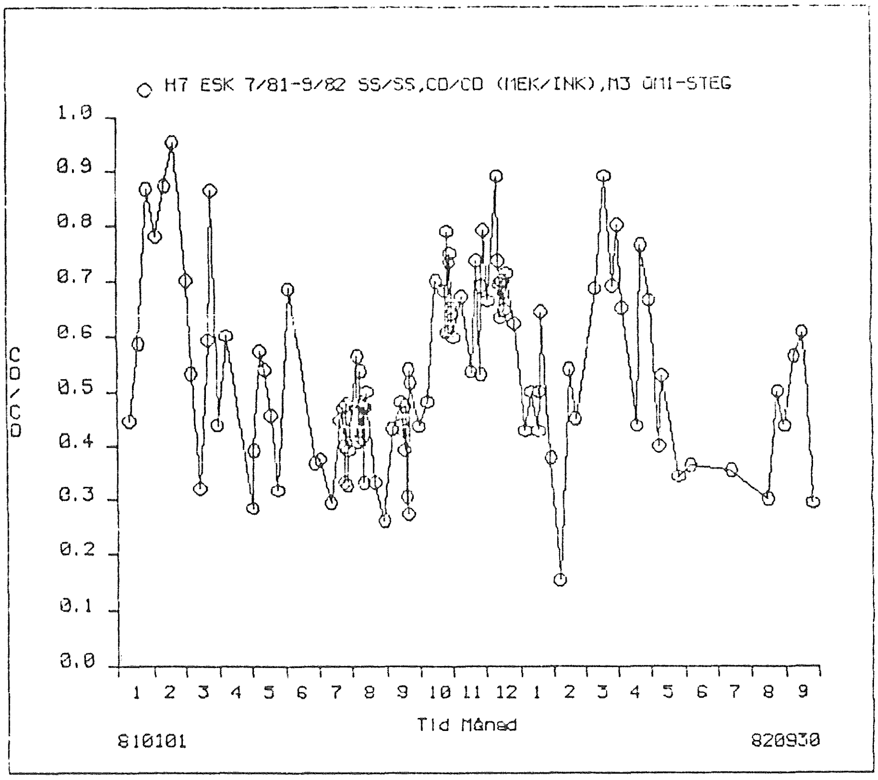


Figure 3.3f Primary COD Removal vs Time

Ratio COD_{mek} / COD_{ink} vs time for the period 810101 to 820930.



$$F = \frac{(Q_{ink}+Q_{rts}) * SS_{1su} * \frac{1}{A}}{8{,}85 * (\frac{100}{SSVI})^{0{,}77} * (Q_{rts} * \frac{1}{A})^{0{,}68}}$$

where Q_{ink} = flow through the activated sludge stage (m^3/h)
Q_{rts} = return activated sludge flow (m^3/h)
SS_{1su} = mixed liquor suspended solids (kg/m^3)
A = area of sedimentation tank (m^2)
SSVI = stirred sludge volume index (ml/g)
F = relative solids loading, dim less

It is therefore reasonable that the SS in the effluent from the activated sludge process should increase when the relative solids loading, as expressed above, passes a critical value. This critical value should occur when F = 1.

The performance of a secondary settling clarifier can also be affected by the surface overflow rate and by the horizontal velocity. It has been proposed that the horizontal velocity for secondary basins should be replaced with the flow per unit width. For a given plant all these factors are proportional to the flow.

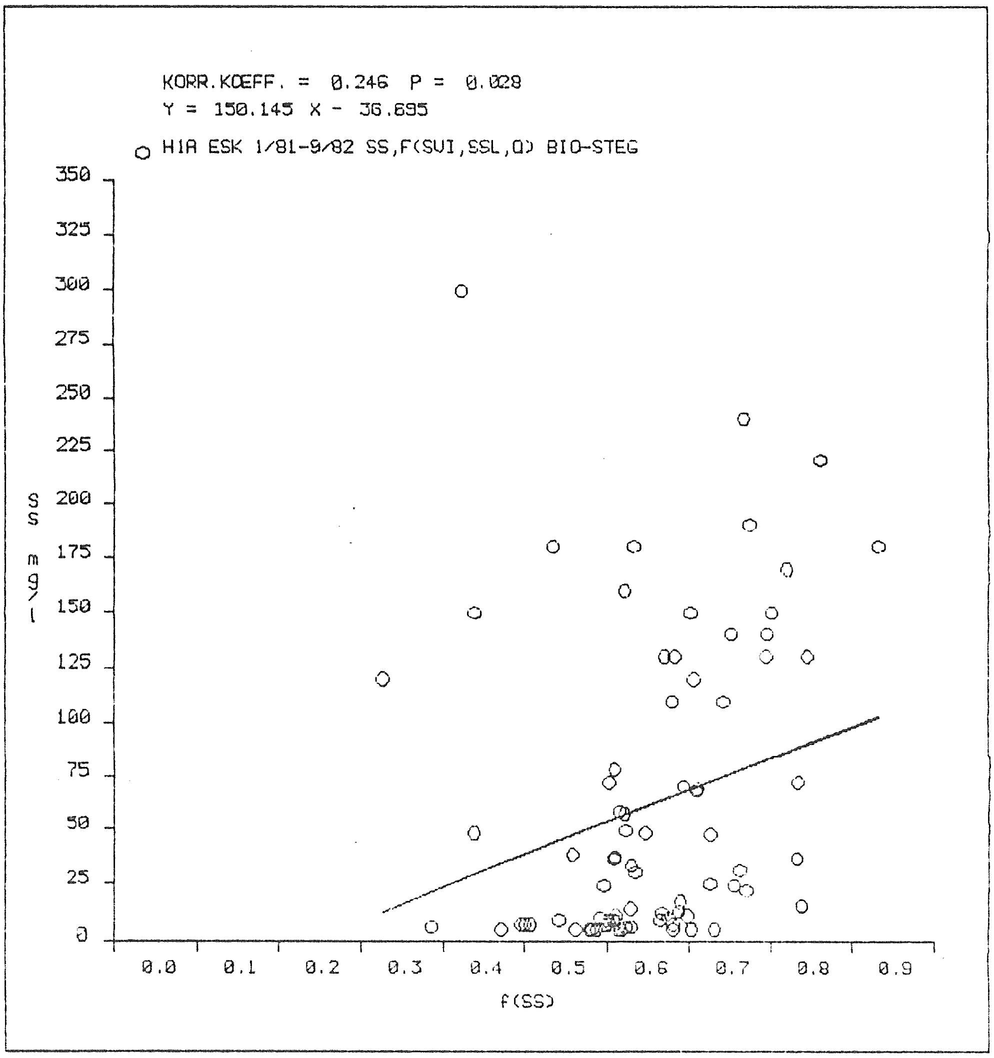
Results

In Figure 3.4.a secondary effluent suspended solids (SS_{bio}) is plotted against the relative solids loading.

To apply White´s equation sludge volume (SV) should be determined with a special stirred settling cylinder, whereas at Eskilstuna the conventional unstirred settling cylinders have been used. The SVI calculated as SV/MLSS is known to give erroneous values at high sludge volumes. At SV-values > 300 ml/l SVI has been calculated as $\frac{200+SV/3}{SS_{1su}}$ also known as the SQI

Figure 3.4a Secondary Effluent SS vs Relative Solids Loading

Effluent SS from biological treatment in mg/l vs relative solids loading factor,dimensionless, for the period 810101 to 820930.



The results however show no indication of any relationship between effluent suspended solids and relative solids loading. This is disappointing as other authors have found such relationship.

The hypothesis that secondary effluent suspended solids depends on flow is tested by a plot in Figure 3.4b. Again there is much scatter in the data with some trends of increasing suspended solids levels with increasing flow.

Looking at conventional design parameters such as surface overflow rate and flow per unit width those are not high for many days with high effluent suspended solids (for example twice the unofficial Swedish guideline for surface overflow rates, 2x0,8 m^3/m^2*h, corresponds to a flow of 108 000 m^3/d and twice the guideline for flow per unit width, 2x40 $m^3/m * h$ to a flow of 85 000 m^3/d for the Eskilstuna plant).

As the performance may be affected by a combination of sludge volume and flow the data was grouped into three sludge volume ranges and effluent suspended solids were plotted against flow in Figures 3.4 c,d,e. The results are also disappointing with no conclusive findings.

3.5 Oxidation of Organics and Nitrogen Compounds

Degradation of organics and oxidation of nitrogen compounds are dependant on the loading of the biological treatment stage. (Under actual operating conditions, degradation of organics can be assumed independant of loading since it is low.)

Loading can be represented by the mean cell residence time, MCRT.

$$\text{MCRT} = \frac{V * SS_{1su}}{Q_{bis} * SS_{bis} + Q_{ink} * SS_{bio}}$$

Figure 3.4b Secondary Effluent SS vs Surface Overflow Rate

Effluent SS from biological treatment in mg/l vs surface overflow rate in $m^3/m^2.h$ for the period 810101 to 820930.

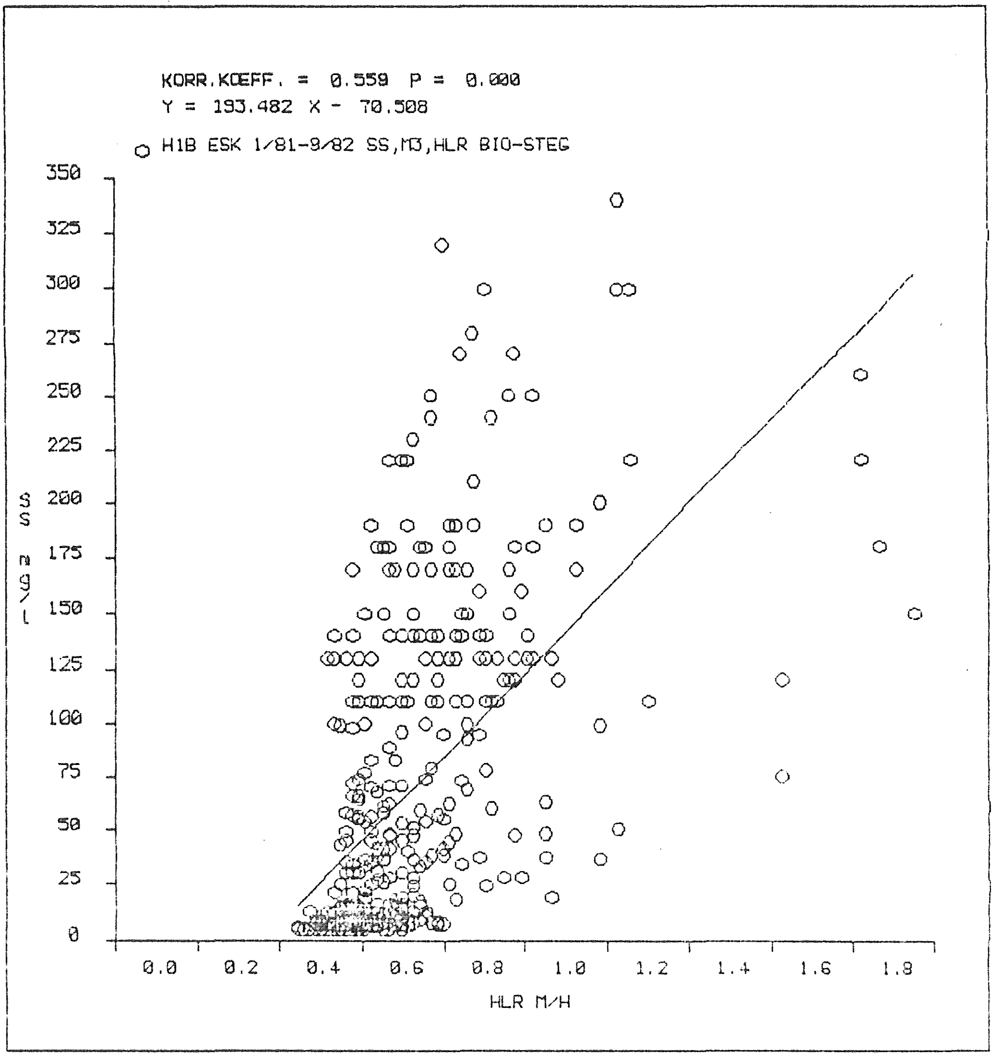


Figure 3.4c Secondary Effluent SS vs Surface Overflow Rate - Low SV

Effluent SS from biological treatment in mg/l vs surface overflow rate in m^3/m^2.h and SV<200 ml/l for the period 810101 to 820930.

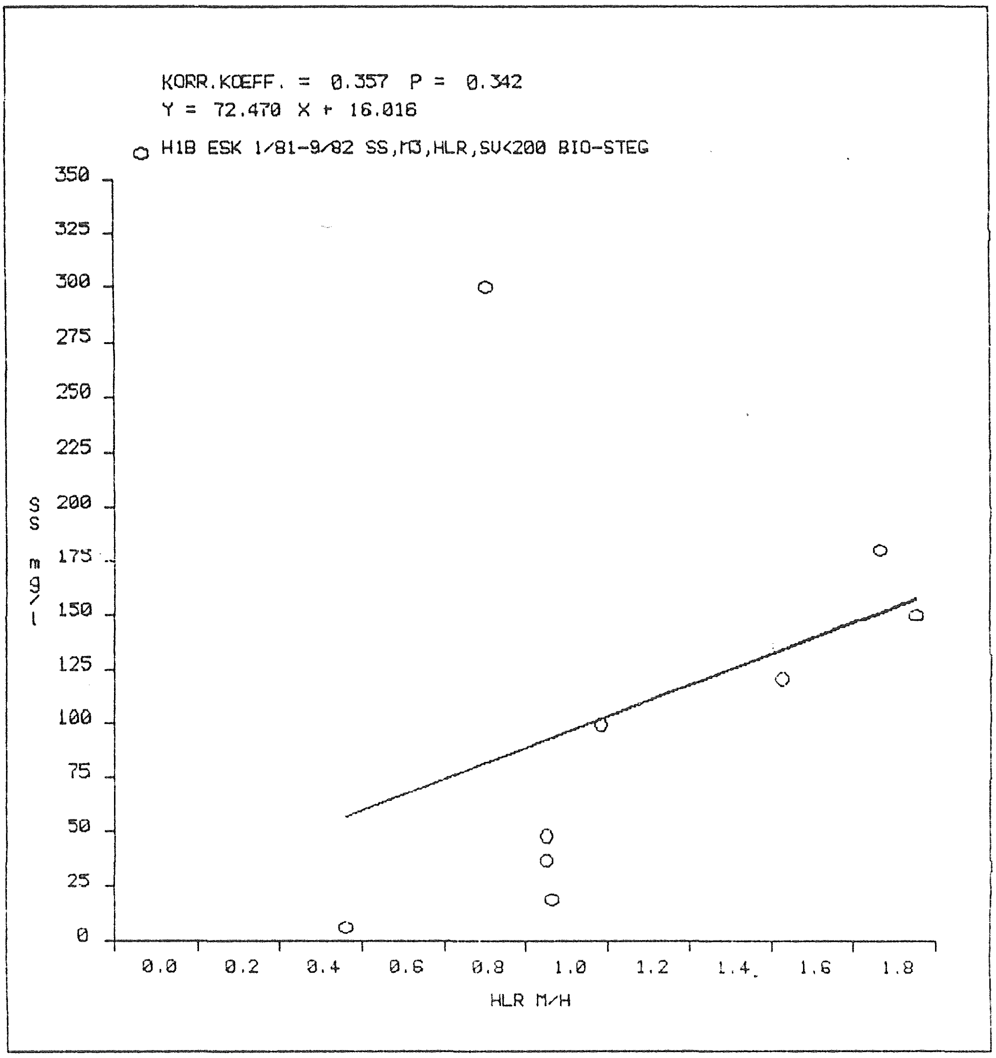


Figure 3.4d Secondary Effluent SS vs Surface Overflow Rate - Medium SV

Effluent SS from biological treatment in mg/l vs surface overflow rate in $m^3/m^2.h$ and 200<SV<400 ml/l for the period 810101 to 820930.

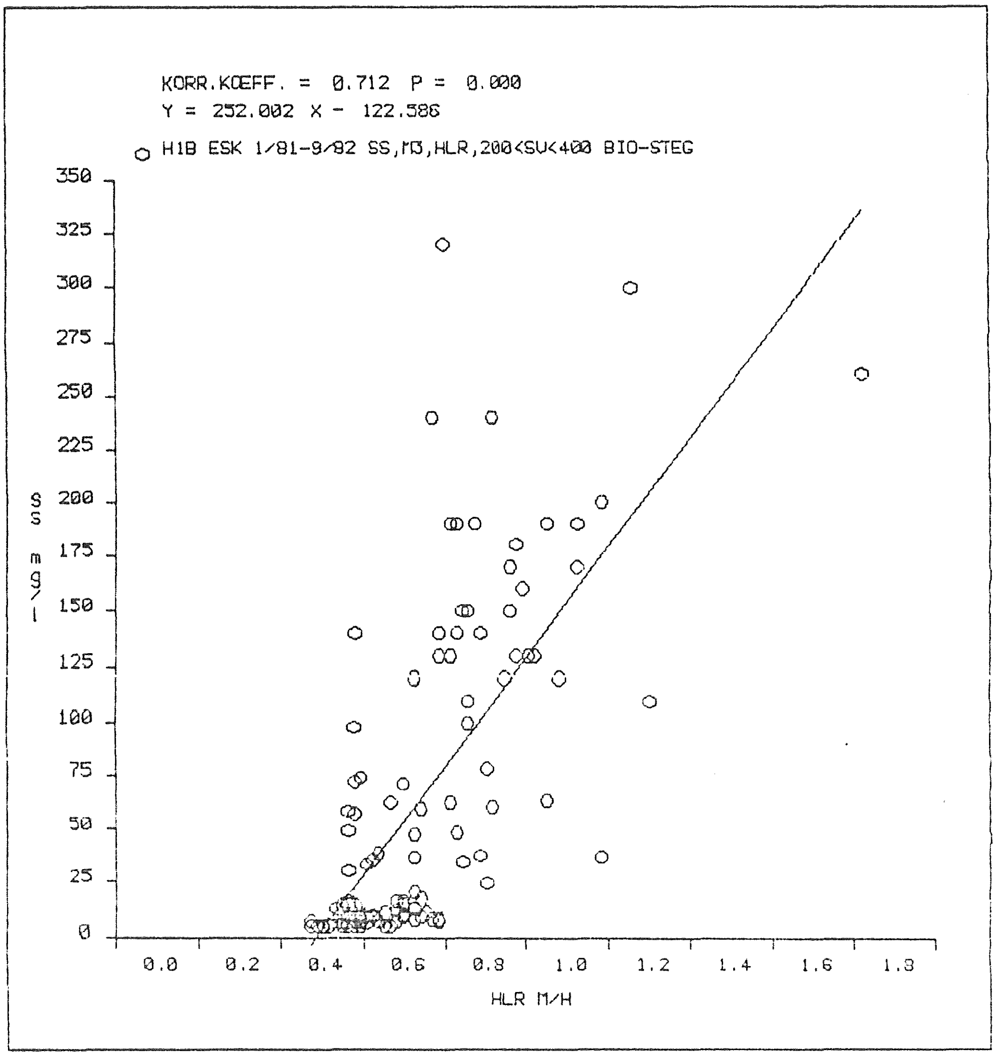
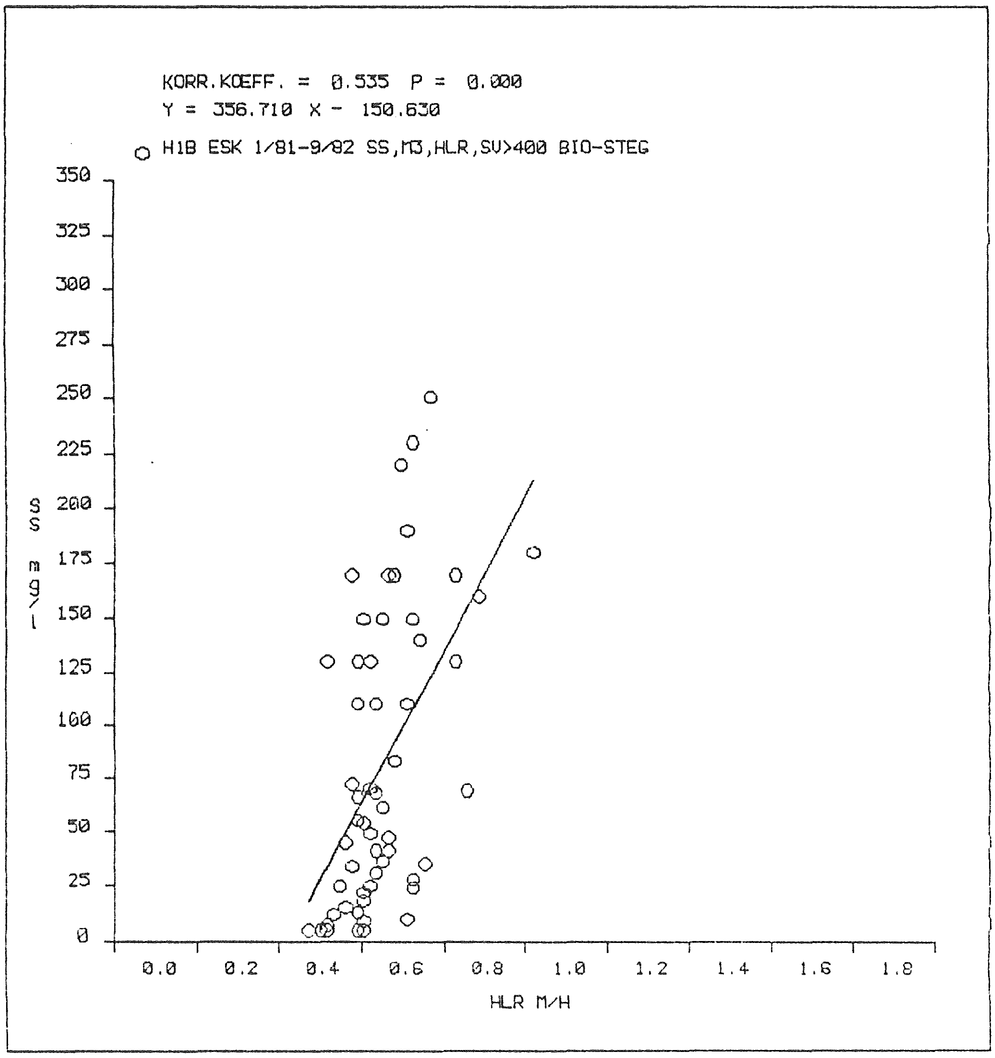


Figure 3.4e Secondary Effluent SS vs Surface Overflow Rate - High SV

Effluent SS from biological treatment in mg/l vs surface overflow rate in $m^3/m^2.h$ and SV>400 ml/l for the period 810101 to 820930.



where V = aeration tank volume (m^3)
SS_{1su} = MLSS (g/m^3)
Q_{bis} = wasted sludge flowrate (m^3/d)
SS_{bis} = microorganism concentration in return sludge (g/m^3)
SS_{bio} = microorganism concentration in biologically treated effluent (g/m^3)

Oxidation of nitrogen compounds is heavily temperature dependant. MCRT estimates are therefore corrected to 15°C with the relationship:

$$\frac{MCRT(15^{o}C)}{MCRT(T^{o}C)} = e^{0,098(T-15)}$$

$$BOD_{FILT,bio},\ NH_3\text{-}N_{kem}/N_{TOT,kem} \quad \text{or} \quad (NO_2+NO_3)_{kem}/N_{TOT,kem}$$

can be plotted with the mean cell residence time.

Results

The plot of MCRT vs. time is shown in Figure 3.5a and temperature corrected MCRT vs. time in Figure 3.5b. The large variation from 0,9 days to 39 days was not expected. To check the reliability of the data, the MCRT was also calculated by the relationship

$$MCRT = \frac{V * SS_{1su}}{Q_{bis} * \frac{1+r}{r} SS_{1su} + Q_{ink} * SS_{bio}}$$

where r = sludge recycle ratio (dimensionless)

Nearly twice as many MCRT values were generated using this alternative calculation as seen in Figures 3.5c,d,e. In Figure 3.5c, MCRT and NH_4/N_{TOT} are plotted against time and the expected trend of decreasing ammonia with increasing MCRT is found. Interpreting the data can be risky since so few data

Figure 3.5a Mean Cell Residence Time vs Time

MCRT by the standard method in days vs time in months for the period 810101 to 820930.

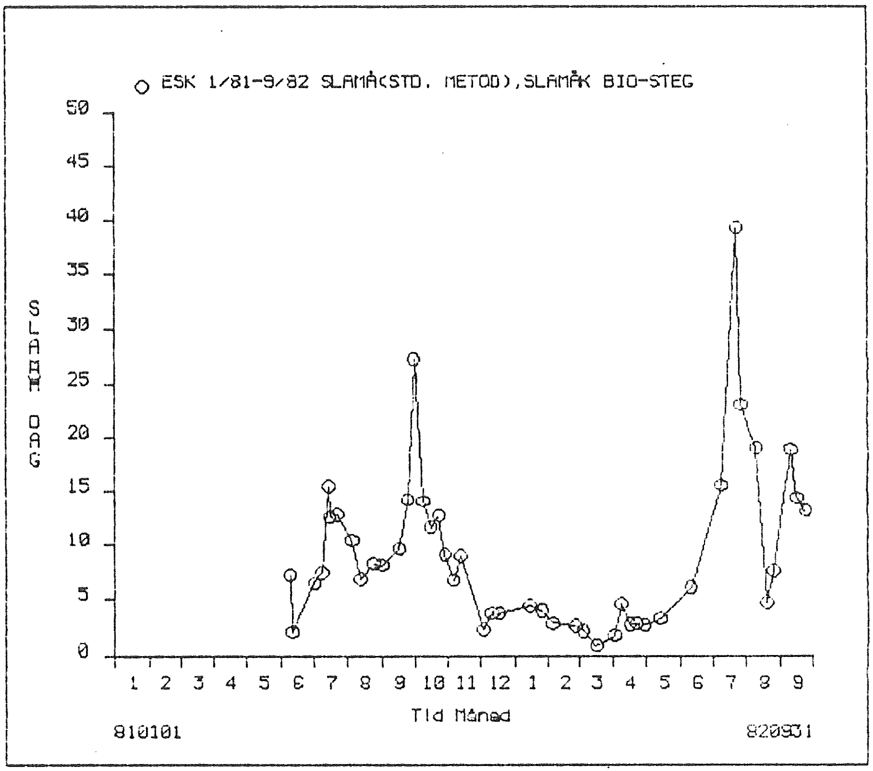


Figure 3.5b Temperature Corrected MCRT vs Time

Temperature corrected (to 15^{o}C) MCRT by the standard method in days vs time in months for the period 810101 to 820930.

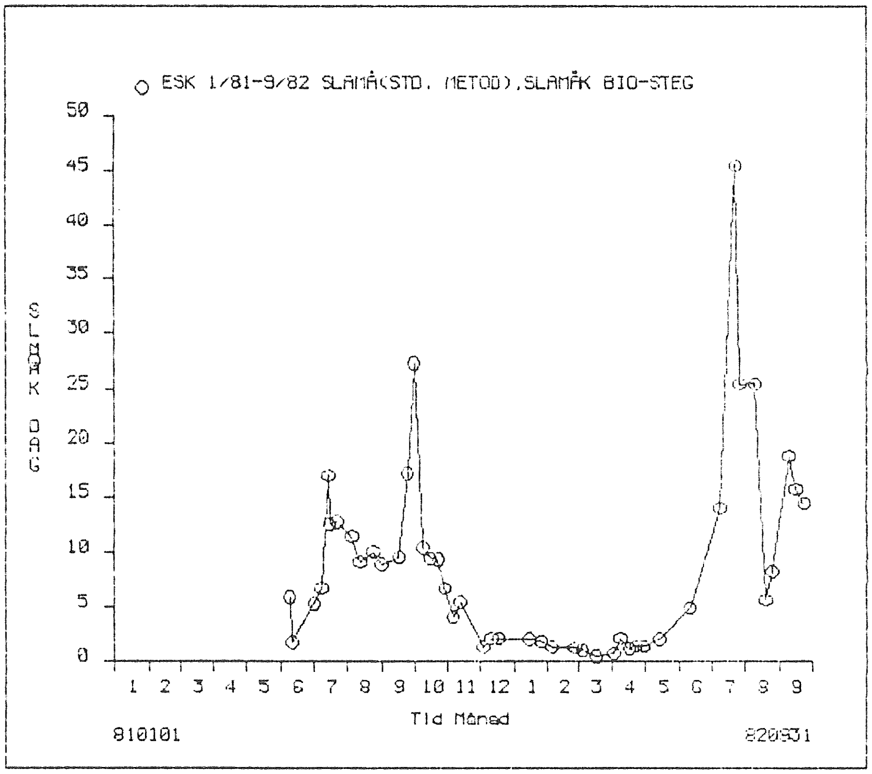


Figure 3.5c MCRT and NH_4 / N_{TOT} vs Time

MCRT by the flow ratio method in days and NH_4 / $N_{TOT,kem}$ vs time in months for the period 810101 to 820930.

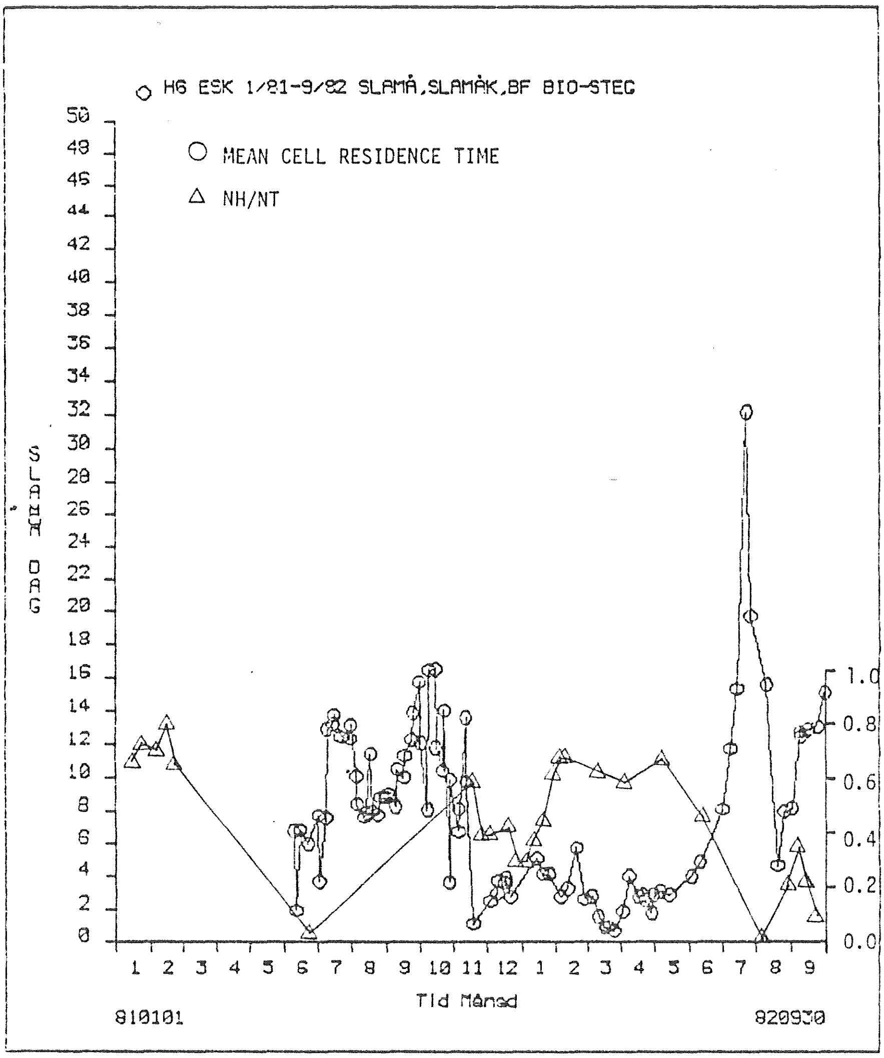


Figure 3.5d MCRT and NO_2+NO_3 / N_{TOT} vs Time

MCRT by the flow ratio method in days and NO_2+NO_3 / $N_{TOT,kem}$ vs time in months for the period 810101 to 820930.

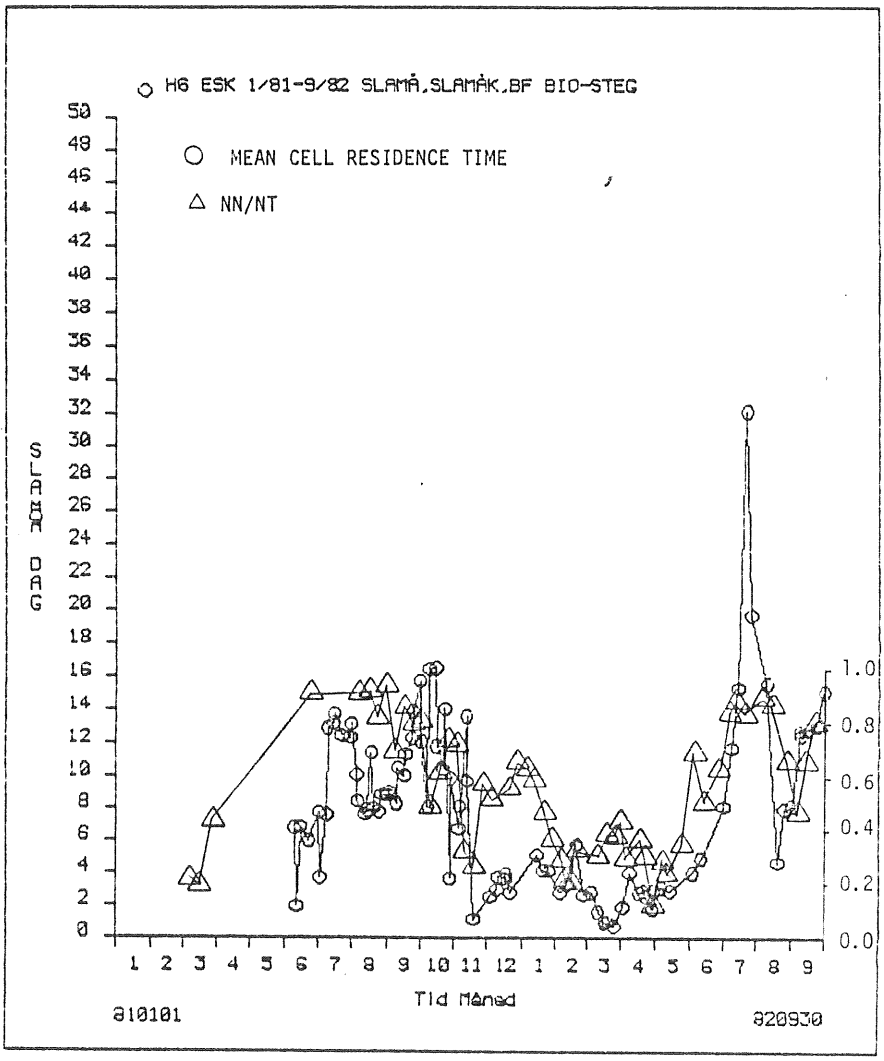
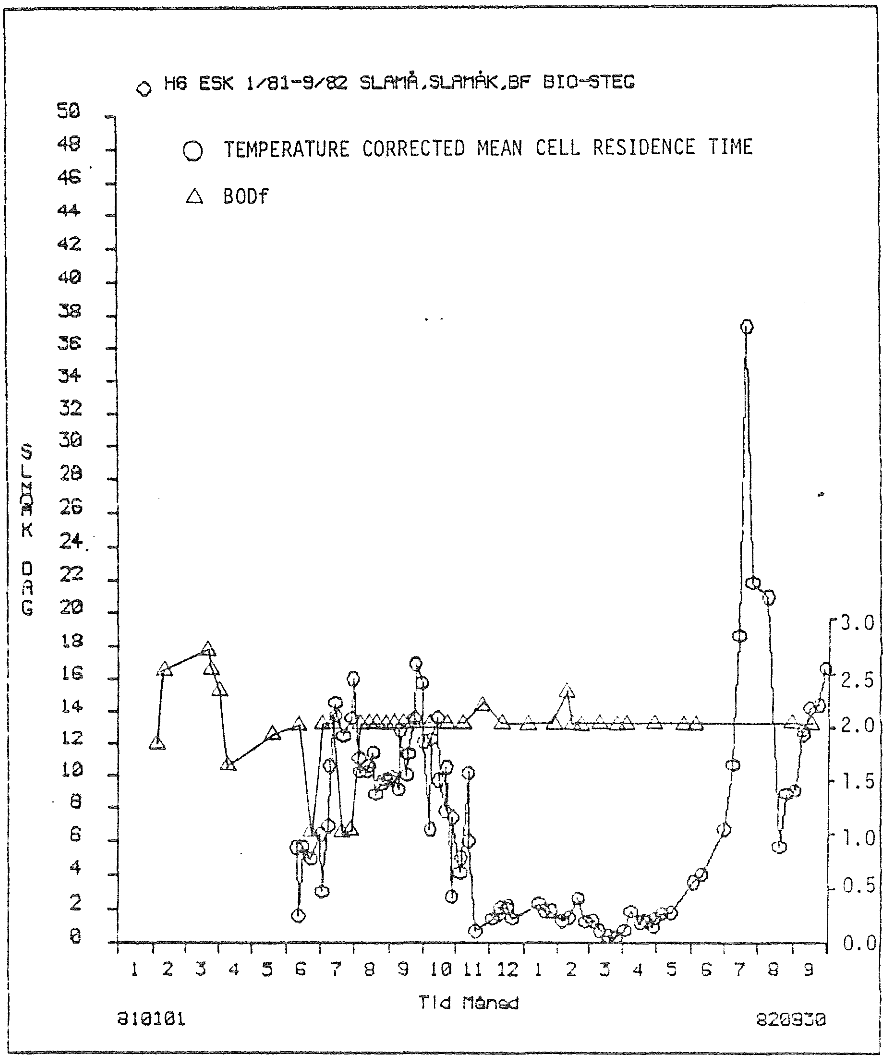


Figure 3.5e Temperature Corrected MCRT and BOD_{FILT} vs Time

Temperature corrected (to 15°C) MCRT by the flow ratio method and $BOD_{FILT,bio}$ vs time in months for the period 810101 to 820930.



points exist (for example the period 3/81 to 11/81 is represented by only one data point).

From the plot of MCRT and NO_2+NO_3/N_{TOT} vs. time in Figure 3.5d, the complement trend to that in Figure 3.5c is as expected found. Increasing the MCRT increases the conversion of NH_4 to NO_2 and NO_3.

Figure 3.5e, the plot of temperature corrected MCRT and $BOD_{FILT,bio}$ vs. time, is inconclusive. The small variation in BOD values leads one to believe that the representativety of the samples can be questioned as well as the ability to detect changes in BOD at low concentrations.

A comparison of MCRT vs. time and SS_{bio} vs. time (Figure 3.3e) indicates that the MCRT in Eskilstuna is not controlled by process operation but rather by unintentional sludge wastage in the secondary effluent.

The spike in July 1982 is characterized by below average daily flows, low SV and average MLSS. The return to an expected MCRT range in August may be more a result of high effluent SS.

3.6 Effluent COD from Biological Treatment

It can be assumed that effluent soluble COD from biological treatment is composed of:

i) a non-degradable part of the influent COD
ii) non-degradable metabolites from the biodegradation process
iii) remaining degradable material
iv) COD from infiltrated water

In an activated sludge plant with MCRT >2 days, the concentration of remaining degradable material should be low (pt. iii).

Non-degradable material (pts. i and ii) is assumed to be proportional to the influent concentration.

The concentration of infiltration water is assumed to be constant under the summer half of the year.

Under these assumptions, the following relationship can be developed:

$$Q_{bio} * COD_{FILT,bio} = \frac{Q_{bio}}{Q_{ink}} (Q_{ink} - Q_s) * COD_{INF} + b$$

where Q_{ink} = influent flow (m^3/d)
Q_{bio} = flow through biological treatment (m^3/d)
Q_s = domestic wastewater water demand (m^3/d)
COD_{INF} = COD concentration of infiltration water (g/m^3)
$COD_{FILT,bio}$ = filtered COD concentration of infiltration water (g/m^3)
b = $Qs * COD_s * C$ (g/d)
COD_s = COD concentration of domestic wastewater (g/m^3)
C = non-degradable portion of COD_s

Plotting ($Q_{bio} * COD_{FILT,bio}$) against ($Q_{ink} - Q_s$) should result in a linear relationship with slope COD_{INF} and intercept b, the non-degradable COD from domestic wastewaters.

To increase the amount of $COD_{FILT,bio}$ data, it is first tested that ($COD_{bio} - COD_{FILT,bio}$) is directly proportional to SS_{bio}.

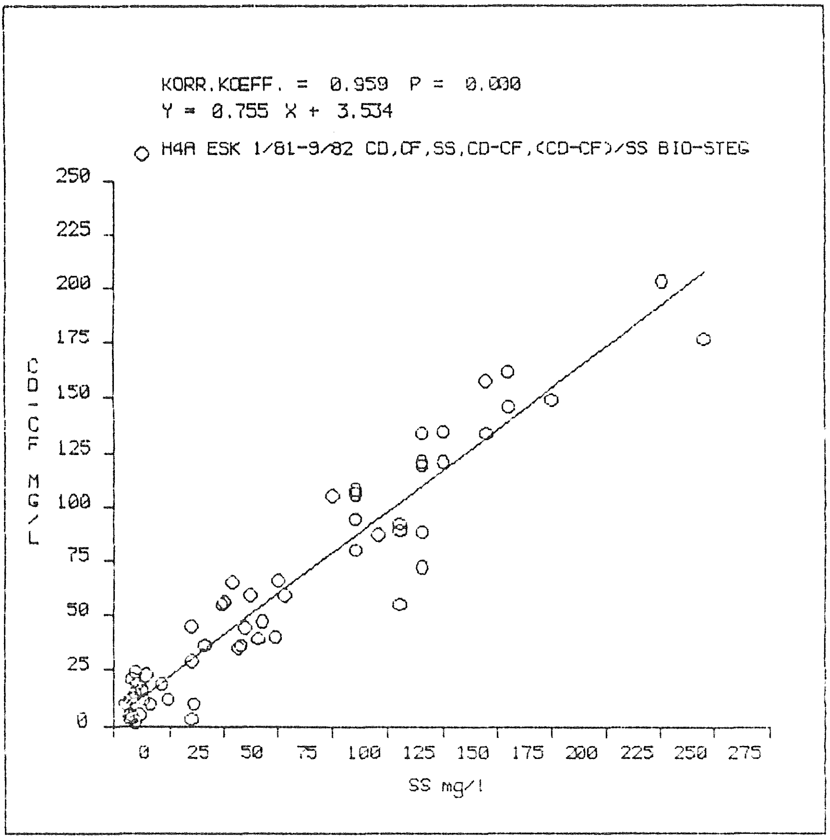
Results

The plot of COD - COD_{FILT} vs. SS, shown in Figure 3.6a has a regression slope of 0,755, intercept of 3,534 and correlation of 0,959. Thus COD_{FILT} values can be estimated by the equation:

$$COD_{FILT,bio} = COD_{bio} - 0,755 * SS_{bio} - 3,534$$

Figure 3.6a Non-Soluble COD vs SS after Biological Treatment

$COD_{bio} - COD_{FILT,bio}$ in mg/l vs SS_{bio} in mg/l for the period 810101 to 820930.



This relationship was used to improve the data set for the major hypotheses. The resulting regression (Figure 3.6b) has slope 0,025 and intercept 1,181. Therefore the estimated COD_{INF} based on the regression is 25 mg/l. The estimated intercept of 1181 kg/d is equal to Q_S * COD_S * C and Q_S is estimated to be 24 600 m^3/d based om the average daily water consumption. The total COD load of 80 000 p. is estimated at 12 000 kg/d. Thus

$$C = \frac{1181}{12000} = 0{,}10$$

This means that the removal of COD could not be expected to exceed 90%. The estimated COD_{INF} of 25 mg/l is the right order of magnitude. Daily values of water consumption would make these estimates more reliable than using an average calculated from the yearly consumption. The COD_{INF} estimates of section 3.2 are 8 and 2 times, respectively, those found here.

The regression correlation is upset by the presence of outliers in the negative range. If these two points are rejected, as in Figure 3.6c, the resulting regression has slope 0,032 and intercept 1,093 with correlation 0,628. The estimate of COD_{INF} is increased to 32 mg/l and C decreased to 0,09 .

3.7 Phosphorus Reduction with Recirculation of Chemical Sludge

When sludge from the chemical postprecipitation stage is recirculated to the preceeding stage, the phosphorus reduction there should depend on the unconsumed chemicals in the recirculated sludge and on the total phosphorus in the influent wastewater. (Total phosphorus due to the complete conversion of organic phosphorus and polyphosphorus to orthophosphates, PO_4-P, during biological treatment) i.e.

Figure 3.6b Amount of Soluble COD vs Infiltration Flow after Biological Treatment - All Data

Soluble COD load per day in tons vs the estimated infiltration flow in $10^3 m^3/d$ for the period 810101 to 820930.

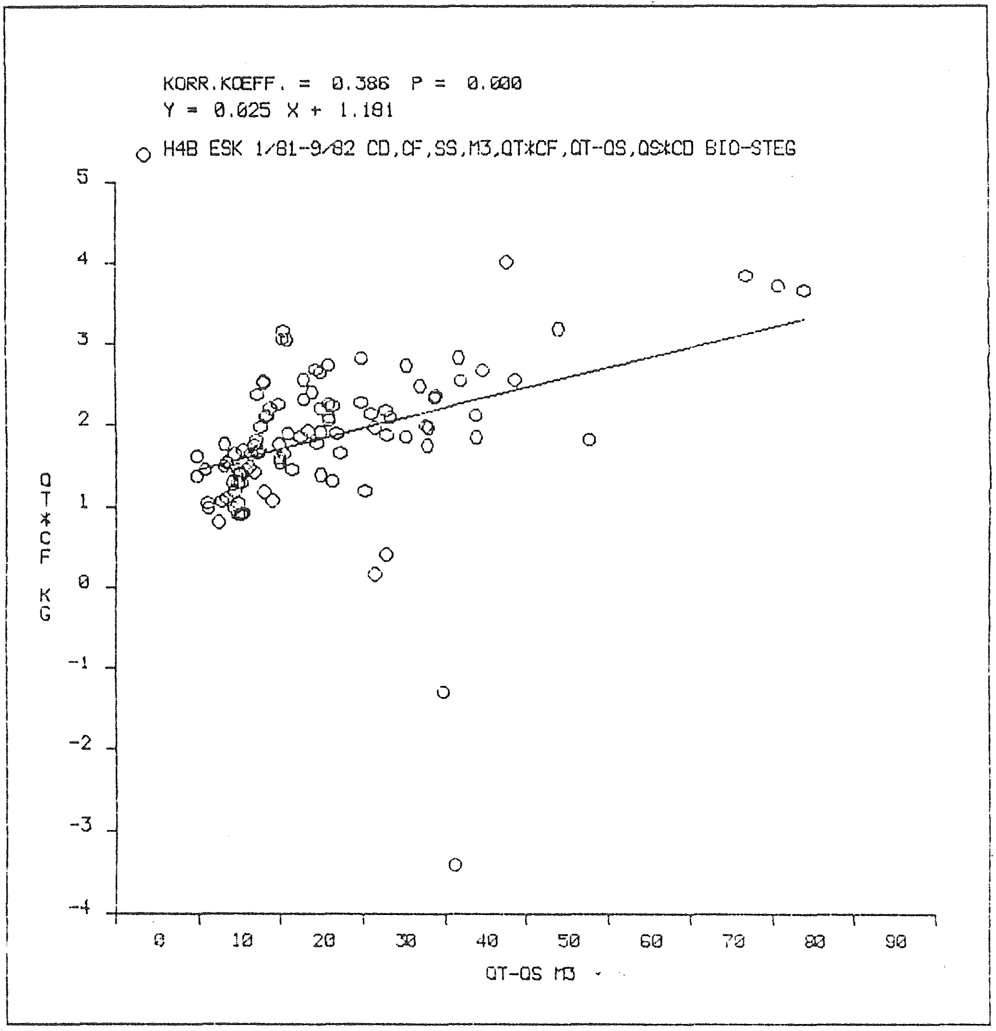
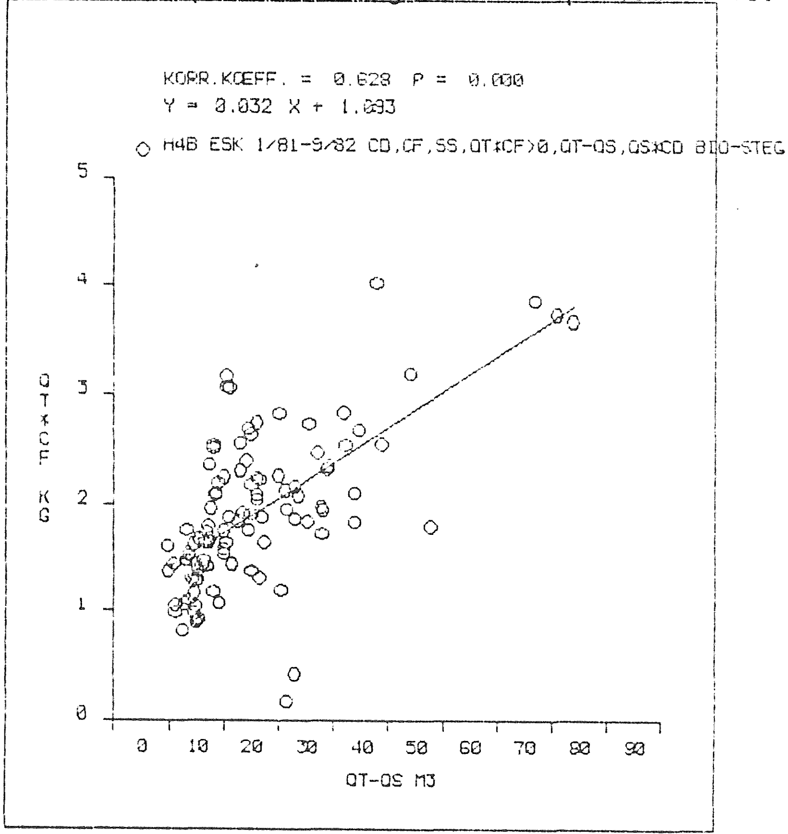


Figure 3.6c Amount of Soluble COD vs Infiltration Flow after Biological Treatment - Corrected Data

Soluble COD load per day in tons vs the estimated infiltration flow in $10^3 m^3/d$ for the data in the positive range for the period 810101 to 820930.



$$\frac{PO_4\text{-}P_{bio}}{P_{TOT,ink}} = f\ \left(\frac{DOS * k\ -\ (PO_4\text{-}P)_{bio}}{P_{TOT,ink}}\right)$$

where DOS and k are as previously defined.

A simplification of the above, where phosphorus reduction under biological treatment is a function of the unconsumed chemicals i.e.

$$\frac{PO_4\text{-}P_{bio}}{P_{TOT,ink}} = f\ (DOS * k\ -\ (PO_4\text{-}P)_{bio})$$

is also investigated .

Results

Both the first model (Figure 3.7a) and the second model (Figure 3.7b) are negatively correlated and widely scattered (-0,21 and -0,76 respectively). The second, simpler model indicates the expected result that increased chemical recirculation increases the phosphate removal. An excess of coagulant of 0,2 - 0,3 moles/m^3 will give a high phosphorus insolubilization in the biological stage.

3.8 Effluent Soluble Phosphorus as a Function of pH

When phosphorus is precipitated from wastewaters, it is assumed a precipitation of $AlPO_4$ or $FePO_4$, both reactions being strongly pH dependant.

pH is measured daily but experience shows that pH-values from daily composite samples are often not representative of the true pH value and thus it may improve accuracy to use a pH value based on alkalinity data, e.g.

Figure 3.7a Phosphorus Insolubilization vs Unconsumed Coagulant per Unit Influent Total Phosphorus

PO_4-P_{bio} / $P_{TOT,ink}$ vs unconsumed coagulant per $P_{TOT,ink}$ in moles/g for the period 810101 to 820930.

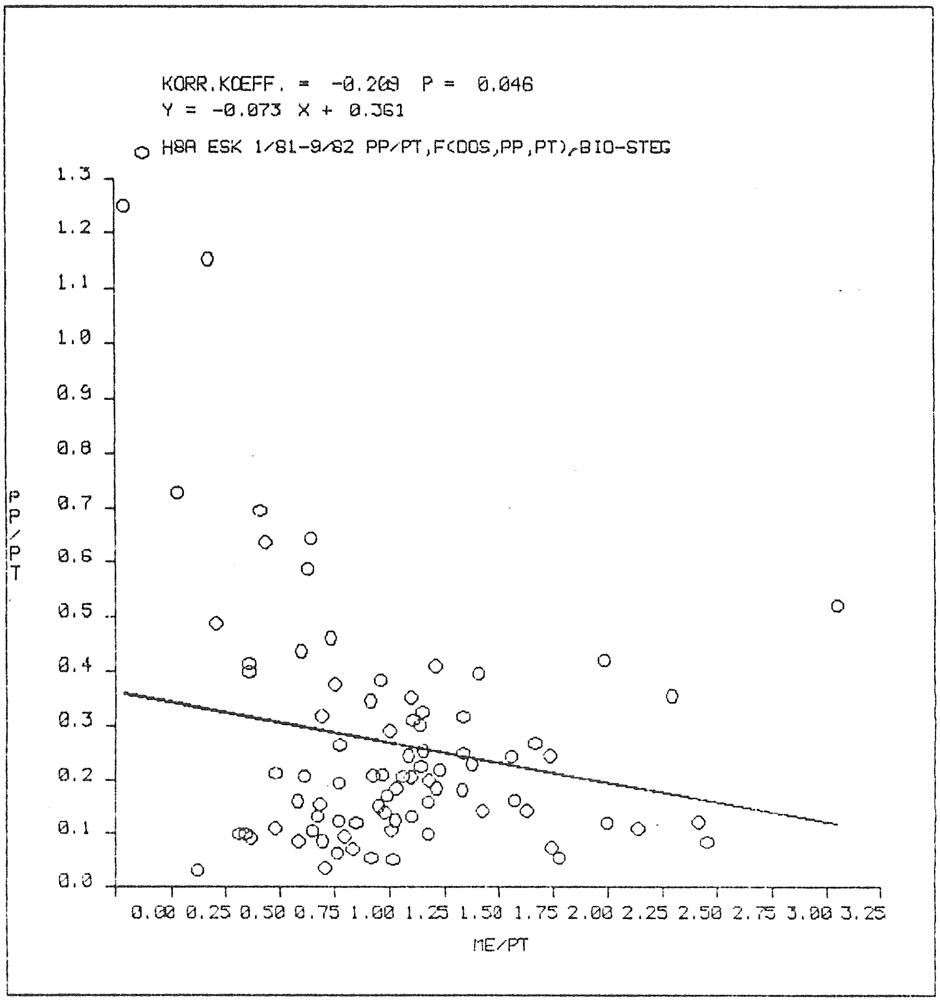
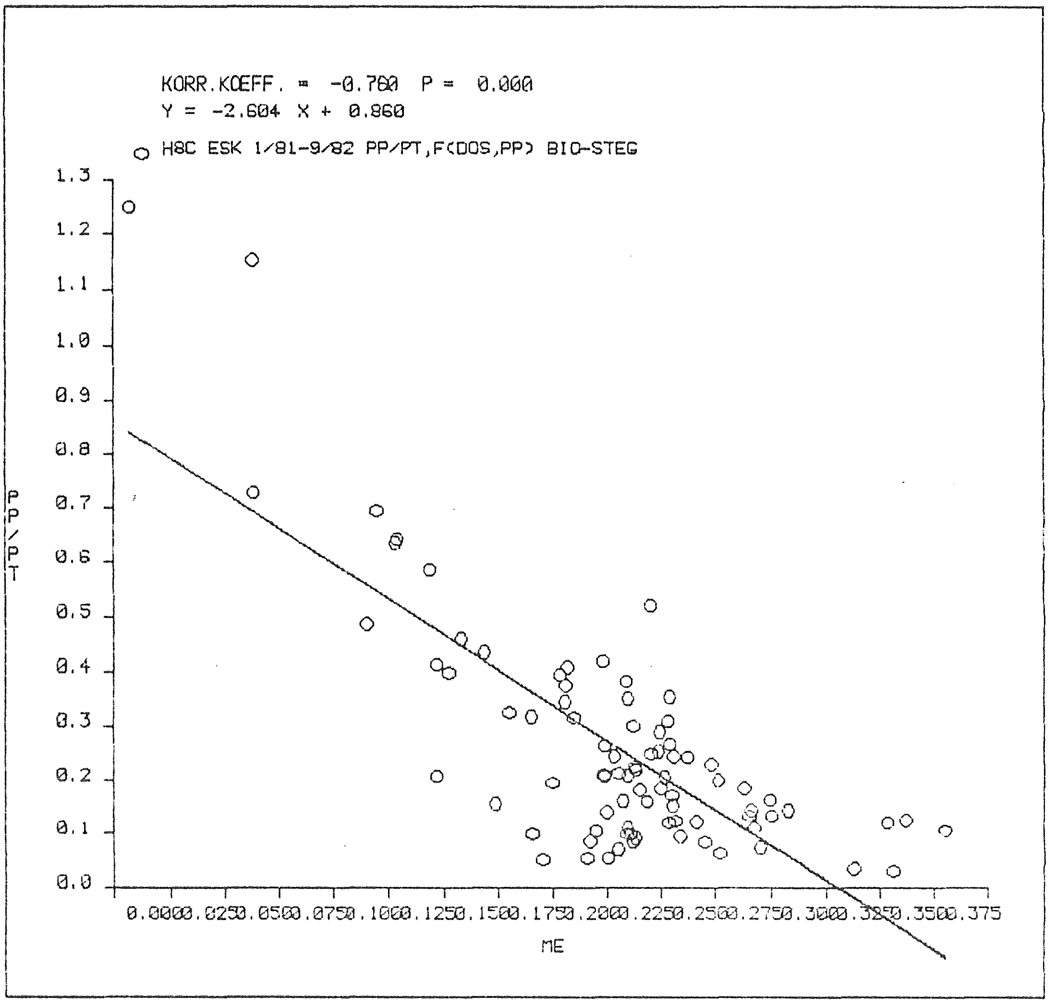


Figure 3.7b Phosphorus Insolubilization vs Unconsumed Coagulant

PO_4-P_{bio} / $P_{TOT,ink}$ vs unconsumed coagulant in moles/m^3 for the period 810101 to 820930.



$$pH_{THEORY} = 6,38 + \log \{Alk_{kem} / (\exp(10)(\log(Alk_{bio}) - pH_{bio} + 6,38) + Alk_{bio} - Alk_{kem})\}$$

pH is also determined from grab samples.

Results

The hypothesis that composite pH-values are systematically too high is supported by Figures 3.8a and 3.8b. Almost all composite sample pH- values and grab sample pH-values are higher than the corresponding pH-values calculated from alkalinity data. The average deviation from the calculated value is considerably larger for the composite samples.

Relationships between daily composite sample phosphate-phosphorous and grab sample pH, composite sample pH and theoretical pH (with and without grab samples) are shown in Figures 3.8c,d and 3.8e,f repectively. There are no correlations. This is surprising as both theory and practical experience from controlled pilot plant studies have shown good correlations.

3.9 Alkalinity Reduction in the Postprecipitation Stage

When Fe^{3+} or Al^{3+} are added to a wastewater, there is a reduction in the alkalinity due to the precipitation of phosphates and hydroxides. For example, Fe^{3+} follows the stochiometric relationships:

$$Fe^{3+} + HPO_4 \longrightarrow FePO_4 + H^+ \quad (1)$$
$$Fe^{3+} + H_2PO_4 \longrightarrow FePO_4 + 2H^+ \quad (2)$$
$$Fe^{3+} + 3H_2O \longrightarrow Fe(OH)_3 + 3H^+ \quad (3)$$

Distribution of the three reactions is dependant on the biologically treated water´s pH and the Fe^{3+} dose in relationship to the PO_4-P concentration in the wastewater. If Fe^{3+} is

Figure 3.8a Measured pH vs Theoretical pH

Combined grab and composite sample pH vs the theoretical pH for the period 810101 to 820930.

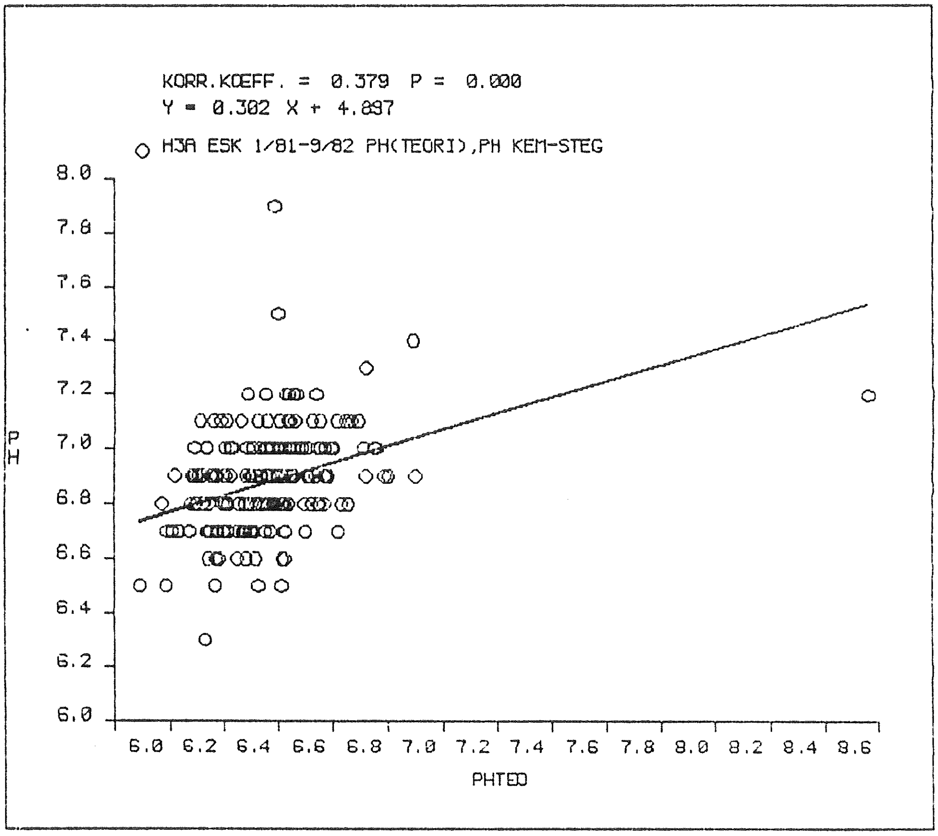


Figure 3.8b Composite Sample pH vs Theoretical pH

For the period 810101 to 820930.

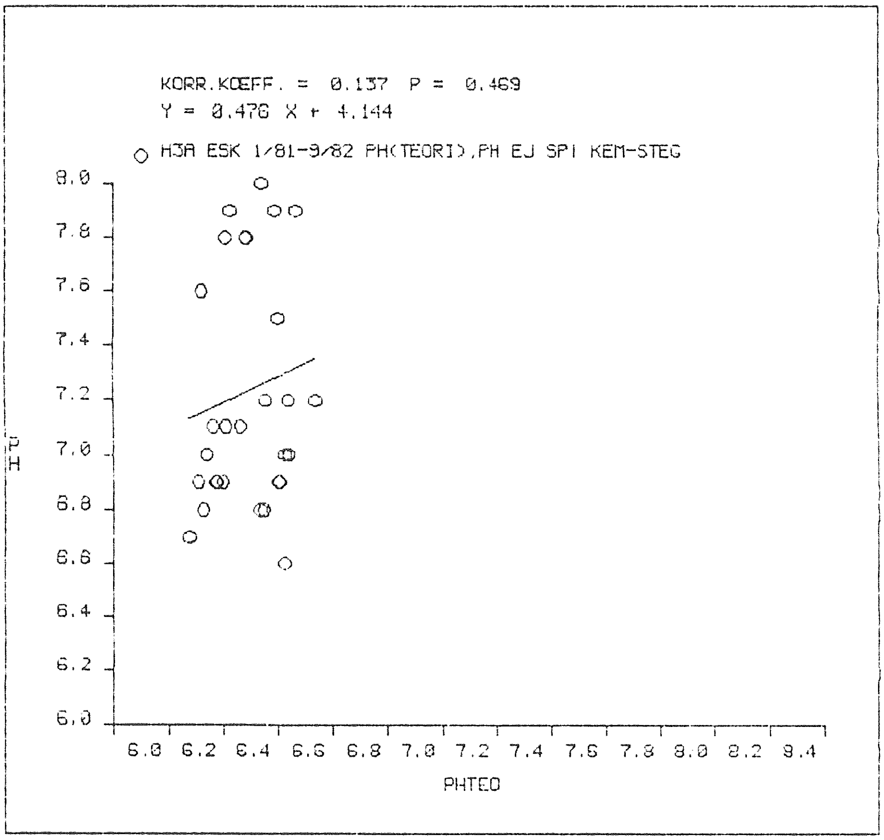


Figure 3.8c Phosphate-Phosphorus vs pH

Log of PO_4-P_{kem} vs pH_{kem} (all samples) for the period 810101 to 820930.

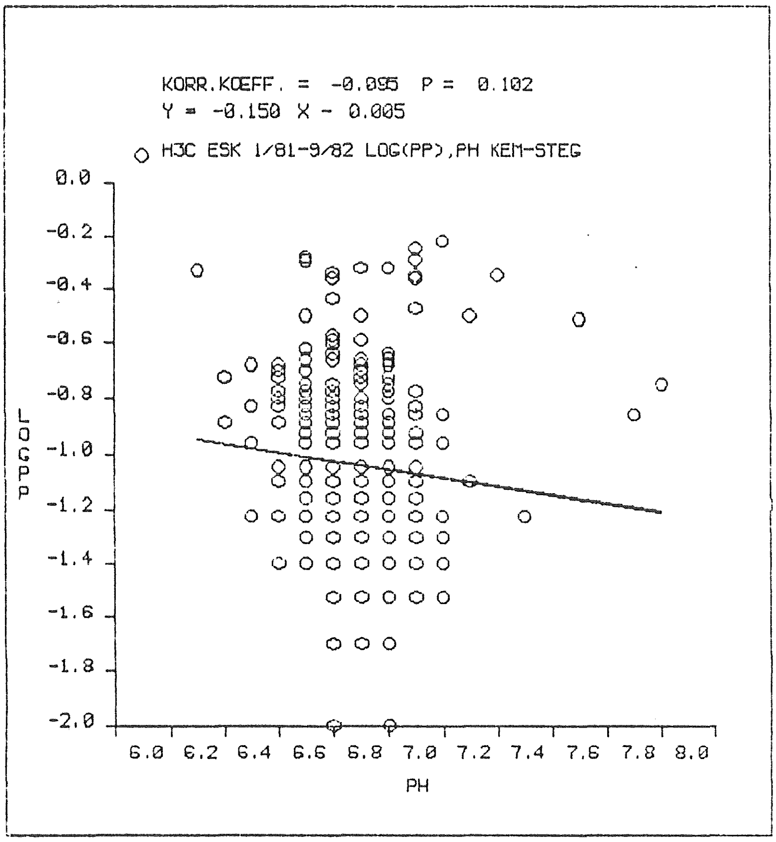


Figure 3.8d Phosphate-Phosphorus vs Composite Sample pH

Log of PO_4-P_{kem} vs composite sample pH_{kem} for the period 810101 to 820930.

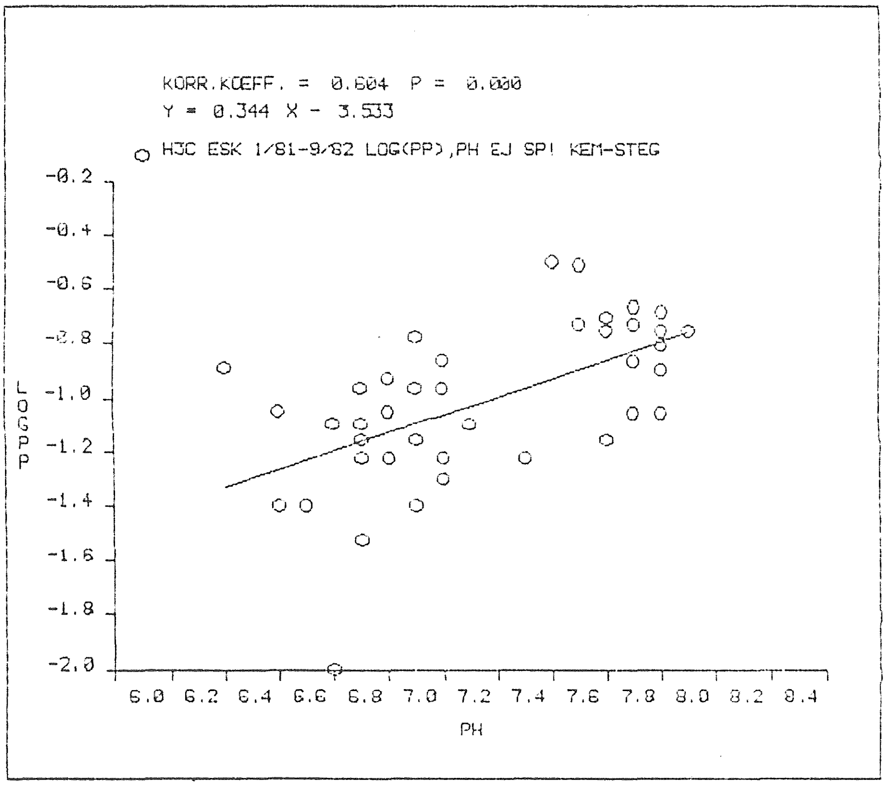


Figure 3.8e Phosphate-Phosphorus vs Theoretical pH

Log of PO_4-P_{kem} vs theoretical pH (all samples) for the period 810101 to 820930.

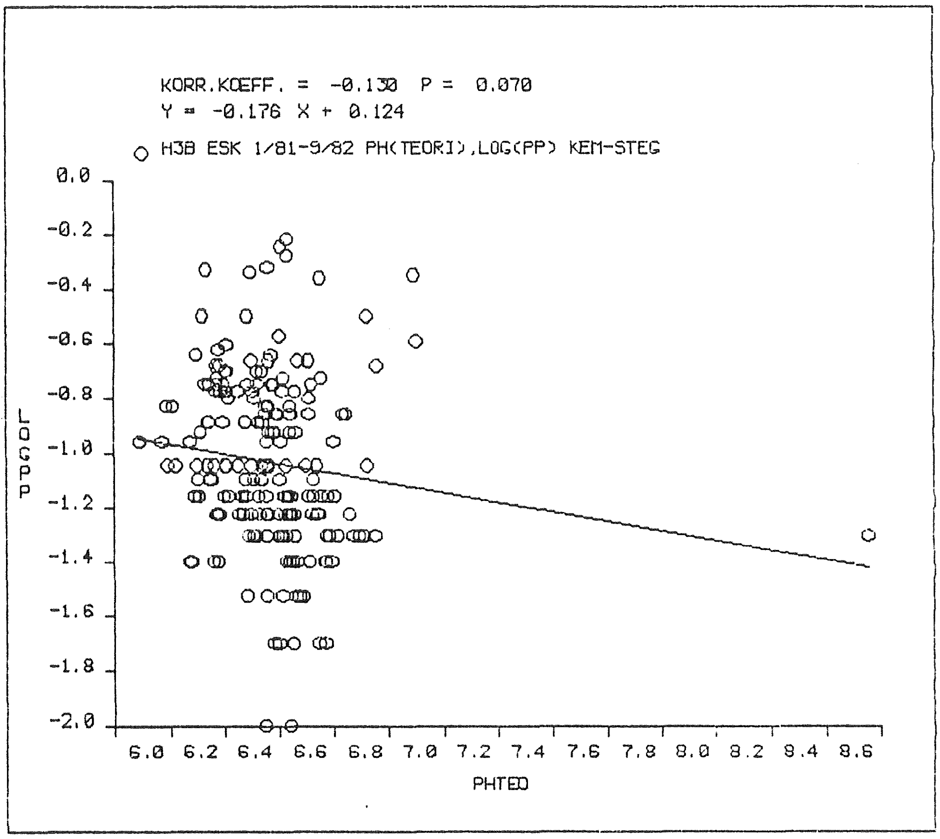
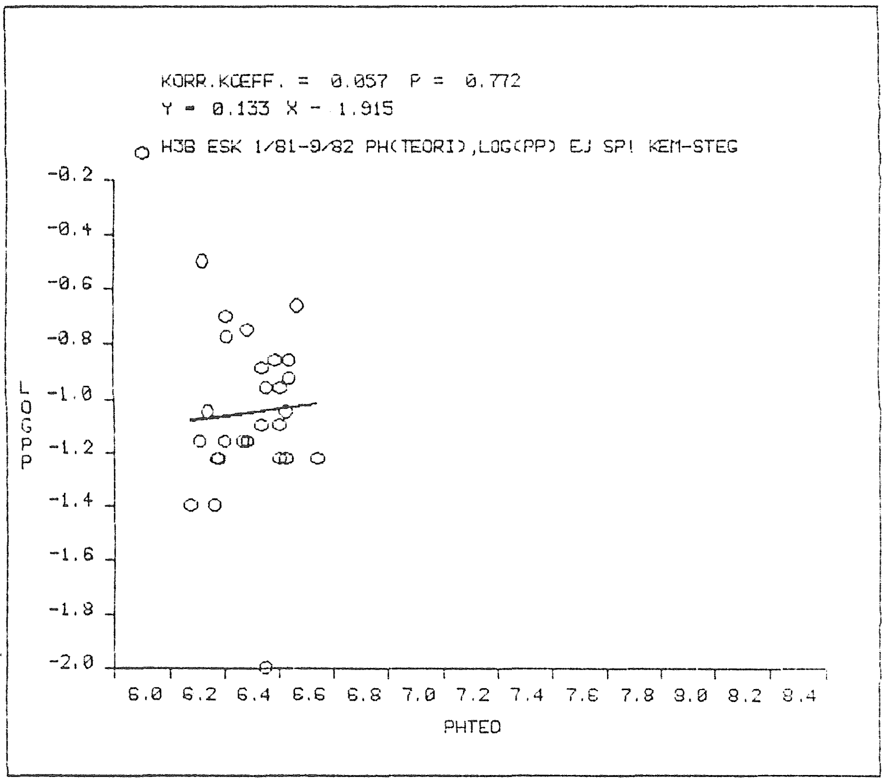


Figure 3.8f Phosphate-Phosphorus vs Composite Sample Theoretical pH

Log of PO_4-P vs composite sample theoretical pH for the period 810101 to 820930.



assumed to first precipitate all phosphate and the remaining Fe^{3+} to hydrolize to ferric hydroxide, then:

$$Alk_{bio} - Alk_{kem} = f \{ \frac{(2+a)}{(1+a)} \cdot PO_4\text{-}P_{bio} + 3(DOS) \cdot k - b) \}$$

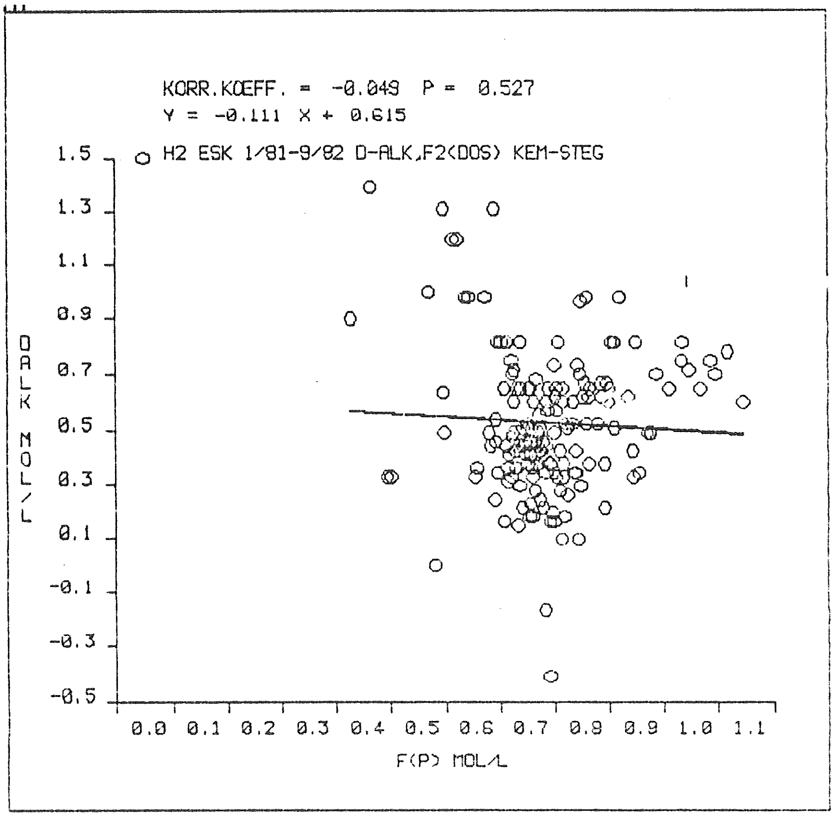
where Alk = alkalinity (mmol/l)
a = exp(10) $(pH_{bio}-7,2)$
k = factor representing how many moles of Al^{3+} or Fe^{3+} are contained in 1 g or 1 ml of coagulant
DOS = coagulant dose in g/m^3 or ml/m^3
P - concentrations are given as mmol/l

Results

Measured alkalinity decrease vs the calculated decrease is plotted in Figure 3.9. On the average the measured alkalinity decrease is about 70 % of the calculated. No relationship between the measured and calculated alkalinity decrease has been found. This is surprising as in our previous experience alkalinity decrease and chemical addition are closely related.

Figure 3.9 Observed Change in Alkalinity vs Theoretical Change in Alkalinity

$Alk_{bio} - Alk_{kem}$ in mol/l vs the theoretical change in alkalinity in mol/l for the period 810101 to 820930.



4. DISCUSSION

When this study was undertaken, it was hoped that with the amount of data available it would be possible to identify some general process relationships. However, the expected success has not been achieved. The explanation for this is not known and one can only speculate.

Several of the tested models are quite simple. Reality is more complicated. Many relationships have however a strong theoretical basis and even if factors not accounted for also are of importance, it is believed that better correlations should be expected. Some of the tested relationships e.g. alkalinity reduction by addition of coagulants, are strongly believed to be quite accurate discriptions. Still there is no correlation. Having this in mind it is doubtful whether more complex models or more refined statistical analysis is the way to go.

The quality of the data could always be questioned. There are many factors affecting data quality such as flow measurements, sampling procedure, sample handling and analysis. Laboratory analysis quality can to some degree be checked by testing correlations between parameters. The rather good correlation between suspended solids and particulate COD (Figure 6a) indicates that laboratory analysis is not the major reason for the disappointing results of this study.

Some objections could be raised against a study of this type:
The sampling interval is quite coarse. In the best case there is data each day. For many parameters there are data only once or twice a week. At the same time we know that changes such as a large increase in flow can occure within a few hours. We have registered daily averages, if the rate of change of process conditions is an important parameter our data is probably quite insufficient. Short but large disturbances give little effect on input data but may have large influence on performance.

Another objection is that the detention time in the Eskilstuna plant is long, about 15 hours at a flow of 50 000 m^3/d. It is not the same water that is sampled in the daily composites. This is however not believed to be a major reason to the disappointing results as most of the process relations tested are for one treatment stage only. At each treatment stage the detention time is only a few hours.

Looking at plots of performance over time one has the impression that during certain time periods the plant functions better or worse. The reasons for this could be many. The sludge may for some reason have developed certain properties or there is a certain operator that runs the plant. Temperature effects, other than the well-known effects on viscosity and microbial growth rate, probably exist. This could be interesting to analyze further.

Another approach could be to use models that are still simpler than the ones tried here. A few master variables could be identified e.g. flow and temperature (or season).

5. PRACTICAL EXPERIENCE USING THE SWEP DATA BASE

5.1 Data Limitations

Finding process relationships from historical operational data is often difficult because of uncontrollable system disturbances. Experience from working with the SWEP data has shown that the amount of usable data is quickly reduced when several parameters are required by a model. Table 5.1 shows the number of observations (all the data recorded for a particular day can be called an observation) with the necessary information for the models tested in Section 3. The degree of difficulty is a subjective measure used to categorize each model according to the relative availability of the required parameters. The relatively simple models had the highest number of observations, the more difficult fewer, as could be expected. What is surprising is the number (7 of 17) which have frequencies of less than once per week (15%). The difficulty in calculating some of the more common control parameters, such as mean cell residence time, is disappointing. The frequency with which observations will satisfy a model unfortunately is generally not predictable. The sampling programme and its practical execution should be reexamined. Minor adjustments may increase the number of usable data.

5.2 Outliers and Documentation

Outliers are those measured values that lie outside the normal clustering of data and can be isolated by choosing some arbritrary boundary (1%, 5%, 10%, etc) and noting those data points which lie in the chosen upper (and/or lower) percentile. Outliers may represent process disturbances, effects of weather, inaccurate sampling measurements, other unexpected operating conditions or may realistically represent true operating conditions. When working with data sets, outliers can often significantly affect statistical results, especially standard deviation, and therefore it is often desired to determine if an outlier can be rejected on the the basis that it does not fairly represent operational conditions.

Table 5.1 No. of Complete Observations for Each Model.

Model tested in section	No. of Observations	% of Maximum-Calculated	Degree of Model Complexity
3.1	120	-	C
3.2	123	19	C
3.3	109	17	C
	393	62	C
3.4	80	13	A
	421	66	C
3.5	45	-	A
	84	-	A
3.6	61	10	B
	114	18	B
3.7	92	14	B
	92	14	B
3.8	224	35	B
	196	31	B
	296	46	C
3.9	171	27	C

Note: A = complex
B = medium complexity
C = simple

Maximum possible observations 638. (810101 to 820930)

In this study, the highest 10% of measured values were examined for the sampling parameters: SS, COD, BOD, P-TOT, COD-FILT and BOD-FILT after biological treatment. It was found that about a quarter of the outliers occured during periods of high flow (>70 000 m^3/d). Thus washout of the secondary clarifiers may account for some of the outliers. Other causes were investigated to explain the remaining outliers by examining the daily log book.

Recordings in the daily log books for 1980 and 1981 were rather sparce. Those days which had outliers and which had some event recorded in the log books are summarized in Table 5.2. (Comments in the original Swedish.) Upon examination there were no outliers that could be explained by events recorded in the daily log books!

For the SWEP project the daily log book can be a valuable communications tool for the post interpretation of wastewater treatment plant performance and operating conditions. All deviations from the norm should be recorded by the plant operator. These can include adbrupt changes in inflow and weather, high influent SS or BOD loading, settling problems, clarifier washout, mechanical failures and what effect they have on operations, changes in operational strategy (e.g. changing the rate of sludge wastage) and why these changes were made. The daily log should reflect the experience of the plant operator and contain as much relevent information as possible:

Niku and Schroeder (1981) summarize the importance of the daily log book in identifying outliers:

> "The nature of these outliers is determinable only if the source and reason for each outlier is noted and documented properly by the plant operator"

TABLE 5.2 OUTLIERS AFTER BIOLOGICAL TREATMENT

Date	Parameter	Value	Log Book Information	Notes
810612	SS	180	BioKemsteget transf lägger av kl 14.15	high flow
810625	SS	280	Pumpa primärslam från ficka 1-8 2 ggr/dygn	
811102	SS	260	Skrapfel i kemsteget - 5:ans bassäng	extr. high flow
811118	SS	160	Instrumentfel i kemsteget	
811124	SS	200	Membranfel med provtagare eft. Försed paj.	high flow
811210-14	SS		Krångel med provtagare utg	
811102	COD	240	Skrapfel i kemsteget - avstängt 5:ans bassäng	ext. high flow
811123	COD	200	Provtagare eft. försed. paj. Membranfel	high flow
811212	COD	200	Krångel med provtagare utg	
811102	BOD	50,0	Skrapfel i kemsteget - avstängt 5:ans bassäng	ext. high flow
811118	BOD	49,0	Kemsteg - reparerat läckan på instrument luften	
810625	PTOT	16,0	Pumpa primärslam från ficka 1-8 2 ggr/dygn	
810630	PTOT	7,5	Från 810701 - strömavbrott BioKemsteget	
810822	PTOT	7,7	Från 810820 - startat 8:ans bassäng och stoppat 1:ans bassäng, byte av drev omrörare	
810826	PTOT	7,6	1:ans bassäng försed, åter igång efter rep av omrörare	
811102	PTOT	11,0	Skrapfel i kemsteget - avstängt 5:ans bassäng	ext. high flow
811119	PTOT	12,0	Från 811117 - reparerat läckan på instrument, luften till kemsteget - kopplingsfel	
811123	PTOT	8,8	Provtagare efter försed paj - membranfel	high flow
810326	BOD_{FILT}	2,5	Från 810325 - sänkt hastigheten på skrapor i klarbassäng 1 o 2 fr 1,8 till 0,85 m/min	

5.3 Comments on the FYKE System

Maintenance and operation data collected for the SWEP project is recorded and stored in the Digital VAX/VMS Version 2.4 computer at IVL-Konsult AB, Stockholm. The FYKE (FYsikKEmi) package program was developed by IVL for the storing, retrieving and the analysis of recipient water data. Statistical analysis, plotting and FORTRAN programming are available under the FYKE system. The possibilities and limitations of the FYKE system are described by Olsson (1982).

Positive Aspects of FYKE

The FYKE package on the IVL/VAX system is easy for the new user to learn after they are aquainted with the VAX SOS editor language. The FYKE Operatörshandledning Version 2 describes the programs available to the FYKE user and gives general examples for each program.

The operations and maintenance data is logically organized by measurement station (INK, MEK, BIO, etc) type of measurement (grab sample, 24 hour flow weighted composite, weekly average, etc) and parameter measured (SS, BD, NH, etc). With a schematic map over the wastewater treatment plant, it is easy to pinpoint the station desired and to create a file containing data from that station.

The IVL/VAX computer system is very efficient to learn and use, is descriptive of its editor operations (reading, copying and printing of files, etc) and is a timesaver because of the simplified job control language. It is useful that FORTRAN programs can be written, debugged and tested outside of the FYKE package, increasing the multiuse capacity of such programs.

Interactive job execution makes the FYKE system easier to use for the new user although it could be better documented.

The statistics program STSTA is user time efficient but lacks the finesse of larger statistical packages (e.g. SPSS - Statistical Package for the Social Sciences and SAS - Statistical Analysis System).

The plotting program FKXY is useful because it gives the user control over the form plots will have and especially control over the scaling of axis. Many plots can be made holding the axis scale the same for comparison studies.

Recommendations for the FYKE System

The documentation of the FYKE system lacks a version of the Operatörshandledning tailored to the SWEP project. The recipient water examples are not fully adequate to illustrate how FYKE can be used to analyse wastewater treatment plant performance and relevant examples should be substituted. The Operatörshandledning should include: a list of ID arguements for program FKUPD (TYP, OMR, AAR, MAAN, DAG, etc); a similar list of ID arguements for program STSE; and be up to date as to what is available on FYKE (e.g. the two stipulated percentiles for PERCEN in program STSTA were not available but were described in Version 2).

To complement the documentation of FYKE, the measurement program used for the SWEP project should be historically documented to assist the user. For each wastewater treatment plant the following should be included: a schematic diagram of the sewage treatment facility showing the location and station code of each measurement station; a list of measurement stations with a sublist of parameters measured at each measurement station; frequency of measurement for each parameter; available record length for each parameter; and the testing method standard followed.

Certain limitations and programming difficulties are noted with the FYKE system. Building large UDF (utdatafil) files containing information from several measurement stations is time consuming and executing FORTRAN programs which use these large input data files is expensive. It should be straightforward to create a file containing, for example, all SS data over each treatment stage in the same table. FYKE is rather limited in the size allotted in RUO translation files for parameter symbols, parameter descriptive names and dimensioning for parameters. This makes descriptive programming more difficult. It would be an improvement if each parameter was uniquely defined by its type and measurement station instead of the present sorting by measurement stations. Tabulation and calculations would be simplified.

When program CALC is used to execute a FORTRAN program, the resulting FOR013.DAT file showing what was executed under CALC is often too large to get a quick survey of the operations performed in the FORTRAN program. This is often of interest when testing a hypothesis to review the input data but with the FYKE system this is not easily done. Every new date receives a data record in the FOR013.DAT file. It should be possible to examine a file containing only the observations where calculations were made (as executed by the FORTRAN program). This is useful in data analysis since trends, etc can be observed in the input data or in the calculated data. This affects also the use of program STSTA for statistical analysis. No distinction is made for those days where calculations were made, thus when program STSTA is run, all the data fitting the STSE specifications is processed which often includes more values than just those used for calculations by the FORTRAN program. Statistics for the input data used in the calculations of the FORTRAN program are not easily compiled. This is significant for determining if the input data is representative.

The above observations show that working with large UDF files is one of the major handicaps with the FYKE system. If each measured value were identified by its parameter name and measurement location, then each is unique in the storage system. It should be possible to create a working data file directly with program FKUPD by uniquely specifying each parameter code (eg. SS(BIO), CD(KEM)) plus any sorting conditions (eg. a specific time interval). MIXUDF, i.e. FKMRG, is eliminated, CALC can be streamlined, more versitile, efficient and significant programming and execution time can be saved.

The statistical program STSTA contains only elementary statistical analysis capabilities and this could be complemented for the SWEP project. Even the analysis of operation and maintenance data to describe the performance of a sewage treatment plant should contain estimates of skewness, kurtosis, variance, range and mode. For a more complete analysis, log normal means and geometric means should also be estimated. For more research oriented data analysis, factor analysis, nonlinear regression, ranking, sorting, spectral analysis, time series, stepwise regression, and variance component analysis, all with parameter testing, are very helpful. These analysis programs may be available on other IVL/VAX library packages and if they are accessible and compatible with the FYKE system, such availability should be mentioned in the Operatörshandledning.

NOMENCLATURE

a = exp (10) (pH_{bio}-7,2)

A = area of sedimentation tank (m^2)

Alk_{bio} = alkalinity of biologically treated wastewater (mmol/l)

Alk_{kem} = alkalinity of post precipitate wastewater (mmol/l)

b = COD loading from domestic wastewaters = Q_s*COD_s*C (g/d)

$BOD_{FILT,bio}$ = filtered BOD of biologically treated wastewater (gO_2/m^3)

C = non-degradable portion of COD_s

COD_{bio} = COD of biologically treated wastewater (gO_2/m^3)

$COD_{FILT,bio}$ = filtered COD of biologically treated wastewater (gO_2/m^3)

COD_{INF} = COD of infiltration water (kgO_2/m^3)

COD_{ink} = COD of influent wastewater (g O_2/m^3)

COD_{mek} = COD of presettled wastewater (g O_2/m^3)

COD_s = COD of domestic wastewater (gO_2/m^3)

DOS = coagulant dose (g/m^3)

F = relative solids loading (dim less)

k = factor representing how many moles of Al^{3+} or Fe^{3+} are contained in 1 g or 1 ml of coagulant

$MRCT$ = mean cell residence time (days)

$MLSS$ = mixed liquor suspended solids (g/m^3)

$NH_3\text{-}N_{kem}$ = ammonia in post precipitated wastewater (g/m^3)

NO_2+NO_{3kem} = nitrite and nitrate in post precipitated wastewater (g/m^3)

$N_{TOT,kem}$ = total nitrogen in post precipitated wastewater (g/m^3)

pH_{bio} = pH of biologically treated wastewater

pH_{THEORY} = pH based on alkalinity data

$PO_4\text{-}P_{bio}$ = phosphate-phosphorus in biologically treated wasterwater (g/m^3)

$P_{TOT,ink}$ = total phosphorus in influent wastewater (g/m^3)

Q_{bio} = biological treatment effluent flow (m^3/d)

Q_{bis} = wasted sludge flow (m^3/d)

Q_{ink} = influent flow (m^3/d)

Q_{r+s} = return sludge flow (m^3/d)

Q_s = domestic wastewater flow assumed equal to the average water consumption (m^3/d)

r = sludge recycle ratio = Q_{rts}/Q_{bio}

SQI = sludge quotient index = $\frac{200 + SV/3}{MLSS}$ (ml/g)

SS_{bio} = suspended solids in biologically treated wastewater (g/m^3)

SS_{bis} = suspended solids in wasted sludge (g/m^3)

SS_{ink} = suspended solids in influent wastewater (g/m^3)

SS_{1su} = mixed liquor suspended solids (g/m^3)

SS_{mek} = suspended solids of presettled wastewater (g/m^3)

SSVI = stirred specific volume index determined at a solids concentration of 3.5 g/l (ml/g)

SV = sludge volume (ml/l)

SVI = sludge volume index (ml/g)

T = temperature (^oC)

V = aeration tank volume (m^3)

Dimensions are sometimes adjusted by a power factor (10, 10^2, 10^3) to accommodate labelling of figure axis.

References

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Olsson, Gustaf (1982)
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White, M.J.D. (1976)
Design and Control of Secondary Settlement Tanks. Water Pollution Control, pp 459-467, 1976.

APPENDIX A

Appendix A contains summary statistics to each figure presented in Section 3. Included are the variable name, average, standard deviation, standard error, T-test at the 5 % significant level, maximum value, minimum value, number of observations and for Figure 3.4 b the correlation matrix containing the correlation coefficient, probability value and number of observation pairs. Dimensioning follows that presented in the figure text.

Figure 3.1

```
ELX-GRP                                                        IVL 22-NOV-82   20:31:18

                   H9 ESK 1/81-9/82 M3,NB,(QT-QS)/NB QMI-STEG
----------------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-     T-0.05      MAXIMI-   MINIMI-    ANTAL
              VÄRDE  AVVIKELSE   FEL(S.E.)     * S.E.      VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------------
TID
 ÅR          81.374      0.505       0.020       0.039     82.746    81.002       638
FLÖDE
 M3       48269.592  15314.886     606.322    1190.654 141000.00028000.000        638
NEDB
 MM           6.332      4.342       0.396       0.785     28.000     2.000       120
Q-QS/N
           6635.718   5189.447     473.729     938.049  29833.334  1265.306       120
```

Figure 3.2a

```
ELX-GRP                                                        IVL 23-NOV-82   11:09:25

                   H5 ESK 1/81-6/81 Q*COD,(QT-QS) INK-STEG
----------------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-     T-0.05      MAXIMI-   MINIMI-    ANTAL
              VÄRDE  AVVIKELSE   FEL(S.E.)     * S.E.      VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------------
TID
 ÅR          81.295      0.139       0.012       0.024     81.495    81.021       131
Q*COD
 KG       12567.308   4674.456     916.736    1887.937  27000.000  2730.000        26
QT-QS
 M3       24053.346  10035.705    1968.164    4053.260  58400.00012400.000         26
```

Figure 3.2b

```
ELX-GRP                                                        IVL 17-DEC-82   12:12:47

                   H5 ESK 6/81-9/82 Q*COD,(QT-QS) INK-STEG
----------------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-     T-0.05      MAXIMI-   MINIMI-    ANTAL
              VÄRDE  AVVIKELSE   FEL(S.E.)     * S.E.      VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------------
TID
 ÅR          82.055      0.380       0.021       0.041     82.745    81.498       340
Q*COD
 KG       11634.742   4671.268     474.295     941.485  40700.000  4680.000        97
QT-QS
 M3       24588.560  16107.037    1635.422    3246.343  98400.000  5400.000        97
```

Figure 3.3a,c,e,f

```
ELX-GRP                                                        IVL 23-NOV-82   09:43:06

                   H7 ESK 1/81-6/81 CD/CD,SS/SS (MEK/INK),M3 QMI-STEG
----------------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-     T-0.05      MAXIMI-   MINIMI-    ANTAL
              VÄRDE  AVVIKELSE   FEL(S.E.)     * S.E.      VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------------
TID
 ÅR          81.248      0.143       0.011       0.021     81.495    81.002       181
CD/CD
              0.581      0.202       0.044       0.092      0.957     0.286        21
 SS/SS
              0.341      0.195       0.019       0.038      1.056     0.039       105
 FLÖDE
 M3       49977.201  13251.816     985.000    1943.568 141000.00032000.000        181
```

Figure 3.3b,d,e,f

```
ELX-GRP                                                 IVL 23-NOV-82   10:18:49

               H7 ESK 7/81-9/82 SS/SS,CD/CD (MEK/INK),M3 QMI-STEG
--------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-    T-0.05     MAXIMI-    MINIMI-   ANTAL
              VÄRDE  AVVIKELSE  FEL(S.E.)    * S.E.     VÄRDE      VÄRDE     VÄRDEN
--------------------------------------------------------------------------------
 TID
  ÅR         82.122       0.362       0.017      0.033     82.746     81.498     457
 SS/SS
              0.333       0.180       0.011      0.021      1.259      0.063     288
CD/CD
              0.530       0.158       0.017      0.033      0.889      0.155      88
 FLODE
  M3      47592.998   16022.072     749.481   1472.892 132000.00028000.000     457
```

Figure 3.4a

```
ELX-GRP                                                 IVL 10-DEC-82   09:37:28

               H1A ESK 1/81-9/82 SS,F(SVI,SSL,Q) BIO-STEG
--------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-    T-0.05     MAXIMI-    MINIMI-   ANTAL
              VÄRDE  AVVIKELSE  FEL(S.E.)    * S.E.     VÄRDE      VÄRDE     VÄRDEN
--------------------------------------------------------------------------------
 TID
  AR         81.369       0.504       0.020      0.039     82.746     81.002     646
  SS
  MG/L       60.610      68.116       7.522     14.967    300.000      5.000      82
  F(SS)
              0.651       0.111       0.012      0.024      0.931      0.326      82
```

Figure 3.4b

```
ELX-GRP                                                 IVL 16-DEC-82   16:37:41

               H1B ESK 1/81-9/82 SS,M3,HLR BIO-STEG
--------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-    T-0.05     MAXIMI-    MINIMI-   ANTAL
              VÄRDE  AVVIKELSE  FEL(S.E.)    * S.E.     VÄRDE      VÄRDE     VÄRDEN
--------------------------------------------------------------------------------
 TID
  ÅR         81.369       0.504       0.020      0.039     82.746     81.002     646
  SS
  MG/L       65.520      71.990       3.538      6.955    340.000      5.000     414
 FLODE
  M3      47505.701   14003.448     682.485   1341.539 132000.00030000.000     421
HLR
  M/H         0.703       0.207       0.010      0.020      1.950      0.443     421
  SS
  MG/L       65.181      71.594       3.439      6.859    340.000      5.000     421

 CO-CORR
 KORRELATIONSMATRIS  (KORR.KOEFF/P-VÄRDE/ANTAL VÄRDEPAR)

               H1B ESK 1/81-9/82 SS,M3,HLR BIO-STEG

 VARIABEL     TID         SS          FLODE    HLR
               ÅR         MG/L        M3        M/H
    SS        0.033
    MG/L      0.497
                414

   FLODE     -0.087      0.559
    M3        0.074      0.000
                421        413

  HLR        -0.087      0.559      1.000
    M/H       0.074      0.000      1.000
                421        413          0

    SS        0.038      1.000      0.561      0.561
    MG/L      0.440      0.000      0.000      0.000
                421        413        421        421
```

Figure 3.4c

```
ELX-GRP                                                     IVL   9-DEC-82   14:28:13

          HIB ESK  1/81-9/82  SS,M3,HLR,SV<200  BIO-STEG
-------------------------------------------------------------------------------------
VARIABEL   MEDEL-   STANDARD-  STANDARD-    T-0.05     MAXIMI-   MINIMI-    ANTAL
           VÄRDE   AVVIKELSE  FEL(S.E.)   * S.E.      VÄRDE     VÄRDE      VÄRDEN
-------------------------------------------------------------------------------------
 TID
  AR       81.369      0.504      0.020      0.039      82.746    81.002       646
  SS
  MG/L     65.620     71.990      3.538      6.955     340.000     5.000       414
 FLODE
  M3    84555.556  31393.117  10464.372  24074.888  132000.00038000.000          9
 SLAMV
 ML/L     154.444     30.459     10.153     23.359     190.000   100.000         9
HLR
  M/H       1.249      0.464      0.155      0.356       1.950     0.561         9
  SS
  MG/L    106.556     94.197     31.399     72.238     300.000     6.000         9
```

Figure 3.4d

```
ELX-GRP                                                     IVL   9-DEC-82   14:51:34

          HIB ESK  1/81-9/82  SS,M3,HLR,200<SV<400  BIO-STEG
-------------------------------------------------------------------------------------
VARIABEL   MEDEL-   STANDARD-  STANDARD-    T-0.05     MAXIMI-   MINIMI-    ANTAL
           VARDE   AVVIKELSE  FEL(S.E.)   * S.E.      VARDE     VARDE      VARDEN
-------------------------------------------------------------------------------------
 TID
  AR       81.369      0.504      0.020      0.039      82.746    81.002       646
  SS
  MG/L     65.620     71.990      3.538      6.955     340.000     5.000       414
 FLODE
  M3    49062.500  13980.724   1235.733   2445.337  123000.00032000.000        128
 SLAMV
 ML/L     314.922     47.818      4.227      8.364     400.000   200.000       128
HLR
  M/H       0.725      0.207      0.018      0.036       1.817     0.473       128
  SS
  MG/L     59.539     72.861      6.440     12.744     320.000     5.000       128
```

Figure 3.4e

```
ELX-GRP                                                     IVL   9-DEC-82   15:02:34

          HIB ESK  1/81-9/82  SS,M3,HLR,SV>400  BIO-STEG
-------------------------------------------------------------------------------------
VARIABEL   MEDEL-   STANDARD-  STANDARD-    T-0.05     MAXIMI-   MINIMI-    ANTAL
           VARDE   AVVIKELSE  FEL(S.E.)   * S.E.      VARDE     VARDE      VARDEN
-------------------------------------------------------------------------------------
 TID
  AR       81.369      0.504      0.020      0.039      82.746    81.002       646
  SS
  MG/L     65.520     71.990      3.533      6.955     340.000     5.000       414
 FLODE
  M3    43864.407   6866.357    893.989   1789.535   69000.00032000.000         59
 SLAMV
 ML/L     522.881    110.532     14.390     28.805     840.000   410.000        59
HLR
  M/H       0.548      0.101      0.013      0.026       1.020     0.473        59
  SS
  MG/L     80.559     67.516      8.803     17.621     250.000     5.000        59
```

Figure 3.5a,b

```
ELX-GRP                                                    IVL 31-JAN-83  16:37:32

                   ESK 1/81-9/82 SLAMA(STD. METOD),SLAMAK BIO-STEG
-------------------------------------------------------------------------------------
VARIABEL     MEDEL-   STANDARD-   STANDARD-    T-0.05    MAXIMI-    MINIMI-    ANTAL
             VÄRDE    AVVIKELSE   FEL(S.E.)   * S.E.     VÄRDE      VÄRDE      VÄRDEN
-------------------------------------------------------------------------------------
 TID
  ÅR         81.994     0.577       0.021      0.042     82.998     81.002      738
 SLAMA
  DAG         9.299     7.583       1.130      2.278     39.315      0.394       45
 SLMAK
  DAG         8.945     9.029       1.346      2.713     45.541      0.370       45
```

Figure 3.5c,d,e

```
ELX-GRP                                                    IVL  4-FEB-83  14:06:08

              H6 ESK 1/81-9/82 SLAMA,SLAMAK,BF BIO-STEG
-------------------------------------------------------------------------------------
VARIABEL     MEDEL-   STANDARD-   STANDARD-    T-0.05    MAXIMI-    MINIMI-    ANTAL
             VÄRDE    AVVIKELSE   FEL(S.E.)   * S.E.     VÄRDE      VÄRDE      VÄRDEN
-------------------------------------------------------------------------------------
TID
 ÅR          81.994     0.577       0.021      0.042     82.998     81.002      738
SLAMA
DAG           8.140     5.329       0.565      1.122     32.219      0.676       89
SLMAK
DAG           7.723     6.358       0.674      1.339     37.321      0.230       89
BODF
MG/L          1.973     0.319       0.043      0.097      2.700      1.000       44
NH/NT
              0.494     0.223       0.040      0.082      0.789      0.011       31
NN/NT
              0.553     0.241       0.033      0.066      0.938      0.125       53
```

Figure 3.6a

```
ELX-GRP                                                    IVL 17-DEC-82  13:04:01

             H4A ESK 1/81-9/82 CD,CF,SS,CD-CF,(CD-CF)/SS BIO-STEG
-------------------------------------------------------------------------------------
VARIABEL     MEDEL-   STANDARD-   STANDARD-    T-0.05    MAXIMI-    MINIMI-    ANTAL
             VÄRDE    AVVIKELSE   FEL(S.E.)   * S.E.     VÄRDE      VÄRDE      VÄRDEN
-------------------------------------------------------------------------------------
 TID
  ÅR         81.859     0.504       0.020      0.039     82.746     81.002      646
 COD
MG/L        102.293    57.069       5.299     10.495    240.000     26.000      116
COD F
 MG/L        36.786     8.698       1.011      2.016     50.000     22.000       74
 SS
 MG/L        55.520    71.990       3.538      6.955    340.000      5.000      414
CD-CF
 MG/L        59.831    52.382       6.497     12.989    203.000      2.000       65
CD-CF/S
              0.729     0.502       0.062      0.125      2.667      0.035       65
```

Figure 3.6b

```
ELX-GRP                                                          IVL 22-DEC-82   10:55:09

               H4B ESK 1/81-9/82 CD,CF,SS,M3,QT*CF,QT-QS,QS*CD BIO-STEG
-----------------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-      T-0.05       MAXIMI-    MINIMI-    ANTAL
              VÄRDE   AVVIKELSE   FEL(S.E.)      * S.E.       VÄRDE      VÄRDE     VÄRDEN
-----------------------------------------------------------------------------------------
 TID
  AR          81.869      0.504       0.020       0.039       82.746     81.002      646
  COD
 MG/L        102.293     57.069       5.299      10.495      240.000     26.000      116
 CODF
  MG/L        36.986      8.698       1.011       2.015       60.000     22.000       74
  SS
  MG/L        65.620     71.990       3.533       6.955      340.000      5.000      414
 FLODE
  M3       49596.491  13340.315    1249.482    2475.493  108000.00035000.000         114
 QT*CF
 KG            1.322      0.909       0.085       0.169        4.022     -3.420      114
QT-QS
 M3           25.182     13.309       1.293       2.562       33.847      9.676      114
QS*CD
 KG            2.511      1.370       0.123       0.254        5.904      0.640      114
```

Figure 3.6c

```
ELX-GRP                                                          IVL 31-JAN-83   10:25:21

               H4B ESK 1/81-9/82 CD,CF,SS,QT*CF>0,QT-QS,QS*CD BIO-STEG
-----------------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-      T-0.05       MAXIMI-    MINIMI-    ANTAL
              VÄRDE   AVVIKELSE   FEL(S.E.)      * S.E.       VÄRDE      VÄRDE     VÄRDEN
-----------------------------------------------------------------------------------------
 TID
  AR          81.869      0.504       0.020       0.039       82.746     81.002      646
  COD
 MG/L        102.293     57.069       5.299      10.495      240.000     26.000      116
 CODF
  MG/L        36.986      8.698       1.011       2.015       60.000     22.000       74
  SS
  MG/L        65.620     71.990       3.538       6.955      340.000      5.000      414
QT-QS
 M3           24.909     13.778       1.302       2.580       83.847      9.676      112
 QT*CF
 KG            1.397      0.708       0.067       0.133        4.022      0.169      112
QS*CD
 KG            2.521      1.380       0.130       0.258        5.904      0.640      112
```

Figure 3.7a

```
ELX-GRP                                                          IVL 22-NOV-82   19:14:23

               H3A ESK 1/81-9/82 PP/PT,F(DOS,PP,PT) BIO-STEG
-----------------------------------------------------------------------------------------
VARIABEL      MEDEL-  STANDARD-   STANDARD-      T-0.05       MAXIMI-    MINIMI-    ANTAL
              VÄRDE   AVVIKELSE   FEL(S.E.)      * S.E.       VÄRDE      VÄRDE     VÄRDEN
-----------------------------------------------------------------------------------------
 TID
  AR          81.869      0.504       0.020       0.039       82.746     81.002      646
PP/PT
               0.266      0.213       0.022       0.044        1.250      0.031       92
 ME/PT
               1.295      0.609       0.063       0.126        3.299      0.037       92
```

Figure 3.7b

```
ELX-GRP                                                  IVL  22-NOV-82   20:06:47

                H8C ESK 1/81-9/82 PP/PT,F(DOS,PP) BIO-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-    STANDARD-     T-0.05       MAXIMI-   MINIMI-    ANTAL
             VÄRDE   AVVIKELSE    FEL(S.E.)     * S.E.       VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.869       0.504       0.020       0.039       82.746    81.002       646
 PP/PT
              0.260       0.213       0.022       0.044        1.250     0.031        92
 ME
              0.228       0.062       0.006       0.013        0.380     0.007        92
```

Figure 3.8a

```
ELX-GRP                                                  IVL  18-NOV-82   14:34:05

                H3A ESK 1/81-9/82 PH(TEORI),PH KEM-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-    STANDARD-     T-0.05       MAXIMI-   MINIMI-    ANTAL
             VÄRDE   AVVIKELSE    FEL(S.E.)     * S.E.       VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.938       0.501       0.015       0.030       82.746    81.002      1103
 PHTEO
              6.505       0.231       0.015       0.030        8.756     6.090       224
  PH
              6.878       0.184       0.012       0.024        7.900     6.300       224
```

Figure 3.8b

```
ELX-GRP                                                  IVL  22-DEC-82   11:34:18

                H3A ESK 1/81-9/82 PH(TEORI),PH EJ SP! KEM-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-    STANDARD-     T-0.05       MAXIMI-   MINIMI-    ANTAL
             VÄRDE   AVVIKELSE    FEL(S.E.)     * S.E.       VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.379       0.507       0.020       0.040       82.746    81.002       627
  PH
              7.233       0.437       0.080       0.163        8.000     6.600        30
 PHTEO
              6.491       0.125       0.023       0.047        6.738     6.275        30
```

Figure 3.8c

```
ELX-GRP                                                  IVL  18-NOV-82   15:45:08

                H3C ESK 1/81-9/82 LOG(PP),PH KEM-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-    STANDARD-     T-0.05       MAXIMI-   MINIMI-    ANTAL
             VÄRDE   AVVIKELSE    FEL(S.E.)     * S.E.       VÄRDE     VÄRDE      VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.938       0.501       0.015       0.030       82.746    81.002      1103
 LOGPP
             -1.041       0.337       0.020       0.039       -0.215    -2.000       296
  PH
              6.902       0.211       0.012       0.023        8.000     6.300       316
```

Figure 3.8d

```
ELX-GRP                                                 IVL 22-DEC-82   14:11:52

               H3C ESK 1/81-9/82 LOG(PP),PH EJ SP! KEM-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-  STANDARD-   T-0.05      MAXIMI-   MINIMI-   ANTAL
             VÄRDE   AVVIKELSE  FEL(S.E.)   * S.E.      VÄRDE     VÄRDE     VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.879     0.507      0.020     0.040      82.746    81.002     627
  PH
              7.342     0.489      0.063     0.135       8.100     6.400      52
LOGPP
             -1.007     0.273      0.039     0.075      -0.495    -2.000      51
```

Figure 3.8e

```
ELX-GRP                                                 IVL 18-NOV-82   15:23:55

               H3B ESK 1/81-9/82 PH(TEORI),LOG(PP) KEM-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-  STANDARD-   T-0.05      MAXIMI-   MINIMI-   ANTAL
             VÄRDE   AVVIKELSE  FEL(S.E.)   * S.E.      VÄRDE     VÄRDE     VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.879     0.507      0.020     0.040      82.746    81.002     627
 PHTEO
              6.566     0.234      0.016     0.032       8.756     6.090     211
LOGPP
             -1.032     0.320      0.023     0.045      -0.215    -2.000     196
```

Figure 3.8f

```
ELX-GRP                                                 IVL 22-DEC-82   13:52:39

               H3B ESK 1/81-9/82 PH(TEORI),LOG(PP) EJ SP! KEM-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-  STANDARD-   T-0.05      MAXIMI-   MINIMI-   ANTAL
             VÄRDE   AVVIKELSE  FEL(S.E.)   * S.E.      VÄRDE     VÄRDE     VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.879     0.507      0.020     0.040      82.746    81.002     627
 PHTEO
              5.493     0.128      0.021     0.047       5.733     5.275      39
LOGPP
             -1.043     0.294      0.055     0.114      -0.495    -2.000      28
```

Figure 3.9

```
ELX-GRP                                                 IVL 18-NOV-82   13:50:49

               H2 ESK 1/81-9/82 D-ALK,F2(DOS) KEM-STEG
----------------------------------------------------------------------------------
VARIABEL     MEDEL-  STANDARD-  STANDARD-   T-0.05      MAXIMI-   MINIMI-   ANTAL
             VÄRDE   AVVIKELSE  FEL(S.E.)   * S.E.      VÄRDE     VÄRDE     VÄRDEN
----------------------------------------------------------------------------------
 TID
  AR         81.879     0.507      0.020     0.040      82.746    81.002     627
F(P)
MOL/L         0.786     0.115      0.009     0.017       1.147     0.427     171
DALK
MOL/L         0.528     0.260      0.020     0.039       1.393    -0.410     171
```

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