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Notes for J.-P. Steyer's course from 'Control of Wastewater Systems in Practice'

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INSTRUMENTATION CONTROL AND AUTOMISATION

SCIENTIFIC AND TECHNICAL REPORT

PART 3

CONTROL OF WASTEWATER SYSTEMS IN PRACTICE

by Marinus K Nielsen

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1 SCOPE OF THE STR REPORT ON ICA

This scientific and technical report (STR) from the International Water Association specialist group of Instrumentation Control and Automation, (IWA ICA group) is an attempt to collect an updated state of the art report in wastewater systems.

The editors for the three parts of the report were selected to make a plenary presentation at the conference of the ICA group in Malmø 2001 (held every 3rd year). It was decided to make the report as a discussion forum for all interested and, the report is available on the www.SMAC.dk homepage before the conference with possibility for everybody to make their points. The editors has however authority to select from the discussion what to include in the final edition. The final report is scheduled to be finalised at the end of year 2001. Professionals can before, during and after the conference give their input to the discussions.

We are not aiming at making a textbook or a complete manual of present practice, but more to focus on the edge technology where we are still expected to see new understanding and development. Therefore, there will be some contradictions in the different parts and between different contributions, dependent on the different assumed hypotheses in the ICA area.

Prof. Gustaf Olsson, the chairman of the ICA group, is head of the editor collegium, and the main editor for measurements is Anders Lynggaard-Jensen, for control Yuan Zhiguo and for practical operations Marinus K Nielsen.

2 PREFACE TO PART 3

This practical part is based on a technical and economic approach to control. The economic benefit of the different control possibilities is quantified. The more qualitative benefits, such as better process understanding and more challenging work for the operator is described. The report focuses on how modern control systems can improve operation and how it can identify the improvements and mistakes made by the operator's adjustments of the available control system. It also deals with the ability of ICA to solve many of the documentary tasks necessary for environmental and economic reporting, by using the available measurements and information technology to adapt model online. Also data reduction is pointed out as an important task for a modern control system in order to improve the evaluation of the total system performance and robustness.

The basis for the new control improvements is a varity of theories or hypotheses combined with the available online information in the system. The main aim is to point out, that models are a simplified description of reality. When new control repeatedly reveals a new effect that indicates differences from the modelled effect, this effect should not be rejected, but it should be investigated further in other places to see if it gives a general relation that can improve control generally.

More speculative result is presented in this part of the report to reveal new hypotheses. However, to postulate a hypothesis is correct need all the boundary conditions to be fulfilled. As the necessary boundary conditions are seldom available in full-scale control, proving of a new hypothesis by full-scale documentation and boundary condition confirmations must be substituted by multiplying the experiments over periods and, if possible, used in more plants. Hereby rejecting new correct understandings is avoided.

The results of a good control are often so small improvements that they cannot be identified in the normal noisy environment on the full-scale systems, but this does not mean that say 10% improvement is an insignificant improvement. It just means that the disturbances from load and operations etc. are higher, and more experiments are needed before a significant quantifiable conclusion can be extracted.

3 SUMMARY

In the past decade, more holistic approach for management and control of wastewater systems consisting of sewer systems and treatment plants has been developed, by use of new models and measurements. To be able to put the many different available controls on the list of priorities, there is a need for a structured decision hierarchy within the control systems.

By introduction of integrated controls, ICA has increased capacity by 10 - 30% today in biological nutrient removing wastewater treatment plant (BNR WWTP). The better understanding of mechanisms today produces an increased understanding of the processes and their sensitivity to control. The control of sludge retention time at different environments of O_2 and substrate levels will affect the reactions, their rates and even the microorganism population selections in the plants. These effects are obtained by adjustment of conventional controls and mixing in different reactor sections of the plant and load distribution control. If these possibilities are exploited in the future, the improvements of ICA by intelligent use of measurements and IT may reach 20-50% within the next 10-20 years.

The gain by ICA in the last decade has been possible due to:

- The new reliable and maintainable online measurements.
- Improved control and modelling methodology
- The development of more open and transparent structured data handling and data distribution systems.

In the future, the operation will probably move towards more integrated control between unit operations within the WWTP and between WWTP and sewer system. The optimal control conditions are decided from the state of multiple criteria, dependent on the plant and often also on the status of the sewer system.

The efficient use of information technology is today a must that will join offline data and online data seamlessly. The newer measurements and simplified modelling tools will produce a lot of new information for control, as well as reduce the excessive amount of data to manageable reports; this will further improve research and understanding of control possibilities. An important task today is to evaluate what is the right level in ICA for a given wastewater system for control, tuning and reporting.

In this evaluation, 3 online levels are defined, and one offline level on top of the online levels to form the ICA for the wastewater systems.

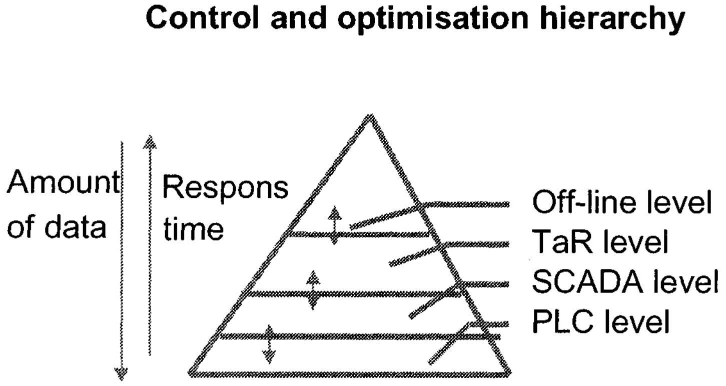


Figure 1 *Information hierarchy*

Level 0 is the lowest level necessary to make the system work is level 0 in the above figure called PLC level, which is generally a copy of the logic from old relay and timer-logic from 30 years ago.

Level 1 where often only human input and output is added to adjust and view the logic in level 0. This level is often called the man machine interface MMI and represents storage and presentation of data. Together level 0 and level 1 are called SCADA level, which is the normal level for most treatment plants today.

The conventional SCADA control approach, constant values are often considered optimal. The apriori knowledge of the control system is expressed as set points for the different control loops. The controls are adjusting the available final elements to keep the measured value close to the specified set point, by single loop controls.

Level 2 take advantages of that experience has shown, that the set points for the different control loops are strongly interrelated and dependent on the situation in the different unit operations of the system. To handle this dependence, a tuning and reporting level is added to the normal two-level control hierarchy. This level 2 is called TaR level in the following.

To be able to handle the challenges of defining the variable optimal control conditions, large amounts of data have to be considered. In the large data handling from more complex origin, a tuning and reporting level (TaR) in the control hierarchy makes it cost-efficient to handle much more data with less dense information value. The TaR level also distributes the extracted important pieces of information to where the information is of value. As the decision level is more process oriented, the reuse of experiences from plant to plant is much larger than for lower levels in the hierarchy, where the optimal conditions are strongly dependent on available equipment.

The more integrated a control is, the more dependent it is on different information, and the control must be able to prioritise between multiple evaluation criteria. To avoid loosing the overview and the dynamic prioritisation, structured systems are expected to be more necessary in the future.

The skill to handle this integrated system will need more self-educating operation. The ICA system must provide the evaluation of the improvement as reports of key figures from the huge amount of online and offline data. The operator must have the tool to extract quantification of the control improvements out of the detailed data, in order to evaluate the effect of his adjustment of the control. These evaluations must take the total system performance into consideration over longer periods of time, to be representative. An improvement of saving energy by O_2 control, is not acceptable if it deteriorates the sludge settleability and reduces the plant capacity over a longer period.

In the future, the operator will need to be skilled in more disciplines, from mechanical, electrical and process understanding, to development of the best control. The operator may get support from experts, but mostly they will educate themselves by "learning by doing". Hereby he will be expert on his own system for most topics, but there will probably always be some topics where periodic external help or discussion partners are beneficial for the operator. User groups for different types of treatment plants and sewer systems ought to be developed for normal use in the future wastewater treatment. The Internet can make these groups close to global for any special topics.

4 INTRODUCTION

This 3'rd part of the STR report on ICA is focusing on practical implementation and operation of full-scale systems. Hence the basic aim is to illustrate different techniques used to create a cost efficient control, from the understanding of the physical possibilities in the given plant, and use them with the available measurements to fulfil as many of the improvements as the control theory and model understanding reveal.

In the sections 5 and 6 is a short extract of the report on control from Yuan Zhiguo and measurements from Anders Lynggaard-Jensen.

In section 7 we will discuss the driving force for ICA in the system, and Economics are described.

These data are not systematically reported, so based on the Danish experience the most important relations is presented. It is hoped that others can supplement with general and significant changes from other countries.

In chapter 8, the terminology and the tools used in the ICA are introduced, while chapter 9 gives examples on control in different scopes mainly from the TaR level control approach.

Chapter 10 summarises the future for operation and development in ICA, and chapter 11 gives the conclusion of this preliminary report on practical use of state of the art control on wastewater systems.

5 CAUSE AND EFFECT MATRIX

According to the literature, the biological process is the most control relevant part of a wastewater system, and especially the biological nutrient removal (BNR) processes are very sensitive and dynamically loaded, so the greater part of the following is concentrated on these processes.

Biological nutrient removal processes inherently offer little operational flexibility. Few inputs and control handles are available for the process engineer to compensate for disturbance attenuation. Indeed, it is questionable how many of the different process configurations are flexible enough to be controllable (i.e. can all outputs be controlled by manipulating the available variables). When a undesirable operational condition is predicted. Is there any operational procedure that can bring the plant from the present state to a desired state? At present, there is very often insufficient knowledge to answer this question.

It is well known that the sludge recycle rate, sludge removal rate and airflow rate are the most common manipulated variables in activated sludge plants. However, their relationship with plantcontrol objectives is only partly understood. These controls are in very different time scales, and normally the control just keeps constant set-points. There are no reasons to believe that set-points independent on load and capacity is optimal.

How to adjust the set-points can be evaluated from the cause and effect matrices as presented below. All control affects the total plant, and hence on a longer scale will affect each other, however it is common knowledge that a plant are robust to biologic peak loads. Such an example appears from excellent return sludge control without problems, although the return flow were operated by a signal from industry operation in 8-hours shift each day and not during weekends. This could be interpreted, as no control is necessary, or that a very big spare capacity is available to be activate by good control. Optimal control will use this capacity to handle the available disturbances, taking all time-scales into consideration (Nielsen 2000a).

Du to the variating operation condition the importance of differnet control are strongly dependet on load situations, this depends maijor goals: 1 keep sludge in plant 2 keep nutrient down and 3 select a good biological population in the sludge. So in a lifte time of a plant the typical importance are shifting like

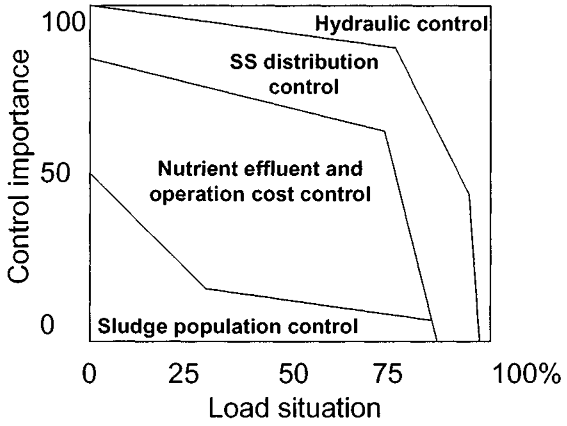


Figure 2 *Importance of different control goals*

Table 1 summarises a qualitative cause and effect analysis of wastewater treatment plant manipulated variables edited by Olsson and Jepson (1994). Note the wide range in dynamic behaviour of the process variables, which for transparency necessitates the structured information handling.

Table 1 *Cause and effect relationships of manipulated variables*

Manipulated Variable "Control handle"	Main Influence	Goal-Constraints	Measurements Estimates	Time Scale
Influent flow rate	Dilution; Clarifier load	Dampen hydraulic disturbances Use hydraulic capacity	Flow rate; Hydraulic retention time, MLSS Effluent susp. solids	min-hrs
Waste sludge flow rate	SRT; Organism composition	SRT set point	MLSS; SRT; Filament content; Sludge settleability	days-weeks
Return sludge flow rate	Sludge distribution; Clarifier hydraulics; Sludge blanket Anaerobic time % for	Keep settler mass inventory within margins; Hydrolysis; Sludge blanket level; Recycle concentration; Effluent sus-	Use sludge buffer in settler to damp hydraulic or organic disturbances;	hr-day

	sludge	pended solids	SVI	
Aeration tank Settling	Hydraulic load	Increase sludge in aeration tank during rainstorms	Flow rates; MLSS, SVI Rain gauge	¼ hour
Step feed	Sludge distribution in aerator	Dampen load disturbances	Flow rates; MLSS, SVI distribution along reactor	hours
Nitrate recycle	Denitrification rate; Oxygen carried over to DN	Carry adequate nitrate for DN; Nitrate reduction of the Bio-P processes	Nitrate; DN rate; redox; OUR	hours
Recycle flows or filter backwash	Hydraulic load	Proper timing; Minimise hydraulic load; Nitrate poisoning	Flow rate; Effluent susp. Solids and NH3	min-hrs
Supernatant recycle (e.g. sludge digester)	Carbon, ammonia load; Denitrification rate; P release;	Proper timing; minimise COD load and NH3 in effluent	COD; DN rate; P removal	<hrs
Chemical dosing	Floc formation; Phosphorous removal; DN-capacity	COD and P removal Proportional to P load or water flow	Effluent susp. solids; PO4, flow	<hrs - days
Carbon addition	DN rate; P release	Dosage for DN; Dosage for bio-P removal	NO3; rate of PO4 release ,flow, OUR	hrs
Air flow rate	DO (locally, globally); Respiration rates; Filament formation Energy saving	Keep DO profile; Intermitting DO; Influent on DN rate in recycle Increase bio-P removal	DO conc.; NH3 OUR; Oxygen transfer rate; CO_2 production; Nitrification rate	min
Phase control	Completion of denitrification reactions; Settling, activity protection	Adequate time for nitrification, denitrification, hydrolysis and P-release reactions	Nitrate, ammonia, phosphorus, OUR susp. solids	min

The craftsmanship is to select the right combination of important controls for the expected operations situation at a given plant with the obtainable reliability of selected measurements.

6 INSTRUMENTATION

The online measurements that may be considered as standard in wastewater treatment plants are DO, pH, level, suspended solids and flow rate. The new sensors for real-time monitoring redox, ammonia, nitrate, phosphorus, TOC/COD, sludgeblanket and rain gauges are also coming into use in standard operation due to their reliability and costs/efficiency.

The choice of sensor will be simpler in the future as a new standard ISO 15839, will assure a better description from the suppliers, so different equipments can be compaired.

The key data needed is shown below in Table 2

Table 2 Sensor performance description in ISO 15839

Performance Characteristic	**Unit**	**Result according to ISO 15839**	
Response$^+$time, Response$^-$time			
Delay$^+$time, Delay$^-$time			
Rise time, Fall time			
Linearity (tested range)			
Coefficient of variation	%		▨
Limit of detection (LOD)			▨
Limit of quantification (LOQ)			▨
Repeatability			
Lowest detectable change (LDC)			
Trueness			
Short term drift	%/day		▨
Day-to-day repeatability			
Memory effect		if yes the value	▨
Interference caused by: interferent 1			
Interference caused by: interferent 2			
Environmental conditions (lower/upper) 1		if yes the value	if yes the value
Environmental conditions (lower/upper) 2		if yes the value	if yes the value

Apart from this equipment test, the measurments also need a test in place. Here the following tests are specified:

Performance Characteristic	**Unit**	**Result according to ISO 15839**	
Response$^+$time, Response$^-$time			
Delay$^+$time, Delay$^-$time			
Rise time, Fall time			
Trueness based on (relative/absolute) differences			▨
Long term drift	%/day		▨
Availability, Up-time	%		

Although the sensors are much better to day; there is always disturbances, from operation etc. so som kind of data check is need. The first task in is quality assurance of raw data. This is often made as an on/off check of max/min value and rate of change; but if data are used in more controls, it is often much better to make a continuos check so information's of different quality might be used for different controls.

Here a graduated test for both above types but also for missing or constant values (Gap filling) should be applied as shown in Figure 3, from Lynggaard-Jensen 2001.

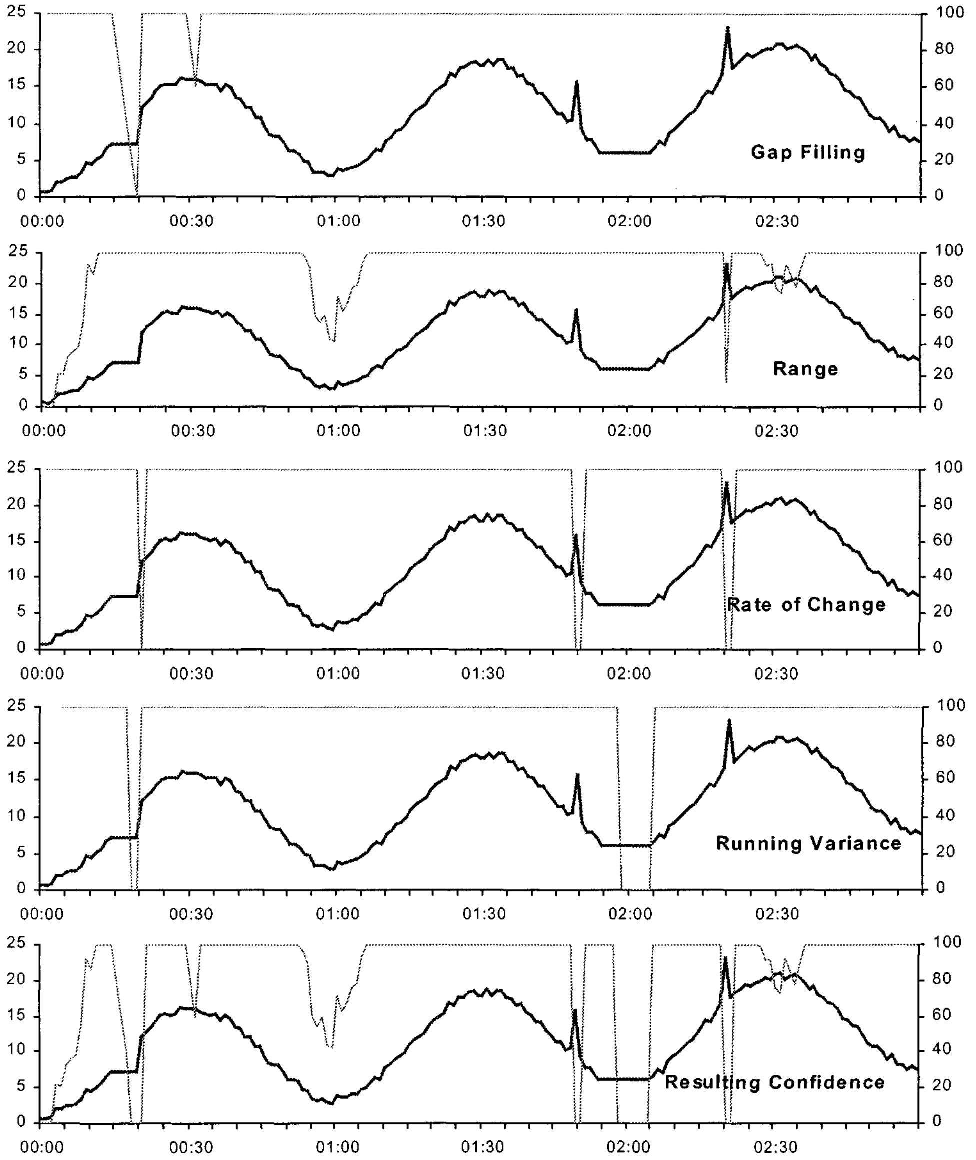


Figure 3 *Data Quality chek with continous quality drop for each type of error.*

The quality decline sensitivity is dependent on parameter and its use. But if we add all the different checks above we get a resulting quality like the lower part of Figure 3. If better quality is to be assured, it is necessary to use a model-based DQC-evaluation, where the physical situation can be introduced in the evaluation, as discussed in section 9.3.2.2.4

7 STATUS IN ICA

The ICA is considered from more angles. In section 7.1.1 is shown the available driving force from investment and operation costs of treatment plants and sewer systems in different countries. In section 7.1.2 the status for applied techniques from the different countries is dealt with, as ICA probably rather follows the techniques applied than the country borders, and finally in section 7.1.3 the use of sensors and control as reported in literature is enlightened.

In section 0 is resumed the typical operation cost distribution for BNR WWTP in Denmark, to see how important the different incentives are from an operation costs view. To also include the effluent quality, the load and effluent quality is introduced in section 7.1.5, as a serious incentive to get the best out of the investment by making the optimal operation of the plants. Finally, in this chapter economic improvements from introducing advanced control and new measurements are evaluated. Development in ICA cost from 1960 till now and the trend for the next 10 years is predicted.

Also in this economic area, more countries' experience will be strongly appreciated.

7.1.1 Investment and operation and management cost for wastewater systems.

As to northern European conditions for nutrient removing plants, the typical investment distribution for the total sewer system is:

25-30% for treatment plants say 300 – 600 Euro/pe for systems larger than 10,000 pe and

70-75% for the sewer systems say 1200- 2400 Euro/pe

The treatment plant investment is distributed with approx. 50% for the water treatment and 50% for sludge handling.

When ICA improves the water treatment facility with say 30%, the saving of the total system cost will only be approx. 5%. This improvement will correspond to 12 –15% of the total WWTP investment. On the sewer, ICA can maybe save 8% of sewer system investment. This will give the same saving for the municipality. Although only small improvement in % might be available for introducing ICA into sewers, it still might be as profitable. The benefit of introducing ICA in the water treatment part of treatment plants is difficult to prove because of the noise level. Also the differences from sewer to sewer system are often larger than the significant ICA improvement of 4-8%.

In the next 10-20 years, investment plans in Denmark are 2-4 billions Euro. Approx. 10-15% of this investment is expected for construction of equalisation or retention basins. It is expected that using combined sewer and plant control will be efficient for down sizing these volumes. In Denmark, this will give a potential saving of say 50-150 mill. Euro during the next two decades. So if the investment in sensors and control is the same size, the benefit/cost relations will be the same.

The control of sludge treatment is normally less needed due to the fact that the loads of the treatment is much less dynamic, so normal operation is not improved to the same degree as for water treatment by optimal control. Although the investment in the water treatment part of the WWTP is not dominating, the ICA provides most potentials in this area, see Figure 4.

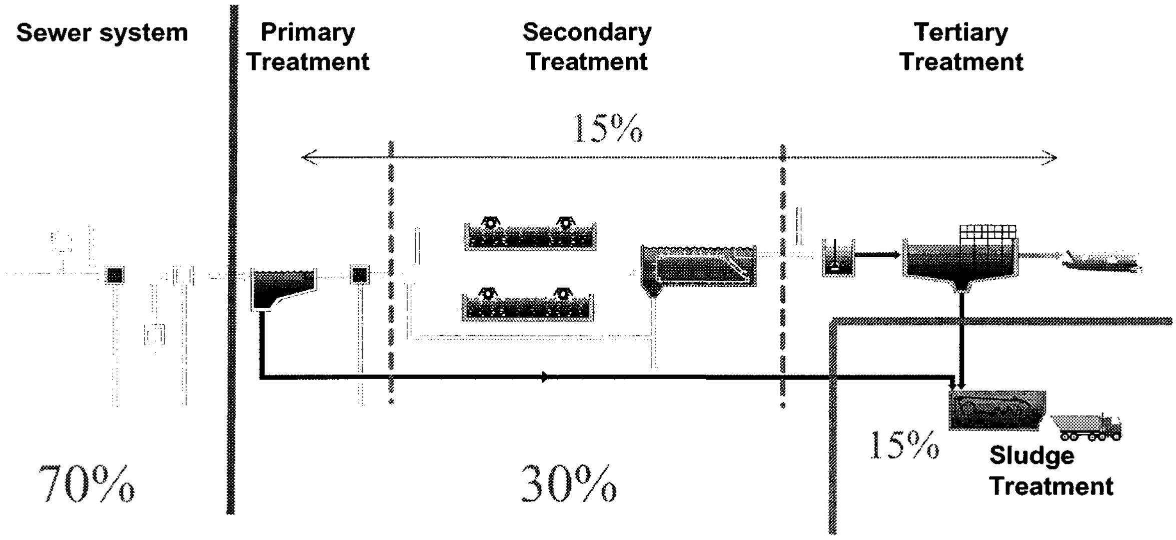


Figure 4 *Investment distribution in wastewater systems.*

Figure 4 is made from a control oriented viewpoint, as it can be seen that the water treatment part, where control has great efficiency, is dominating. The sewer and sludge treatment parts are of less importance, due to the smaller controllability or reduced dynamic in these parts. In control efficiency, the water treatment part typically gives 70% of the improvements obtainable, while sewer and sludge treatment typically only cover 15% each of the improvement obtained by control.

For sewer systems, the investment can be estimated from data given by Nelson 2000. Typically, a sewer contains 7-m sewer/pe and the cost is approx. 350 Euro/m, so the investment is approx. 2450 Euro/pe for American conditions, for a typical sewer with a mean age of 30 years.

The operation cost of sewers in the US have been doubled the last 20 years, mainly due to increased rehabilitation. Also equipment and equalisation are important for the sewer economy in the US. Probably this development is the same in Europe. In Denmark it is planned during the next 20 years to use twice the amount on investment in sewers as has been used on upgrading all plants to nutrient removal during the last 10 years. All the money is planned to be spent on rehabilitation and better stormwater handling, as nearly all areas are already equipped with sewer systems today.

It is especially the for O&M and equalisation volume investment ICA has an important effect. Monitoring of CSO in number and amount via ICA is getting more and more common and the SCADA systems are often extended from the plants to the pumping stations and to each outlet structures in the sewers. When the information is getting into the system, it is the responsibility of ICA professionals to use these data efficiently when they are valuable, as mentioned in section 9.1.1.

7.1.2 Treatment in different countries.

The control is mainly determined by the status of cleaning demand and thereby the technology applied. However, the registration varies in different countries, and there is often more difference in ICA between different plants in the same country than between countries with the same plant technology (= effluent demands). Below data of cleaning demands used are extracted from COST meeting in Vienna, April 2000.

Table 3 Cleaning distribution and size distribution for some European countries.

Status for treatment in Basis for evaluation of Plant wide control R&D in COST Korespomdenz Abw

Treatment	Spain	Romania		Finland		Switzerland		Austria		Denmark		Germany	
degree	% of #pe	% of pe		% of pe		% of pe				% of pe		% of pe	% of #
no		25											
Primary		14						1					
Second.	80,5	61						26				1	7
Chem				10						5			
Sec+P	9,4			25		10						6	32
Sec+Nit													
Sec+Nit+P				40		80		3				16	29
Sec+DN	10,1									75			
Sec+DN+P				25		10		70		20		78	32
size in pe	%of #	#	% of pe	% of #	% of pe	% of #	% of pe	% of #	% of pe	% of #	% of pe	% of #	% of pe
<5000	73					71	9	69	7	82	15	57	0
5-15.000	13					19	24	27	32	8	8	12	4
15-100.000	10	47				5	18			7	28	27	40
>100.000	4	39		<10		4	49	4,4	61	2	49	4	55
Total capacity		15-20 mill pe				18,5 mill. pe		17.520 mill. pe		12 mill. pe		140 mill. pe	
minmal plant size		> 25.000 pe				> 200 pe		>50 pe		>300 pe		> 0 pe	

The figures in Table 3 table are not exact, as different countries use different grouping methods. The difference between the countries in Europe is probably also as diverse as in most of the other industrialised parts of the world, because the development and political priorities are quite different in the shown countries.

As the ICA level is following the plant technology more than the country borders, the necessary organisational and operational skill must follow the technology. The optimal ICA level is probably close to same level all over the world, when relevant educational personnel is available. Therefore the following deals with the ICA operation methods, from the applied treatment technology.

Another interesting information from Table 3 is that control of all plants over 100,000 pe would treat approximately 50% of all wastewater, while 70-80% of the treatment plants are smaller than 10,000 pe and treating less than 10% of the wastewater. There is good common sense in distributing the efficiency of optimisation levels, which is different in different plant sizes, so operation costs are dependent on plant size, as seen in Figure 5. Another aproach is the evaluation presented by Ulf Jeppsson at ICA 2001 in table 4.

*Table 4 Level of instrumentation at WWTPs (>50.000 p.e.) in Europe and the main purpose of the measurements, continued on next page (*usage: *+++ = very often used, i.e. standard, ++ = often used, + = seldom used;* used for: *M = monitoring, B = feedback control, F = feed-forward control).*

	Austria		Belgium		Czech Republic		Denmark	
In-line sensors	usage	used for	usage	used for	usage	used for	usage	used for
Temperature	+++	M	+++		+++	M	+++	M
Conductivity	+++	M	+	M	+		+	M
pH	+++	M	++	M	++	M	++	M
Redox potential	+	M, (B)	+	M, B	+++	M, (B)	+	MB
Pressure	++		+	M	+		++	MB
Water level	+++	M	+++	M, B	++		+++	MB
Water flow	+++	M, B	+++	M, F	+++	M, (B)	+++	MBF
Air flow	++	M, B	++	M	++	M, (B)	++	MB
Dissolved oxygen	+++	M, B	+++	M, B	+++	M, B, (F)	+++	MB
UV-extinction	+	M, B			+		+	MB
Turbidity	+	M, (B)	+	M	+	M	++	MB
Total suspended solids	+	M, B	+	M, B, F	++	M	+++	MB
Sludge blanket level	+++	M, (B)	+	M, B	+	(M)	+	MB
On-line sensors								
BOD			+	M	+			
COD					+		+	MB
TOC			+	M, B, F	+			
Ammonia	+(+)	M, B	+	M	+	(M)	+++	MBF
Nitrate	+	M, (B)	+	M, B	+	(M)	+++	MBF
Total nitrogen					+			
Phosphate	+	M, (B)	+	M, B	+		+++	MB
Total phosphorus					+	(M)	+	MB
Respiration, activity	+++	M, B			+		+	MB
Toxicity			++	M, F	+		+	M
Sludge volume index			+	M, F	+		+	MB

	Finland		France		Germany		the Netherlands	
In-line sensors	usage	used for	usage	used for	usage	used for	usage	used for
Temperature	+++	M	+++		+++		+++	M
Conductivity	+++				+++		+	M
pH	+++	M, B	++		+++		+++	M, B
Redox potential	+++	M			++		++	M, B
Pressure			+++		+++		+	
Water level	+++	M, B	+++		+++		++	M, B
Water flow	+++	M, F	+++		+++		+++	M, F
Air flow	+	M, B	+++		+++		++	M, B
Dissolved oxygen	+++	M, B	++		+++		+++	M, B, F
UV-extinction					+		+	
Turbidity	++	M			++		+++	M
Total suspended solids	+++	M	++		++		++	M, B
Sludge blanket level	++	M, B	++		+		++	M, B
On-line sensors								
BOD	+++	M			++		+	M, (F)
COD	+	M			+		+	M, (F)

TOC					++		+	M, (F)
Ammonia	++	M, B			++		++	M, (B)
Nitrate	++	M, B			++		++	M, (B)
Total nitrogen					+		++	M
Phosphate	+	M			++		+	M
Total phosphorus	+++	M			+		+	M
Respiration, activity					+		+	M, B
Toxicity					+		+	M
Sludge volume index	+++	M, B			+		+	M

	Romania		Slovenia		Spain		Sweden		Switzerland	
In-line sensors	usage	used for	usage	used for	usage	used for	usage	used for	usage	used for
Temperature	+++	M	+++	M	+++		+++	M, B	+++	
Conductivity					++		+++	M	+++	M
pH	+++	M	++	M	+++		+++	M, B	+++	M
Redox potential					++		+	M	++	
Pressure			+	M, B	++		+++	M, B	+++	M, B
Water level	+++	M	+++	M, B	++		+++	M, B	+++	M, B, F
Water flow	+++	M	+++	M, F	+++		+++	M, B, F	+++	M, B, F
Air flow			++	M, B	+++	M, B	+++	M, B	++	M, B
Dissolved oxygen	+++	M, (B)	++	M, B	+++	M, B	+++	M, B, F	+++	M, B
UV-extinction					+		+	M	+	M
Turbidity					+++		++	M	+++	M
Total suspended solids	+++	M			++		+++	M, B, F	+++	M, B
Sludge blanket level	++	M			+		+	M, (B)	+	M
On-line sensors										
BOD					+		+	M	+	M
COD					+		+	M	+	M
TOC			+		+		+	M	+	M
Ammonia					+		+++	M, (B, F)	++	M, B
Nitrate					+		+++	M, B	++	M
Total nitrogen					+		+	M	+	M
Phosphate					+		++	M, B	++	M
Total phosphorus					+		+(+)	M, (B)	+	M
Respiration, activity					+		+	M, B	+	?
Toxicity					+		+	M	+	?
Sludge volume index					+		+	M	+	?

The ICA level in sewer systems is still small, however it is growing quickly, as the importance of separate sewer discharges and combined sewer overflows (CSO) is increasing and the cleaning in the WWTP is improving; however the editor knows no representative information on this area at present.

7.1.3 Status in ICA for WWTP.

Flow and DO are typically the only variables automatically controlled in most systems. These are used for O_2 control, return flow and chemical dosing. Other variables such as SRT and sludge blanket level are normally manually adjusted, by a time or flow proportional control. In anaerobic treatment systems, pH may also be controlled automatically. Further the polymer additions are controlled, but generally we still miss statistics on what is used in typical SCADA systems for sludge handling.

According to Schmitz 2000, most reported control is as described in below Table 5. The data represent what was reported in literature, for control of N removal. The article refers to 29 activated sludge plants. This kind of data is, however, based on incidental report control implementations. This can be seen by the fact that more N measurements are reported than O_2 measurements, which is certainly not representative. It indicates that O_2 control is standard, and therefore not normally worth to report.

Table 5 Reported control in literature

What is controlled	**%**	**Which control**	**%**	**Which input**	**%**
Aeration	51	Two point	21	O2	12
Returnsludg	8	More Point	5	NH3	30
Recirculatio	11	Massbalance	16	NO3	32
Flow	14	Daily fixed	11	redox	12
Excess	11	P:I:D.	5	Q	10
C source	3	Model	21	rNit	2
Chem.Precipi	3	Fuzzy	21	rDenit	2

It is seen that O_2 control is by far the most common control. The conclusion of Schmitz investigation is that control is moving against more multiple input controls.

If we want to have more representative information, we must use questionnaires as executed by Tscheepetzki (2000) for Northeast German plants. He distinguishes between different plant types and sizes and asks what kind of process has been implemented on the different plants and what was successful, as shown in below Table 6 – 6

Table 6 N removal plants technique

Size	**<100Kpe**	**>100Kpe**
technique	**%**	**%**
Cascade	7.3	14
Alternating	9.7	
Simultaneous	24.4	14
Intermitting	19.5	
Predenitrificatio	39.1	72

It is probably common that the distribution of processes for small plants are quite different from large. In most countries also the strong weight on recycling technology using predenitrification is dominating for N removal. Denmark is the only exception, where most of the largest plants are alternating.

Table 7 *Application of measurements in North East Germany*

Which	Measurement %	Adjustment %	Control %
O2	80	32	27
NH3	44	15	15
NO3	44	17	12
PO4	49	17	15
redox	17	10	15
SS	20	5	2

It is surprising that measurements are so often installed, but without direct control use. It seems that less than 1/3 of the measurements are used for direct control, and even O_2 is often not used. I hope this is not representative for other regions, but it shows that ICA has a long way to go before a reasonable control level is reached. This is necessary for the users to get value for their investments and maintenance of measurements. There are however certainly big variation between different countries.

Tschepetzki (2000) in his investigation also asked how successful the implementation of ICA was, whether the operating personnel were satisfied and how the maintenance need was considered. They found that 90% of the projects were implemented as planned, 10-23 % of the controls had to be modified or gave some problems, and 78% of the operators mentioned the maintenance as minor.

It is interesting to observe the difference in the acceptance of new measurements, between northern Europe and North America. North America has a much lower acceptance of measurements especially nutrient measurements in full-scale plants. It is amazing to the editor as this investigation was carried out in Northeast Germany, which was based on the East German technology only 10 years ago.

For this discussion, statistics of how the cost benefit of control used today are still missing. It is difficult to get objective information on this subject, because the interest of suppliers, and the operators is different. The operators do not separate their economy in the control part, design or normal operation.

If some extra capacity is needed at a plant and it is obtained by control, instead of normal extensions of basin volumes, the benefit is enormous, often a factor 5-20 times the conventional alternative. But if operation costs savings alone must carry the investment cost of improving ICA, the cost-benefit analysis will often only be 1-3. However, normally at each plant there are some "de-bottlenecking" benefits in connection with the introduction of advanced control, which can be gained in terms of capacity or in effluent quality. These benefits can be quantified as:

a) Operation cost reductions

b) Investment substitution or

c) Effluent and reporting value

An attempt to quantify this approach for evaluating control is made in section 7.1.6, for Scandinavian conditions.

7.1.4 Operation cost distribution in WWTP

Practical operation of wastewater systems is of growing importance, as the ability to measure and control has been growing considerably during the last years.

The task is to select the right level of complexity in ICA for the available or planned system, with the relevant balance between cost and benefit. Cost/benefit of control is dependent on the physical possibilities, skill and the available technology efficiency.

The cost efficient degree of control is dependent on the size of plant. In Figure 5 below is a typical cost relation in Danish WWTP (modified from Thamdrup 2000). The difference in operation costs is dependent on the relative higher load variations at small plants compared to larger plants and on the fact that the ICA level is lower at small plants. The difference between plants of same size is dependent on the layout of the plant and how efficiently the plant is operated, as well as the degree of automation and advanced control.

It is, however, remarkable that the operating cost per m^3 at a 250,000 pe plant is observed to be the same as for the best operating plants at 5000 pe per m^3 of water treated. This proves that good design, control and management is of major importance for plant operation cost.

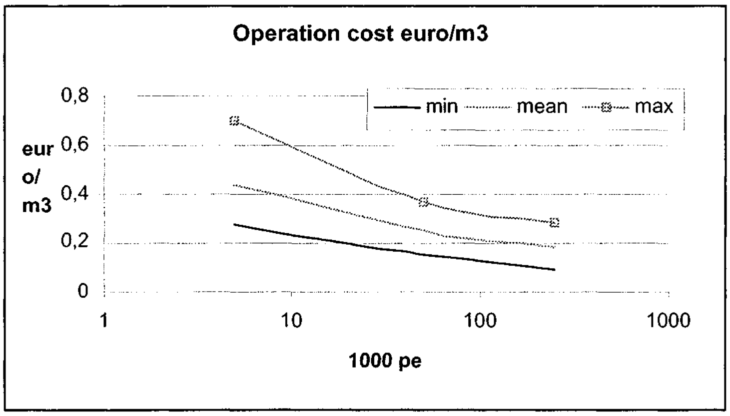


Figure 5 *Specific Wastewater treatment cost in Denmark.*

To be able to prioritise correctly where to introduce improvements by ICA, the local relations between investments and operation cost as well as the distribution between different parts of operation costs must be considered, as shown in Figure 6. Possible improvements in effluent quality or capacity must always be kept in mind.

The operation cost distribution for WWTP, without administrative costs in Danish municipalities is shown in Figure 6

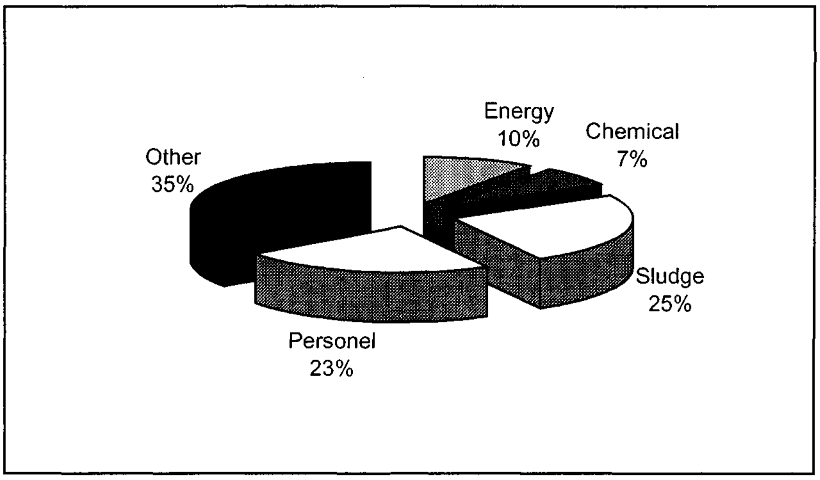


Figure 6 *Operation cost distribution for WWTP in Denmark*

It is remarkable that the part "Other" is large and a rising part of operation cost during the years. This part covers water analysis, tax, insurance etc. The managing, reporting and documentation part is an ever rising task also at WWTP.
The personnel costs are not normally reduced by introducing advanced control, but the other constituents of the operation costs are normally reduced significantly.

7.1.5 Effluent quality

When we try to evaluate the relevance of control, we must also evaluate the security in operation. To do this, we look at the effluent quality of plants, dependent on their relative load (load/design loads). In Denmark, the BOD demands are normally easily met with 25% of requested value, because the need for nutrient removal demands more of the plants than for sufficient BOD removal. Therefore, only the TN and TP effluent qualities are included in Figure 7 below, (The data source is Danish Environmental Protection Agency).

It is remarkable that the effluent quality is very low dependent on the design load. This indicates that it is operation and control that determine the quality of the effluent more than the designed label on the plant. It could also be an indication of a practical safety or over-design. The available extra capacity is the potential for what control and understanding of the dynamics can exploit. This understanding can be used for improvements during normal operation.

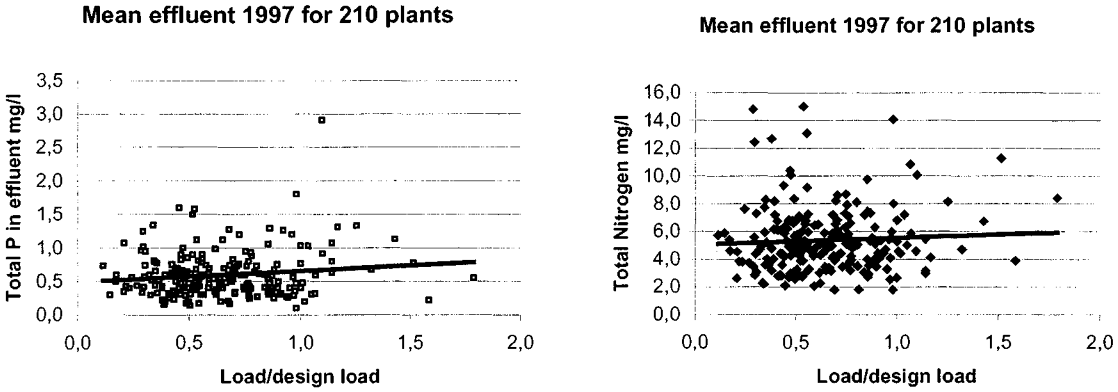


Figure 7 *Yearly effluent mean quality for all Danish BNR plants*

It is remarkable that the effluent quality at over loaded plants is often as good as for normally or under loaded plants. Can it be right that most Danish plants could handle the double load of today without exceeding their effluent limits? However the improvement of the effluent quality reduces the tax paid by all plants by 1.5, 3 and 15 Euro per kg of respectively BOD, TN, TP discharged. Hereby effluent improvement below given discharge limits is of value.

7.1.6 Experienced and predicted economics in ICA for wastewater systems

The need for control at wastewater systems is traditionally evaluated to be very limited. But the saving in investment by introducing new measurements and efficient advanced control is often worth considering, especially when the control uses the co-operation between plant and sewer system. WWTP control can expand the hydraulic capacity of the plant to its maximum, dynamically, as shown in Figure 25. This control can reduce the pollution discharge considerably, dependent on the operation situation, and the need for storage basins in the sewer system to handle storm situations can be reduced considerably.

The benefit from sewer control is bigger on pollution reduction by flow distribution than on flow capacity increase. Due to the frequency of flow situations a little over normal plant capacity, the benefit of control in reducing pollution amount is much higher than the benefit from handling extreme rain-events, according to Figure 25. If the value of control shall be acknowledged, it is necessary that the administrative procedures focus more on pollution than on water flow. But this is still not common for administrative reasons in northern Europe. Therefore we cannot produce a cost benefit analysis for advanced control of sewer systems.

A status evaluation for benefit/cost factors, for retrofitting of WWTP by advanced control, is reported by Nielsen, 2000 b. The results of Table 8 indicate a value between 4 and 10 for introducing advanced control.

Table 8 Size and benefit rate for advanced (TaR) ICA

Plant \	size of plant in 1000 pe.	Benefit/cost
Aalborg V	330	10,5
Harbooere	75	7,2
Aalborg E	100	9,5
Sydkysten	23	4
Frederikshavn	85	5
Borås	130	7,5
Bjergmarken	80	6

There will always be special conditions on each single plant, so the improvements are distributed differently, as can be seen in the referred paper. If it is assumed that these data are representative, a cost/benefit relation for introducing advanced ICA can be deduced for different size plants, as seen in Figure 8.

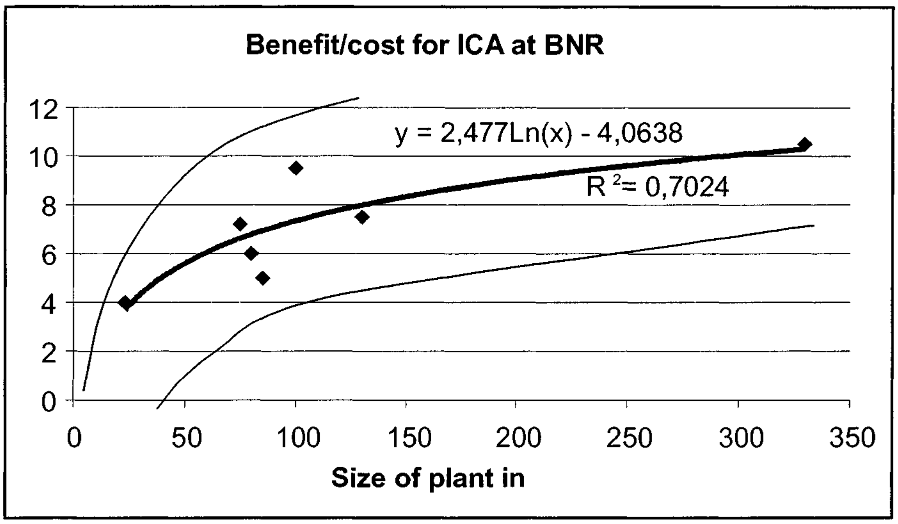


Figure 8 Benefit experience for advanced control in Denmark and Sweden

Of course, specific conditions must be evaluated at each plant and dependent on technology and control is applied. (New supplementing data from different countries and different technology on different plants are much appreciated.)

The result of introducing modern ICA philosophy with nutrient measurements and advanced control is today a 20-30% improvement of treatment plants, for 2-5% extra cost. The same cost-efficiency relations are expected in the future, when combined sewer and treatment plant control has been implemented, according to the reported philosophy for total system control in section 9.1.

The typical investment cost development in electrical and ICA as % of total WWTP cost in Denmark from 1960 till today is predicted forward to 2010 in Figure 9. It is remarkable that ICA has only during the last years shown significant process improvements of approx. 20% for WWTP. Before this period, the ICA was just applied as a necessary part of the investment, but today we have been collecting the benefit of the increased cost in digitalisation of the control the last 20 years. Figure 9.

A typical ICA installation including all electrical installations is around 10-15% of the plant cost. The advanced TAR control is typically 3%, of which 50% covers new measurements, 20% covers the new system and 30% covers education and fault detection in signals.

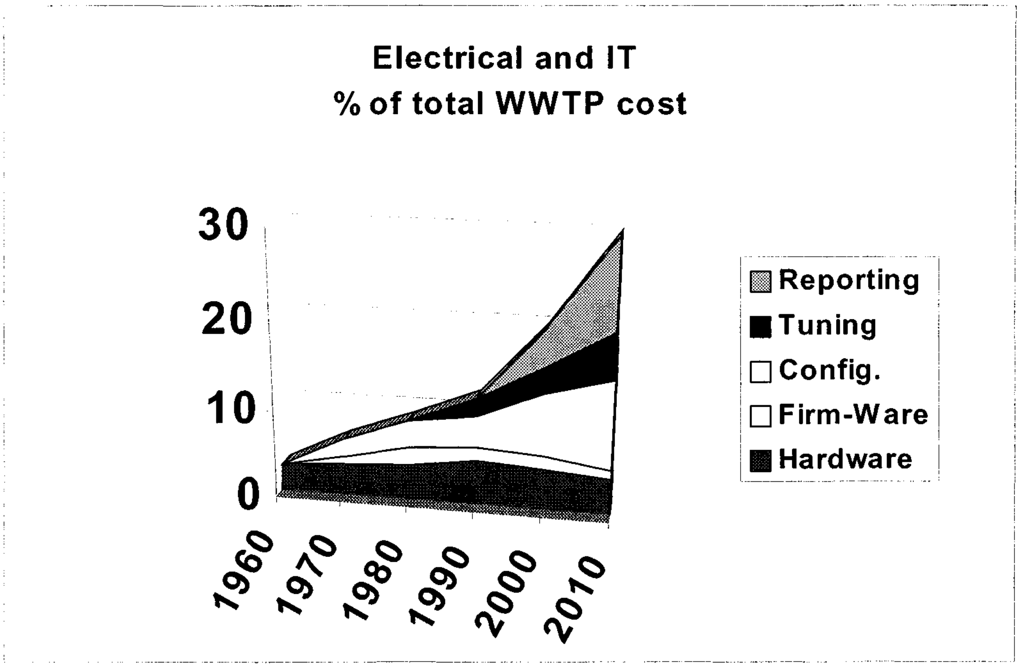


Figure 9 *Cost development in electrical and ICA cost in Wastewater treatment*

In the future, further improvements can be expected when the optimisation of the co-operation between sewer and plant is developed, and likewise between pre, post and main treatment processes in the WWTP.

A new task in ICA for BNR WWTP is to focus control on selecting a better micro-organism-population and managing of stored carbon source pools in the biomass. It is expected that these topics are the most promising approach for future development, which will cover for the extra investment in IT at the WWTP,(Nielsen 2001, Nielsen 2000c).

Finally, the reporting is a strongly growing part of ICA. Today it is reasonable to reduce the online data to consolidated values, describing the daily and monthly key factors. These data will be integrated with laboratory and financial data to Green accounting and will hereby make the ever growing bureaucratic functions easier and documentation and understanding of processes for the total system performance will improve. The result will be seen as greater performance of smaller plants and reduction of the largest operation expenses including "other" costs in Figure 6.

Instrumentation, control and automation (ICA) has traditionally been a rather neglected area of wastewater treatment operation until recently. The reasons for this were many and perfectly justifiable. However, it is becoming increasingly apparent that the wastewater industry is in a transitional phase. Change is inevitable, with driving forces too strong to resist.

8 TOOLS FOR CONTROL IN PRACTICE

Traditionally, PLC- SCADA systems used data seconds to minutes efficiently, but did not consider longer time responses. By introducing a structure, which handles the more slow response included in the process evaluations, and also including the new online measurements and software sensors, the traditional control is extended with a tuning level for the existing controls. The capacity of computers today makes a new level in control cost efficient, so the systems are today able to use online information with much slower response time (up to months). But often these data will not be robust enough for closed loop control, but still informative for process evaluation and maybe adjustments. This situation is today solved by introduction of offline adjustment of the slowest dynamics. The needed adjustment is instead reported to the operator, for him to decides whether new adjustment is necessary.

The level handling of these slow responses is called Tuning and Reporting level (TaR), the technology hierarchy is discussed in section 8.1, while the terminology for levels dependent on approach for more and less online control is discussed in section 8.2. The very slow dynamic for months and years will probably for safety sake still in the near future be handled offline by the operator. His evaluation must be facilitated by the improved reporting facilities in the ICA system, which will work as an advisory system for the optimal adjustment. The level for automation or level for online control will be controlled by the robustness of models and their ability to predict the optimal control situation. Different approaches to models for different parts of the wastewater system are discussed in section 8.3.

For operation of a sewer and WWTP system, the designer's task is to select from available measurements and control combination giving the best benefit. This selection is strongly dependent on:

1. The time constants in the processes

2. The strength of the correlations between final element and measurements and

3. The needed adjustments

There are still the traditional simple 3 control questions to be answered before selecting investment in a control and measuring system:

1. Are there important dynamics and variations?	Need
2. Are useful measurements available or obtainable?	Information
3. Are control actions/handles available?	Efficiency

When handling much data with low information value and long time constants as in a tuning and reporting system, it is of utmost importance to use technologies, which are able to handle a significant amount of noise. At the same time the system must be able to reduce data to a valuable identification of the situation to be controlled. An approach to this is proposed in section 8.1.

The sensitivity and the complexity of the decisions set the limits of what is cost-efficient for automation, as the ICA system needs to be robust during operation.

To be able to handle the more advanced data handling for control, it is important to keep a structur, so the maintenance and fault finding is facilitated. Generally we try to keep it simple; but when we integrate more processes and new areas, together with new techniques, this is not possible, then we need to keep it structured.

Below in section 8.2 is described the content of the controls in 4 levels. This reports generally only deals with the 4th level, which normally corresponds to the TaR technology in section 8.1. The first 3 levels will assumably be implemented as standard in SCADA and PLC technology. The tools discussed in this chapter are selected as they refer to implementation of State of the Art Technology.

The models applied as online control tools must be selected, for their ability to adapt to the necessary situations without the model is loosing the physical interpretation of its parameters. The control models need to be able to compensate for time delays in the system. This can be short delays from nutrient sensors say 10 – 40 minutes or long delays from changes in COD after adjusting chemical addition in pre-precipitation process to effect on the denitrification rate in an activated sludge plant, which is often 4-12 hours delayed. These tools are discussed in section 8.3.

8.1 INFORMATION AND TECHNOLOGY HIERARCHY

The traditional PLC - SCADA online systems on the treatment plant are today supplemented by a TAR level in the hierarchy. The control is expanded horizontally into the connecting sewer system using precipitation, flow, level and turbidity data for online control.

Further, the TaR layer in the technology hierarchy also expanded vertically by including model interpretation of information from slow responding systems. The vertical expansion is used for tuning the SCADA control system and reporting to the offline levels for evaluating and documenting the effects of new control adjustments.

When online data are used for new planning, it could be considered a control system, which has a response time of several years, with feed back control. Online data can be used in planning when the measurement by data filtering and data reduction via models provides the planners with more correct data of load and capacities of the sewer and plants. However, before reducing the data to planning level, the online data need to be qualified by an efficient data brushing functionality, which often demands a check against correlated data, only available in higher level systems.

When knowledge of measurements and controls are available, the task is to select the right combination and place for measurement and final elements, and further to operate these measurements and controls so maximum benefit that can be obtained. Here the education of the operators and their co-operation with available experts/ consultants are an important logistic function, to benefit the most from modern ICA capabilities.

The objective goal has to be transferred to operational goals. In practice, the objective goals as maximum cleaning for less money has to be structured into sub-goals, dependent on time-scale and the system considered. In the planning stage of a project, maximum benefit is available as design can be modified and investment benefits can be included. However, at this stage the load dynamic is seldom known, so the optimal operation need is normally only realised after ½ to 2 years after start up.

To be able to improve the operation in different levels, the operative goals must also be structured in different levels.

For each control loop to be introduced, the disadvantage of both cost and complexity has to be taken into consideration, so the right level of automation is chosen. Especially, the organisational responsibility to operate and maintain the needed machinery, measurements and computer programs, as well as process understanding, must be planned.

Further, the operating ability during emergencies, where different parts of control, measurements and machinery are out of operation of unforeseen reasons, must be secured. Also, the system must be so robust that the available less educated operator is able to handle the system, when needed.

The main operational concern is therefore to keep the structure at so low level that the basic functions are as reliable and easy maintainable as possible, while the more complex decisions dependent on more data need to be backed up by simpler control. The more integrated and complex a system is, the bigger amount of safety layers is needed. It must be ensured that the plant can operate without all complex functions, to secure that the running in of the processes and the maintenance and calibration of these complex functions can be implemented. These safety demands are secured by the right structure for the given complexity and stability in measurements and process.

We have to accept that today ICA consists of many components and functions that can break down, and some times need specialists, which are not always available to do the repair within the hour. Further, ICA is subjected to the IT industry, where spare parts are only available a few months after purchasing, the new versions are only available and this might demand much more change than to substitute a single damaged part in a control system. This situation is according to the editor's opinion the most important reason why PLC is still around, and why we must build up a hierarchy of the safety levels in all advanced ICA systems. Otherwise, we would have changed all new logic to soft-PLC and integrated everything very cheaply into a few computers.

On the other hand, there are today many unproven rejections of beneficial controls, because of lack of knowledge of available information and their stability and efficiency in different timescales, which cost efficient can be applied, with reasonable design of advanced ICA.

In this paper we want to point out the needed condition for today's useful operating status and point at possibilities and limitation for operating ICA in wastewater systems. To do this, we first look at general implementation conditions on existing controls, but also point at new promising controls for different systems, which have still not been documented at many plants.

8.1.1 Tuning and reporting design

The distinguishing between online systems and offline report systems is more diffuse today, because suppliers of both systems are using the new possibilities of extending the potentials in all directions. To improve the full interaction, a new level of systems covering tuning of online system and reporting to users (TaR) is developed. This level substitutes expert systems and supervisory systems. By including the data driven TaR philosophy in online systems today, they are very efficient to improve design data for system extensions or even to evaluate revision of data for planning and management, as demonstrated by Bundgaard et al. (1995).

Combining the cause and effect matrices with actual needs, information and expected efficiency, as described in section 5 above, will be the fundament for the developer to quantify the need for and efficiency of model based controllers.

By explicitly employing process models within the controller, the effect of manipulated variable changes on process objectives may be predicted online, thereby enabling ‘optimal' quality control. Dochain and Perrier (1993) performed this with a simple, two-substrate model.

It is envisaged that such controllers are incorporated in the TaR level in the control hierarchy. The control algorithm will calculate optimal set points for lower level control loops, usually controlled at PLC or SCADA level. At present, most of these evaluations are performed offline and the results are, as in the *K*rüger STAR system, implemented for adjusting the criteria functions. After proven robustness, the model or input/output relation can be taken into online use.

The development of online consideration is scheduled to be developed in the next 3 years in a project like SMAC (Thornberg 2001). Apart from the evaluation of how much should be automated, another important aspect has to be evaluated in future control plans. How do we best handle the time delay between different control actions and their response? Many relations in WWTP are dominated by a daily relatively stable variation, which can be used for improving control.

There are typically 2 approaches to solve the task of delay:

1) To select another correlated information for the control with less delay, and update the correlation retrospective. (Cascade control)

2) To use a combination of a model adapted after the previous behaviour at the actual situation. (Pattern recognition).

Both methods are very empirically adjusted and based on the fact that the relation in the wastewater system normally follows fixed patterns, so often the identification of a simple transfer function can identify most of the experience dynamics. However, if serious disturbances of the identified patterns occur, the control can be negative. This disturbance is mostly due to change in response time for the process. Examples of both approaches are described in chapter 9.

8.2 LEVELS OF CONTROL IN PRACTICE

The purpose of control is to optimise the running of the WWTP and sewer system primarily to meet effluent standards and secondarily to keep operational (and construction) costs as low as possible. As control in practice is most efficient on nutrient removing plants, in the following is focused on this area.

The best way to do this is to make the biological nutrient removal as good as possible, for instance by "saving" internal carbon in the wastewater to use in denitrification periods, because the optimal biological nutrient removal demands a minimum amount of energy consumption and chemical addition.

The way in which to perform the best control differs somewhat from plant to plant, mainly according to the design of wastewater treatment processes, but the principles and goals are still the same.

The control on a WWTP can be divided into four levels

1. Traditional control / adjustments based on manual samplings
2. Manual adjustment of control based on online nutrient measurements
3. Simple online control strategies implemented in a SCADA system involving permanent online measurement typically single loop controls
4. Advanced online control from a special process optimising computer supervising the standard SCADA control system by tuning controls and reporting performance, e.g. "STAR, Superior Tuning And Reporting" system, (Nielsen and Lynggaard-Jensen, 1992).

Considerable process expertise and knowledge are required to select the appropriate level of control, because each WWTP has a different load and process design. Furthermore, the composition of the specific wastewater and the control action possibilities on each plant must be evaluated. The use of online measurements requires committed maintenance, and in the advanced online control systems very strict automatic data handling is necessary to avoid disturbances from the measurements and control systems.

8.2.1 Level 1.

The first level of control is the simplest and most traditional way of performing WWTP control. The information used to adjust controls usually comes from time or offline analysis.

8.2.2 Level 2.

The second level of control is characterised by the use of online nutrient measurements to provide the information of how to make manual adjustments in the existing SCADA control system. The online measurements can either be from permanent meters on the plant or from a mobile monitoring station employed for a short period of time.

If a mobile monitoring station is used, it is possible to get online information from the process at any plant only by placing the submerged pump in the tank. The mobile monitoring station should contain monitors for ammonium, nitrate, phosphate and suspended solids plus a PC able to monitor and control the plant and to transmit the acquired data by a modem. A mobile station in Denmark has been monitoring various plants for about 14 days at each plant. This period of time is sufficient to get a good understanding of the dynamics in the load pattern and performance of the plant and whether it would be beneficial to establish permanent online measuring equipment for control of the plant.

With permanent online measurements in the process tank, the plant operator can now actually see what is going on, how fast the processes are performed and what effect different control actions have on the important parameters. The measurements provide information on the process dynamics, and daily/weekly variations can be identified. From these known variations, the traditional process control scheme can be adjusted manually and process performance improved.

The visit by the mobile monitoring station could be part of a service routine once or twice a year to ensure proper adjustment of the plant performance. From the online measured data series and some specific samples, it is possible to calibrate and test a few control strategies offline. This can be done in a process simulation program e.g. EFOR, to find out which adjusted simple control is optimal in terms of both effluent quality and economy (Henze, 1993 Aspegren, Andersson, Nyberg and Jansen, 1992).

8.2.3 Level 3.

This level contains simple online controls, which can be implemented into traditionally SCADA systems. The calculation part of the standard SCADA system allows only simple real time regulations based on real time measurement. There is no historical data available in the control evaluation, but historical data must be extracted and used in manual adjustments of the simple online control criteria.

Control in a SCADA system is performed as simple rule based control on the basis of single point values on the online meter, e.g. the oxygen set point in a starting nitrification phase is determined once from the actual ammonia value at that moment. In the same way, one ammonia reading at the start of a nitrification period is used in a table lookup to give the nitrate end point of the nitrification phase starting (Thornberg et. al., 1993).

This use of single values from the online measuring gives a dynamic but delayed control, as the actual loading cannot be followed closely, but only influence the control later on.

8.2.4 Level 4.

The level four control is an advanced and complex control method which includes model based predictive control from online measurements in combination with both short- and longterm statistical treatment of different process and operating data. In this way, the time delays in the measurement system, control system and the processes can be compensated for, and the online control becomes real-time control that follows the actual loading during the whole process time.

To perform the advanced control, the input data from either nutrient online meters or traditional meters has to be highly reliable. To assure this, the STAR system must operate with a Data Quality Check module, DQC^P that gives every single measurement a quality character. The quality character follows the value during calculations and makes sure that any control output is weighted against the quality of the data. If necessary, STAR activates the best alternative control method by using the Multi Criteria Control concept, MCC^P.

Hierarchical control systems like distributed control systems (DCS) have been the norm in the process industries the last 10 years. It has now with the TaR-level been implemented on several of the larger wastewater treatment plants in Denmark, for example Aalborg and Helsingoer as well as Boraas and Poznan in Sweden and Poland. These systems are used not only for ancillary equipment control and reporting for pumps operation, flows and oxygen control, they are also an implementation of advanced process control with new measurements and reporting of the plant performance. It is foreseen by Steffens (1996) that this type of control system hierarchy, with SCADA systems below a Tuning and Reporting system, the TaR philosophy, will probably become standard in wastewater plants over the next decade, whether it is implemented in separate systems or built into an existing standard program.

Although it is definitely necessary with cost/efficiency evaluations, this technology with accompanying supervisory control and data acquisition (SCADA) or Tar level system is most economical. Tar level controls are implemented cost effectively on large and medium sized municipal plants down to 15,000 PE for Danish conditions, Figure 8. The largest cost efficiency is often reached by applying the Aeration Tank Settling (ATS^P) where the capacities of the plant are distributed between hydraulic and organic capacity.

Remote process monitoring has also recently been introduced at some facilities. This must be viewed as the first step to achieve centralised (remote) process supervision of several process facilities. Indeed, there are examples of such technology being successfully developed and implemented (for example, Huntington (1993) in the UK.). To make the information available from all relevant people, the Man Machine Interface MMI must be available from relevant machines anywhere, preferably without special configuration. Hereby a new adviser can be given access to data whenever necessary. This technology is today available as the internet technology TCP/IP, HTML, Java and Perl. These technologies are independent on an operating system, when used correctly, and secures easy updating and maintenance of the system, as all maintenance is joined on one server.

8.3 MODELLING FOR CONTROL

Crucial to the efficient operation of advanced control schemes, and indeed to all model-based controllers, is the robustness of the models. Model parameters have to be constant or estimated periodically to allow for changing environmental conditions, changing feed characteristics, temperature and biomass adaptation.

The model complexity must therefore be kept at a reasonable low level, if not for computational reasons, then for the possibility of identifying parameters from the available noisy online data. When a model is so strongly reduced that the parameters that need adaptation can be adapted by statistical online data, we call this model a Grey Box model. This is for control the alternative to blackbox models as neural networks NN or AutoRegressiveIntergratingMoving Averages models ARIMA models that are based on an input/output data analysis, (learning or calibration from retrospective data sets).

When simple deterministic structures are building the apriori knowledge into the models, the Black Box models develop into Grey Box models. The definitions are not totally clear, as NN today often is diverted into a bunch of many sub NNs, where the substructure are taking care of a main deterministic structure. Hereby the Black Box's non transparency of NN is limited, and maybe NN can even give physical interpretable data from sufficiently structured NN, so the structured NN can earn the description of: Grey Box models? When the correlation can be interpreted into physical understandable parameters, the adapted parameters can be fed back to the conventional white box models (deterministic models) and calibrate these. By doing so, we have created synergetic relations between the different technologies used for design and planning versus online control models.

In the same way, the stochastic tool is developing into Grey Box models by including apriori structure into ARIMA models, then they are described as extended or ARIMAX models. Carstensen (1994b).

If the estimation methods for the adaptable parameters are not robust enough due to the available input data, at a given plant, or the calculation is too demanding for online use, the models can be substituted by criteria functions, as described in section 8.3.1. Criteria function is a shortcut from control input to control output for the models. Hereby the operator can adjust the main input/output relations from evaluating retrospective data from his control performance. In this way, any disturbances from physical and mathematical instabilities are bypassed in the model based control, during the running-in period, and only when the models and their adaptations have proven to be robust, they can be given free to control in practice, (Nielsen 1983).

There is an ongoing discussion on which complexity is beneficial in models for different purposes. The designers of models do often not understand that the control people do not use their models, which are considered reliable and correct and even benchmarked, when they have been calibrated. But for control it not sufficient that the model is correct. If the necessary input or calibration is not available, the models are still not useful. The criteria functions are a shortcut to be able to introduce the newly developed correlation recommended by the researcher. Without having to wait for sensors or model development for the new ideas, the introduction of a criteria function describing the new correlation is just testing the relation in full-scale, whether the general tendency is measurable in the system performance or not.

The most important part of the advanced control system for control purposes is the use of the predictive control models. On the basis of the well-known process ideas and reactions, it is possible to estimate the actual process values and measurements from the previous measurements and process dynamics. The control therefore often acts without delay on dynamic loads. The model structures can be evaluated offline or online on a weekly or monthly basis, to adjust the predictive models, in accordance with the slow changes in the sludge activity and change in load digestibility etc.

8.3.1 Criteria functions

A way of performing online control without getting the complexity of models into the control is to use criteria function control. A criteria function is defined as a diagram in which a certain function gives the control value or decision as expected from the model relations between input and output. Non linearities are easily handled in criteria functions, by bending the relations.

One type of criteria function is the reading of a set point value (Y-axis) from a given function of one input value (X-axis). Another type of criteria function has two or more input values (X1 .... and Y-axis), which gives the Multi Criteria Control concept, MCC. The control decision is based on whether or not the actual value (x,y) is above or below a given line (substitute of model prediction from Monod kinetic calculations) in the diagram.

An example of how to use a criteria function is to adjust the phase lengths in the alternating plant, where the same process tanks alternate between nitrification and denitrification periods. The control principle is that a nitrification phase is ended when ammonium is low, and the denitrification is ended when the nitrate is low.

The control of the phase lengths is based on the criteria functions that are shown in Figure 10.

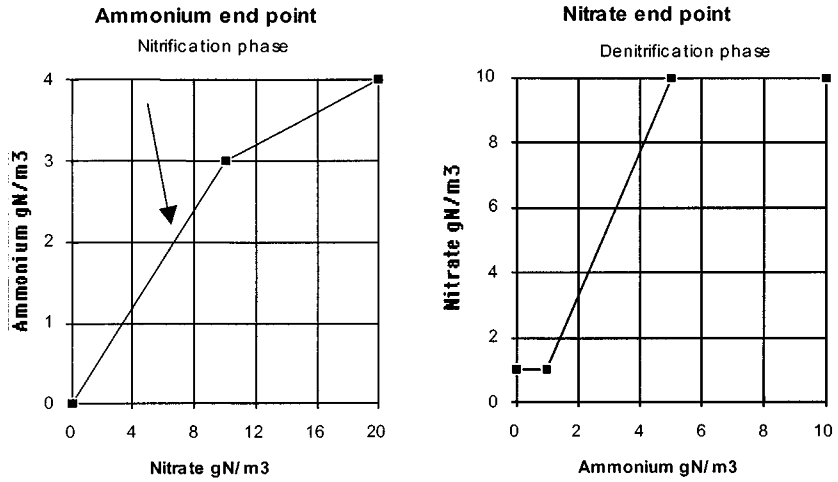


Figure 10 Criteria function for shift from nitrification phase to denitrification phase

In the nitrification phase, the computer checks the (NO3-N, NH4-N) point in the diagram above every 6 minutes. As the phase proceeds, the point will move from the upper left down towards the lower right, as indicated by the arrow (less ammonium, more nitrate). When the line is crossed, the phase is ended.

If the loading on the plant increases, as it typically does in the morning, the criteria functions allow both ammonium and nitrate to rise. This leads to an increase in the process rates that are presumably limited in a Monod kinetic fashion.

The shape of the criteria functions can be adjusted according to the time delay in the measuring system, the effluent demands and the characteristics of the treatment plant and wastewater.

In the TaR control results implemented in STAR referred in this part, the criteria functions are often used, while the development of more robust Smart Controls are planned in the SMAC EU project described by Nielsen (2000b).

8.3.2 Modelling for treatment plants

IWA Activated Sludge Model no. 1. – 3. is the reference for all plant modelling of biological systems. Benchmarking has been made for many implementations of this model. However, these models are qualitatively correct for evaluating hypothesis; they cannot adapt to noise in composition and sludge characteristics in full-scale. Reduced models have been used for different specific tasks for online control, Carstensen 1993. The development of simple input/output relations between nutrient measurements and O_2 control set points as in STAR has proven successful in many plants, (Sørensen 1994, Nielsen 2000b).

For control use, often the delay from control action to measurement is a problem that makes control negative, because the control can get in contra phase with wanted needs. Especially, in pugflow systems in recirculating BNR plants, the retention time in the different sections is so long that control actually needs many measurement points to avoid ringing, due to the fact that the measurement does not feel the control action before x hours later. Then we can either give up control or make a model for the expected variations, which are adapted to the actual situation. A simple e concentration estimating model for daily variation is often sufficient to describe the normal expected variations, the deviation from normal can then be adapted from measurement and from flow which determine the variations in delay times.

8.3.3 Concentrations during dry weather.

The daily concentration normally varies significantly depending on infiltration and rain, but also as a response to people's behaviour. Further, the retention time in the sewer system is of importance for the distribution of the different fractions.

Table 9. Wastewater composition from Henze et al. ("Wastewater Treatment" Springer Verlage 1995.)

Analysis parameter	**Symbol**	**Unit**	**Waste-water**
Chemical oxygen demand (dichromate)	COD	gO_2/m^3	530
Biological oxygen demand	BOD_5	gO_2/m^3	250
Total nitrogen	TN	gN/m^3	50
Total phosphorous	TP	gP/m^3	12
Suspended solids	SS	gSS/m^3	300

To be able to handle these data, we assume that the distribution during the day is constant, as shown in table 1. Only the total concentration of all components varies an example for COD is described below.

COD(t) = CODmean (1+ aCos(t2_/) +bsin(t2_))+cCos(t4_)+d(sin(t4_))).

The variations as shown in Figure 2 with daily mean of 800 mg/l COD. a,b,c,d = -0,2 -1,0 -0,1 -0,1. These variations strongly depend on local situations, but these variations are common in size and form, and when it adjusted to a given plant it is remarkably stable, because people and industries normally have the same pattern every day.

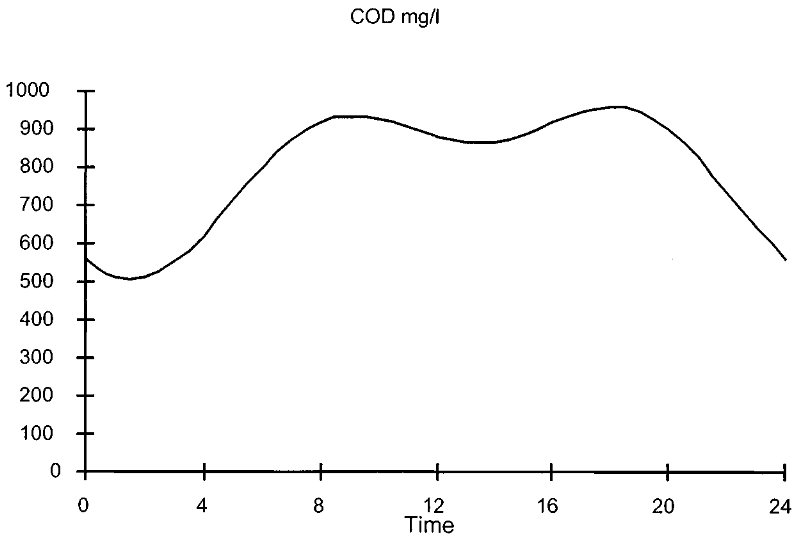


Figure 11 Concentration daily variation

During weekends we assume that the distribution is the same, but with lower concentration. This systematic variation is often so small that it is neglected in the standard load, but it is easily included.

One example of using this approach is shown in Figure 44. O_2 level in the first tanks is kept low during low load, so C is not burnt off during nights, and high O_2 is kept during max load, so the nitrification capacity is sufficient in the later sections, where O_2 level is controlled by the nutrient measurements.

In practice, it is necessary to adjust to the optimal need of this kind of control, because it can actually be so strong that the last tanks operate with low load during the daytime and high load during night Figure 39 observe that NH3 peaks is around midnight. The calibration of the control is still needed, but the operator, who has been introduced to the mechanisms, can easily handle such adjustments. The adjustments are typically needed 2-4 times a year to keep optimal control.

Apart from the load size, it is often important to be able to follow the load wave distribution through the plant.

8.3.4 Modelling of sewers

The control of sewers is still very limited, as the control handles available are relatively weak. Therefore, the control is sometimes called static, which means the control only reacts on local relations coming from statistical retrospective data over a long period. This kind of control needs no models for control. Only when the control reacts dynamically, dependent on the actual situation, identification of models is needed. This dynamic control is the aim of the following description.

Several models and model conglomerates exist. The choice of model depends on its use.

a) Detailed planning of system physical structures – database is planned or registration of length, diameter slope roughness and use of these in hydrodynamic deterministic relations (example MOUSE, Hydroworks).

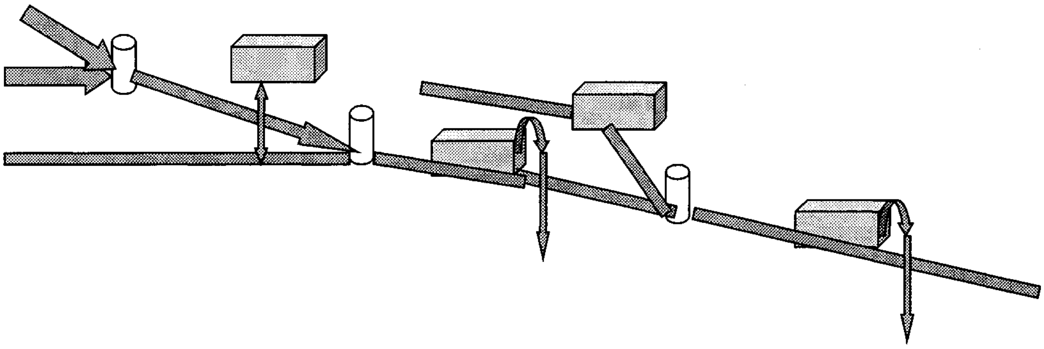


Figure 12 Great detail in physical description

These models are well suited for planning when data are available when using them for control; they are too slow and complicated to update for dynamic control.

b) A lumped deterministic model. These models are used for overall planning of sewer systems based on rain series and critical points (example SAMBA).
By lumping of pipes and manholes into sub-catchment areas, and just including distribution in key points and the dynamic calculation from main trunk sewers in the model. Hereby the model is simpler to calibrate, but so far online calibrations have not been possible to implement, so it is still not used for dynamic control.

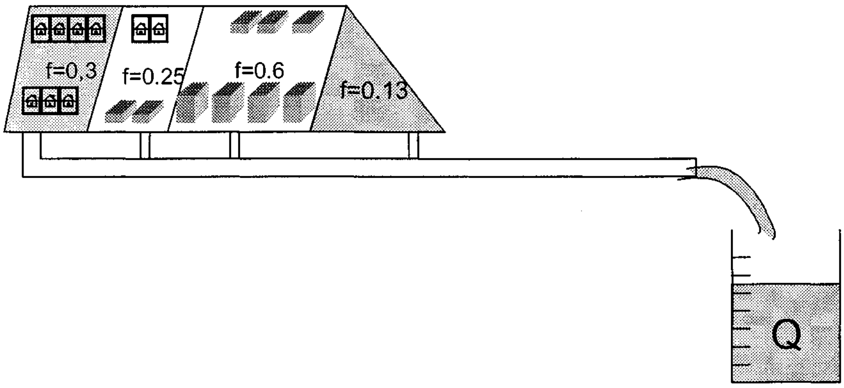


Figure 13 Lumping into sub-catchment areas. f means fraction of rain that passes on to the sewer

8.3.5 Simple deterministic models with stochastic adaptation

Models for control need only be valid for points in the system where control is possible, such as basins or pumping stations. Adaptive identifiable models (definition: "Grey box model" means the model that contains so few constants that it can be identified by a few physical characteristics from the catchment, and the rest can be adapted from available online data.

To make a good control model, we have to be able to follow the actual situation and react from a reasonable estimate at this time and not react from what statistically is right from many rains. Hence the model must be able to adapt to noise that gives significant changes on the optimal reaction.

The two most important noises in the sewer system flow and hence input to the control are:

1) rain distribution.
2) actual runoff area.

Of cause a rain gauge of say 10 times 10 cm is not representative for 2 ha if we are dealing with local thunderstorms, but the rain estimate from flow or level in a sewer can remove most of the error. So if the accepted an adaptation from what is seen in the sewer it will be more correct. Exactly the same evaluation can be used on runoff area; if we are in the beginning of a rain after 2 months drought, the runoff is often much higher than if we are in a humid period at some surfaces. Also here, adaptation to reality could improve the information validity for control actions. To be able to handle a model with adaptation and not loosing the physical understanding as in neural nets, a simple model where an additional model for dry weather flow and rain flow is used, as proposed by Bechmann 1999 and illustrated below.

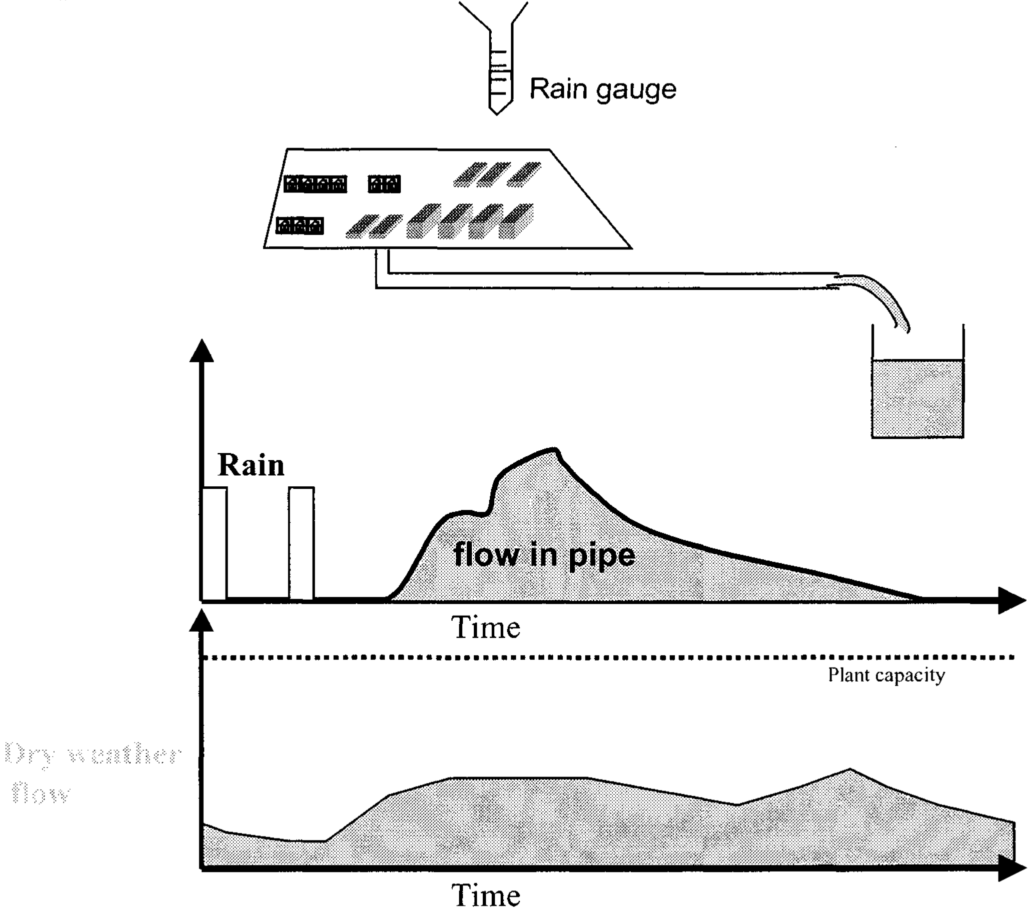


Figure 14 Dry weather flow and rain additional flow after two small rains.

The sewer flow is considered as a sum of rain flow and the dry weather flow. The above principles are applied to as many points as necessary. Sometimes only one area for the whole catchment to one treatment plant is needed for the necessary exactness and speed of the model, but typically a division in 2 - 5 sub-catchments is better.

This type of models is not well developed yet, because data has not been available, and the benefit of controlling from this updated information has not been proven. Unfortunately, the available models as described above cannot verify the benefits, so we must wait for full-scale verifications.

In general, design and modelling are based on flow calculations and very little on compounds/pollution/matter measured as COD, SS, N or P, and hence first flush effects are normally included in design but disregarded in control strategies.

First flush is a result of the rain 'pushing' the concentrated water faster through the sewer system. Figure 21 bottom shows the real concentration time-series compared to the typically used dilution model. The peak on the 'real' curve represents the first flush.

(There is significant difference of how important first flush is considered in different counties, and certainly the effect is very different dependent on sewer slop and size.)

The upper part of Figure 21 illustrates the actions that can be taken towards increased flows in the sewer as described in the following chapter. The lower part of the increased flow can be treated at the WWTP (yellow). Further a part of the stormwater flow can be stored in retention basins (green), until they have been filled and the rest has been discharged as CSO (white area).

Control in sewer systems today hardly exists or is on a research level. Attempts have been made to use 'calibrated' deterministic models with many parameters to predict some time ahead and thereby choose storage and overflow strategy. It has not been very successful mainly because the applied type of model was not suitable for the purpose.

The calibration of deterministic models is tedious and difficult because the constants in the model are not easily identifiable on the basis of the information from the sewer system under rain distributions. Pipes, manholes and slopes may be well described, but the effect of irregularities such as tree-roots, sedimentation, holes, deformations etc. on impulse and flow (Carstensen & Harremoës 1994), is gradually becoming more and more important in an ageing sewer system. Deposits after periods of dry weather are thus of paramount importance with regard to flow and especially pollution run-off. Further, the rain statistics with model rains are often not valid for each rain (errors of a factor 10 are seen during calibration of models), hence control on the basis of wrong predictions is worse than no control.

With new greybox adaptable models, even the concentrations might be applicable by use of simple passive measurements such as turbidity. It is often not water we are designing for, but pollutant reduction, as described by Bechman et al. 2000.

It is thus important to have a relatively simple robust model, which is adapting to the actual conditions in the sewer system. The model parameters should be identifiable from an algorithm, using the available online data and their correlation.

A small corner of this hydraulic concept has been tried in Aalborg where the influent to the treatment plant was predicted 1 hour ahead, on the basis of one rain gauge. This prediction seen in Figure 15 has been used to change the operation of the plant to cope with an increased flow in stormwater situations during the last 6 years, and the simple model performed better than parallel operated deterministic models (Carstensen 1997). The calculation time was much shorter and the flow estimate was more accurate. This was presumably due to an insufficient or unstable calibration of the deterministic model. In all cases the results showed that the simple model was more adequate for the control purpose.

It was also demonstrated that the adaptation of plant capacity was often sufficiently quick to be fully used in a sewer control system for adjusting use of available basins.

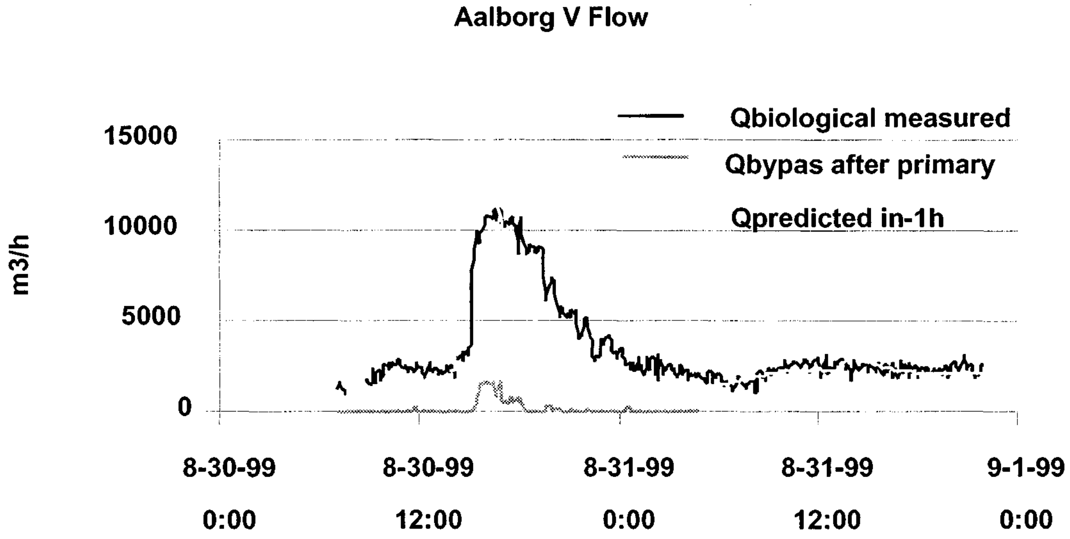


Figure 15 *Flow prediction and measured flows at Aalborg V*

8.3.6 The model adaptation.

The information needed for identifying a given point in a sewer system can be deduced from the online data directly.

First the area from which rain is discharged can be found from the flow versus rain intensity on these days.

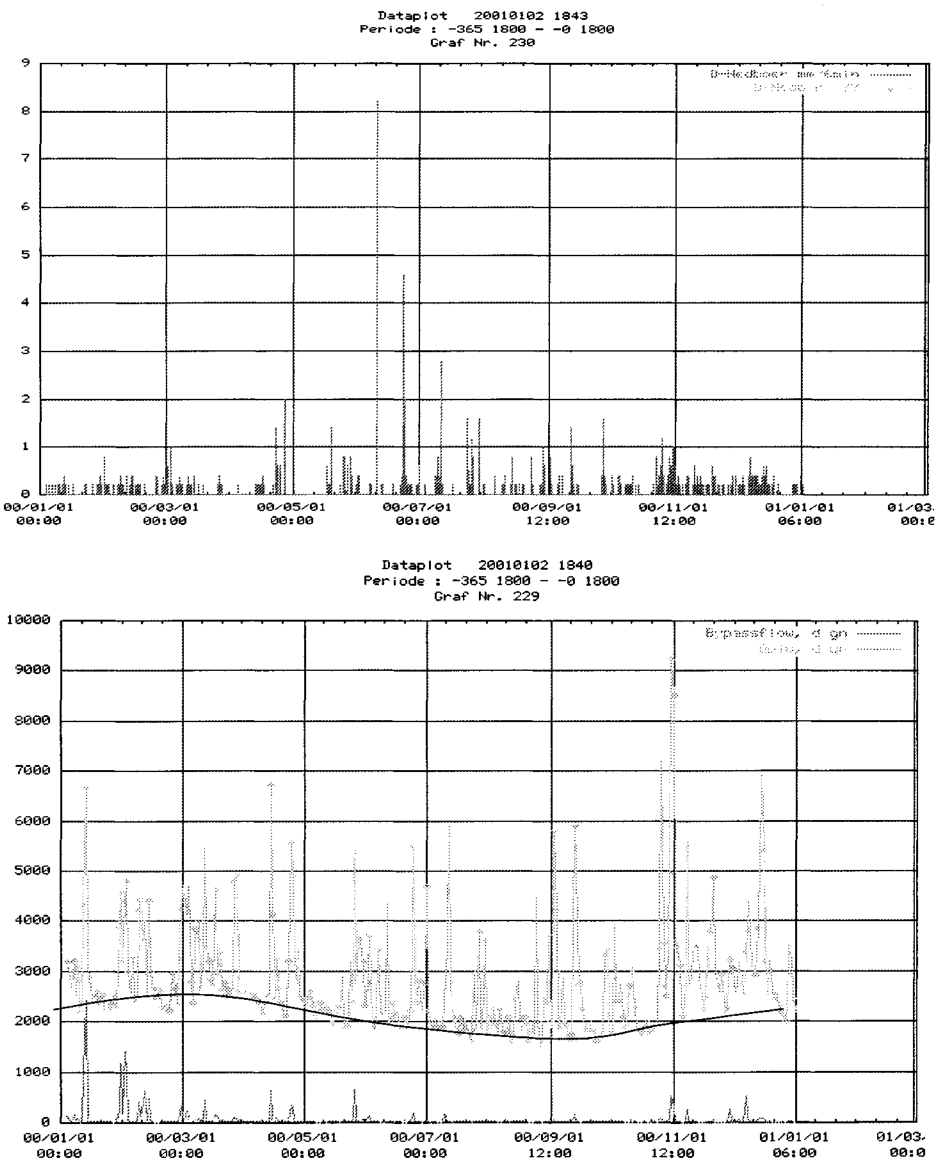


Figure 16 *Years flow and rain at Aalborg V.*

To be able to distinguish dry weather flow that may vary over the year, this value must be extracted and the rest can be fitted as a line in the lower rain intensities, where CSO is not dominating.

Then the normal daily flow is modelled as a simple double sin function and a mean value. As shown in Fig. 12.

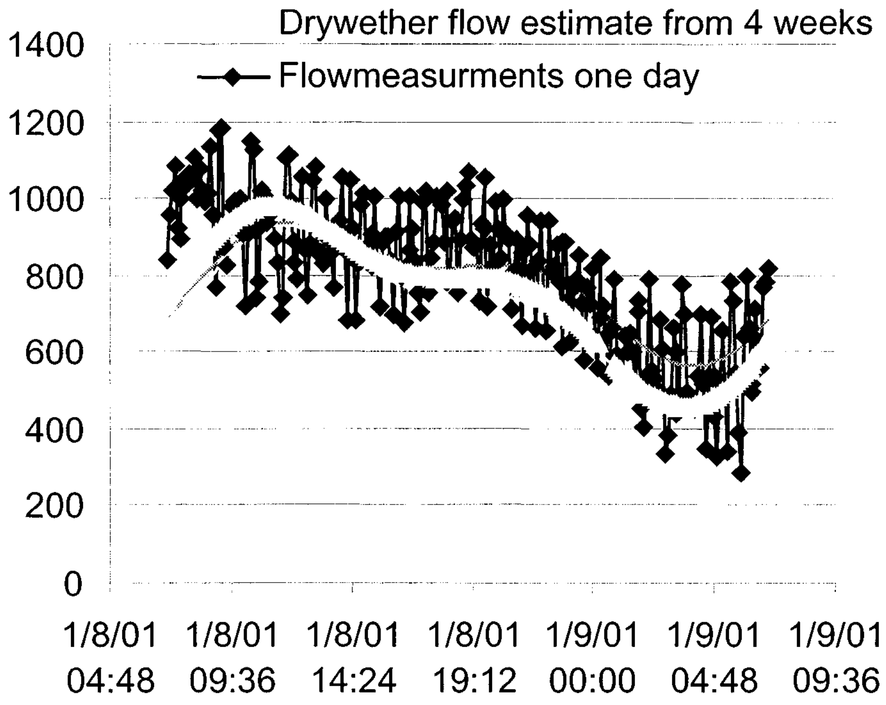


Figure 17 *Identification of daily flow from Roskilde*

Daily dry weather flow can normally be sufficiently modelled as seen in Figure 17, double frequency sinus/cosine functions.

Total flow estimate can then be as simple as a double sin/cos function plus an impulse function for the rain. When the yearly and the daily variations are removed from the data, the rest of the flow variations are assumed to be caused by precipitation distribution. This has been tested in 4-6 years in more plants with good results.

Adaptive grey box based predictions of dry weather flow as well as flow based on unit hydrographs can also be based on neural network or as simple flow distribution as shown below.

A more deterministic approach could be used: say that 1 mm of rain on the given runoff area would give a unit hydrograph, which is characterised by its mean and its variance, which are statistically well identified data and correlate these with a distribution characterising the hydrograph.

(1 mm rain gives delayed weighted norm + log norm curve). The choice must be whatever is easiest and sufficiently robust to handle. The area below the hydrograph will represent the reduced area discharging to the evaluated point, as illustrated in Figure 14.

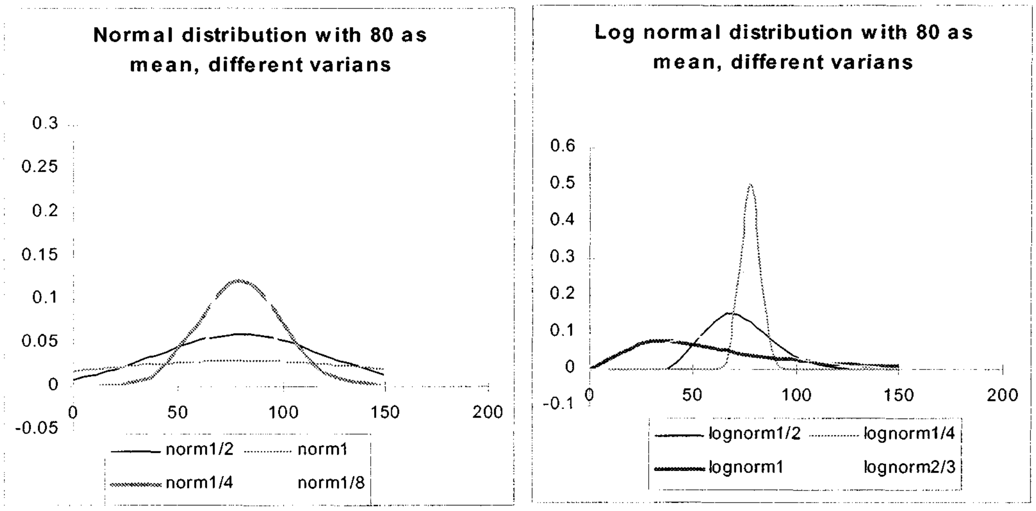


Figure 9: Pulse functions for rain with 80 minutes mean delay

Combining these distributions and a lag-time, a reasonable impulse function can be modelled. For Aalborg V with 80 minutes mean delay-time (Runoff-time) this could look as in figure 10:

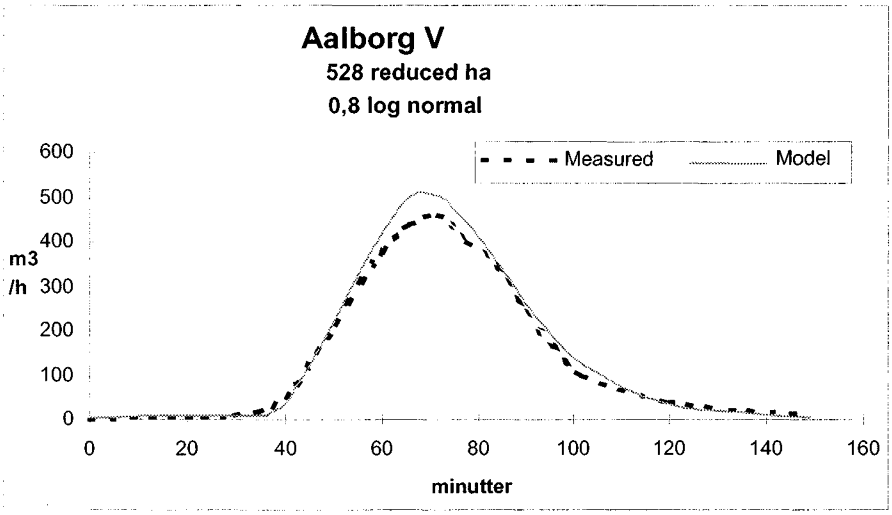


Figure 10 some proposal for hydrograph descriptions

Including organic and nutrient pollution flux on top of flow estimations (Bechmann 1999).

9 IMPLEMENTED EXAMPLES

When implementing control, the most difficult question is often, what is optimal. Often we just assumed that constant conditions would be best, but this is not correct, as discussed in Nielsen(2000 b). In the TaR concept is given an approach of how should the conditions in different parameters can be changed to get the best overall performance. The TaR concept is focusing on the total system, but is also taking the available local conditions and demands into consideration.

9.1 TOTAL SYSTEM CONTROL

The total system is considered to include all controllable sewer outlets, pumping-stations, basins and plants in an area. The control internally on the plant is discussed in later sections, here is only dealt with the hydraulic and material distribution control from the area. Carstensen 1993.

The task is to maintain most of the pollution in the basins or stored in the sewer for later discharge via the treatment plant. When discharge is necessary from the sewer, these discharges of minimising the amount of polluted water to the least sensitive recipient. This is obtained by considering bothe sewersystem and treatmentplant situation as a whole. Often the SCADA control are separated between treatmentplant and sewersystem as shown in Figure 18

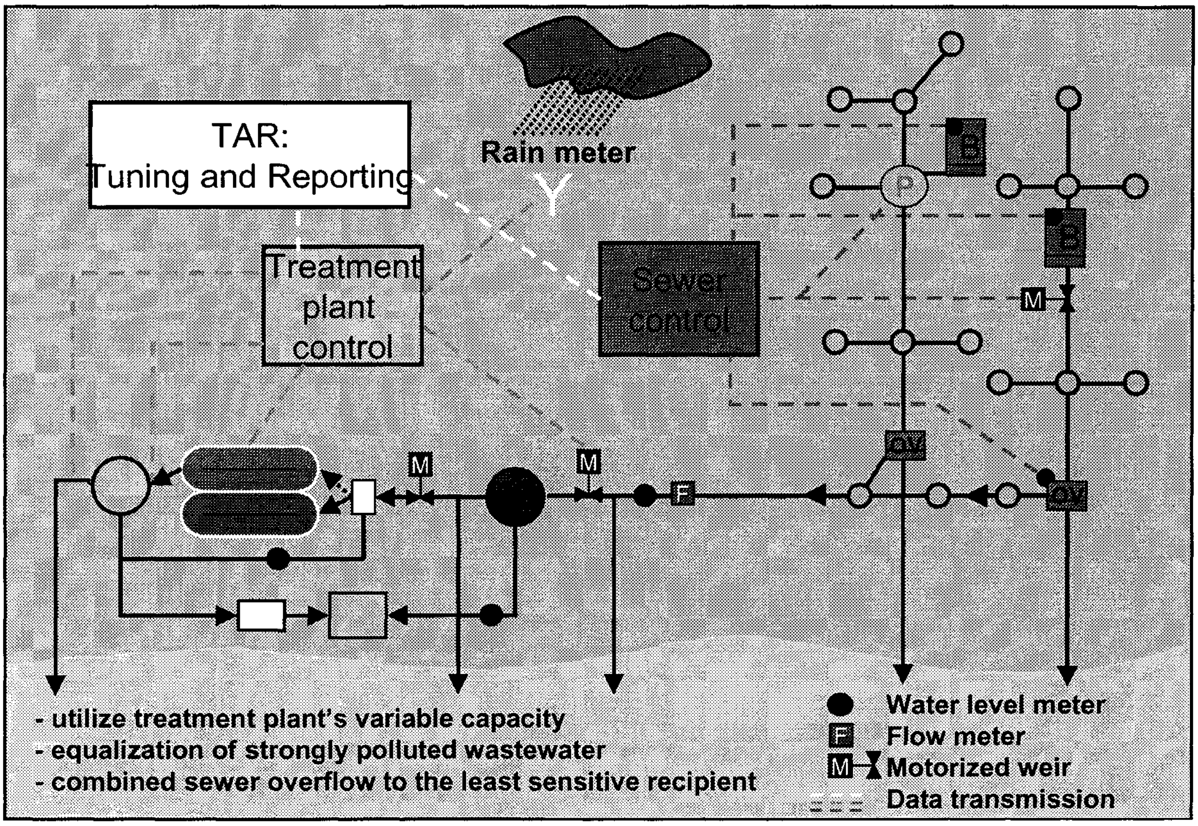


Figure 18 Control integrated via STAR

The small available volumes and adjustable capacities available in the sewer often limit the possibilities for efficient control intervening in the sewer. But the co-operation between different units in the treatment plant and sewer can often reduce CSO pollution significantly by supplementing each other. If the system and its storage capacity is symmetrical, it is very difficult to make a better control strategy better than the traditional operation built into the design. This built-in control is often to store the first water, which cannot be treated, and discharge subsequent water preferably through the equalisation basins.

9.1.1 Objectives integrated control

The overall goal is to minimise overflows and to use the least sensitive recipient if CSO's cannot be avoided. The dynamic flow predictions should at the same time be used to minimise flooding problems of streets and cellars etc.

A basic tool that needs to be developed is the communication between the sewer system and the wastewater treatment plants so the capacities of both systems are exploited to a maximum. The WWTP SCADA should continuously calculate a (dynamic) hydraulic capacity based on the present situation and potentials for increase. The capacity will depend on sludge characteristics, sludge distribution among tanks and amount of sludge in the plant. The physical limits like pump capacities, channel and pipe dimensions must also be taken into consideration.

As mentioned in paragraph 1.3, it is possible to increase the plant flow capacity by controlling the sludge distribution among basins by step-feed or ATS.

The sewer system SCADA should be able to predict the flow and concentrations at important points in the sewer system some time ahead. This tool is still not generally available. The editor firmly believes that the grey box concept is the best tool in this connection (Carstensen et al. 1996), and pollution can be included (Bechmann 1999) in the decision background.

The co-operation with different plants, which have different capacities, is often of value. On the other hand, the storage in sewers might be so strong that certain operation conditions must be included in the maintenance system for the sewers to be able to handle storm, after longer dry weather situations.

Saving in the storage capacity cost is often the greatest benefit in these integrated control systems. The capacity of the plants can often be adapted to the actual capacity instead of the design. Hereby the available storage capacity can be better used by timing the filling and emptying in different parts of the sewer system. These decisions must be based on a full knowledge of flow and concentration knowledge at all points in the system to be optimal.

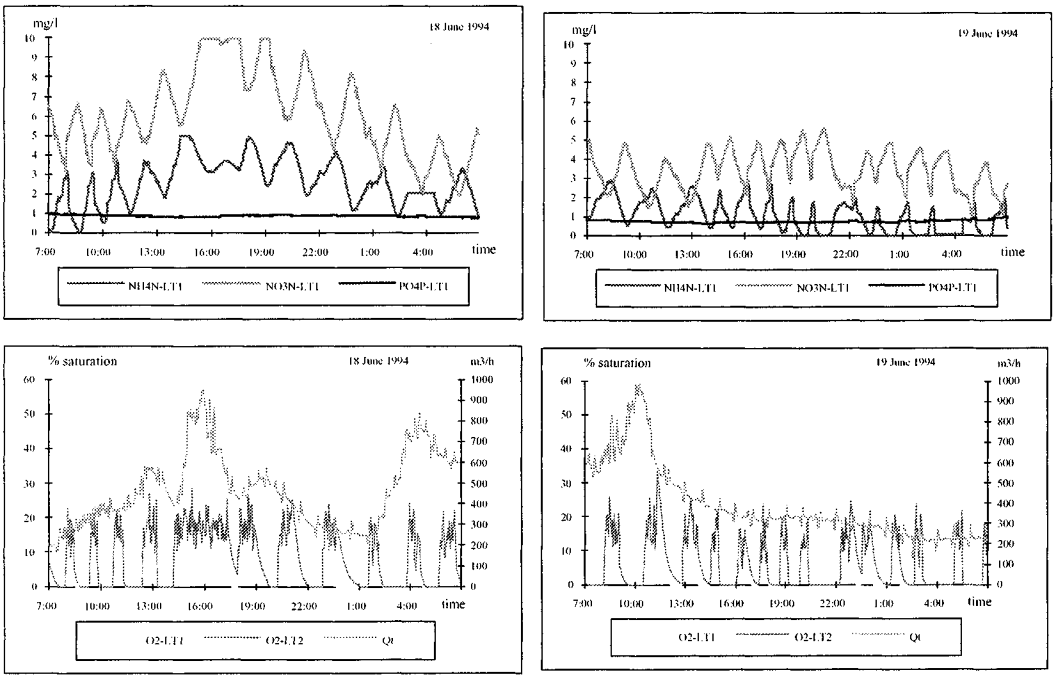


Figure 19 Nutrients, flow and O_2 levels in 3 consecutive rains at WWTP Sydkysten.

Traditionally, the flow and concentrations have not been considered to be changing dependent on flow history for sewer controls, they have normally been based on a mean dry weather flow and concentration dilution modelling. The deterministic modelling of settling and resuspensions of pollutant is still unreliable and unstable, but using the well determined daily variations from plant and sewer system. Both flow and concentrations are available by integrating grey box modelling in the systems. A redistribution of this knowledge to different discharge points in the sewer system is rather simple, however, not documented in control yet.

The flow concentration profiles in a given point in the sewersystem (Beckmann 1999) can be determined and look in principle as shown in Figure 21. The significant variation in concentrations in sewers, are often observed by the plant operator, because concentration dynamics or O_2 consumption variations, as documented by Ønnerth 94, as shown at Figure 19.

The significant higher amount of pollution in the first flush is seen as longer time with demand of O_2 and the higher rate and level of N in the measurements. The tool to quantify the extra load as kg COD/h is still not available.

9.1.2 Uncertainty reduction

The prediction of flow and concentrations will always be uncertain due to the changes of runoff coefficient dependent on length of period with dry weather and temperature, which create different adsorption of water into the surfaces during nex rain. A more important disturbance is the rain distribution is disturbance is added to the many more stochastic disturbances from the sewer design and maintenance. Therefor predictions will always have deviation from mean ideal values in the single rainflow.

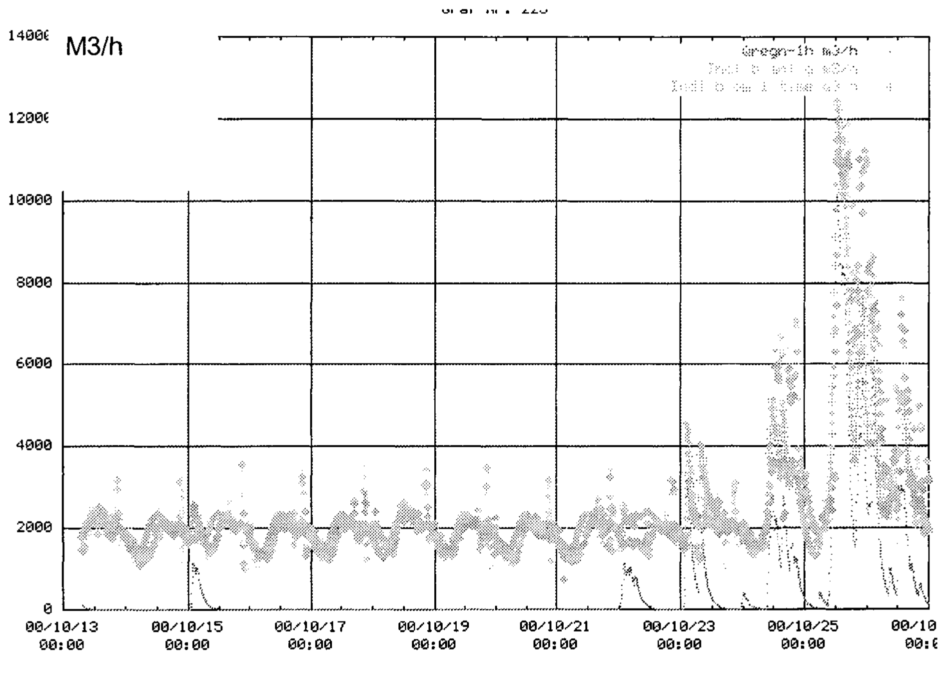


Figure 20 Flow measure, predicted and rain predicted for Aalborg V WWTP

In Figure 20 is shown the flow and the prediction from 2000 of the flow to Aalborg V WWTP estimated by a simple Grey Box model calibrated in 1994 without later adaptation, as discussed by Carstensen 1997. The results from Carstensen 1997 indicate that the adaptation of flow models must be slow, otherwise the adaptation will just follow the distribution of rain from normal equal distribution. Hence the model will be of no value for prediction of flow, due to too much adaptation which will transfer the model to slowly following the measured flow.

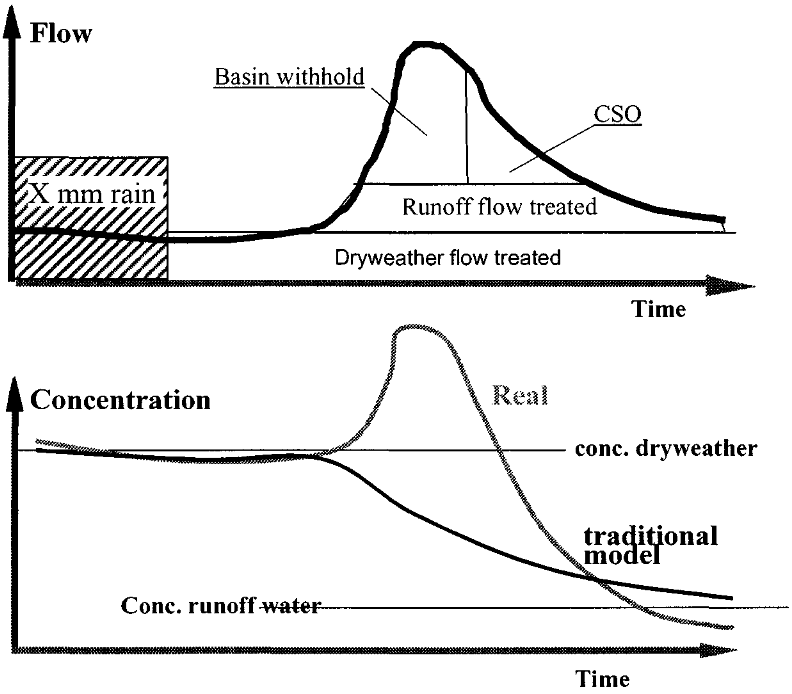


Figure 21 *Flow and concentration relations during rain situation*

Often the difference between modelling and reality is not significant. This will happen, when there is little settling in the sewers due to high slope etc. Under these conditions the control dependent on concentrations is also of less power, so we concentrate on sewer systems with small sloop and with trunk sewers which might crate controllable conditions, due to storage volume and different concentration gradients for control evaluations.

As an example is considered a rain situation at Aalborg V WWTP, where a high first flush peak arrive to the plant, is captured and stored in the primary clarifier. This is obtained by bypassing the clarifier as the peak is going to leave the clarifier. The bypass to the recipient after the primary clarifier is needed due to capacity of the flowing biological plant, as illustrated in Figure 22.

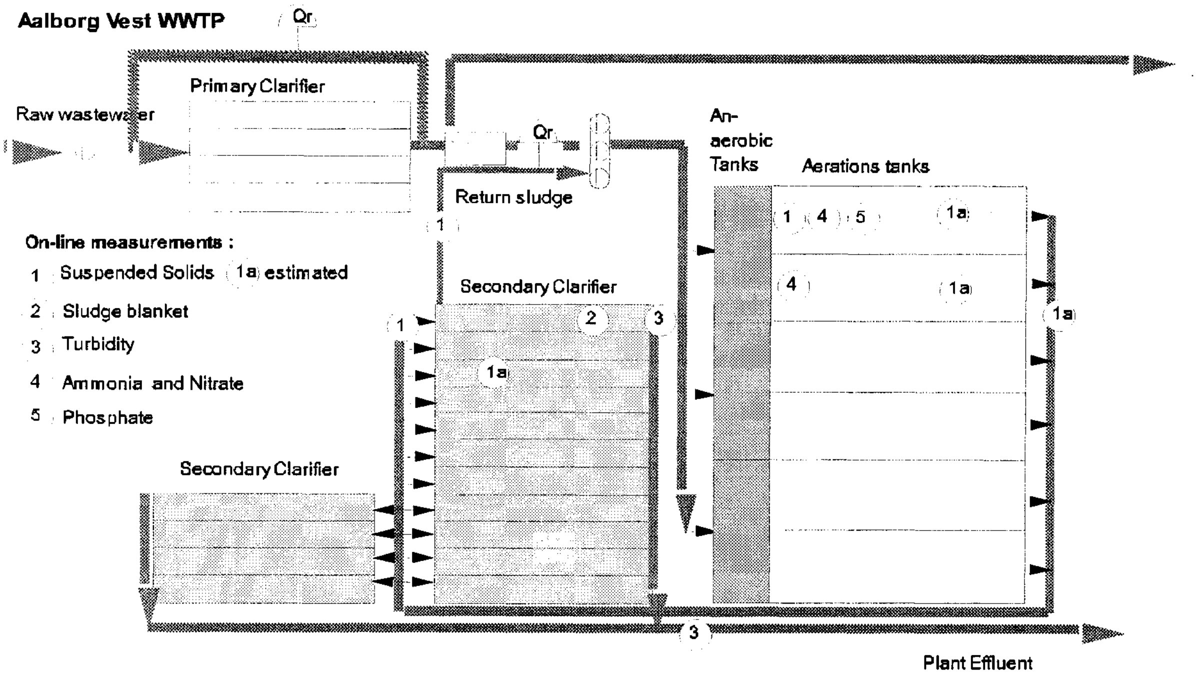


Figure 22 Layout of Treatment plant

In Figure 24 is shown a flow and concentration incident for the plant in Figure 22, the benefit as reduction of SS discharged to the recipient from the point with the lowest concentration and avoiding hydraulic overload of the primary tank.

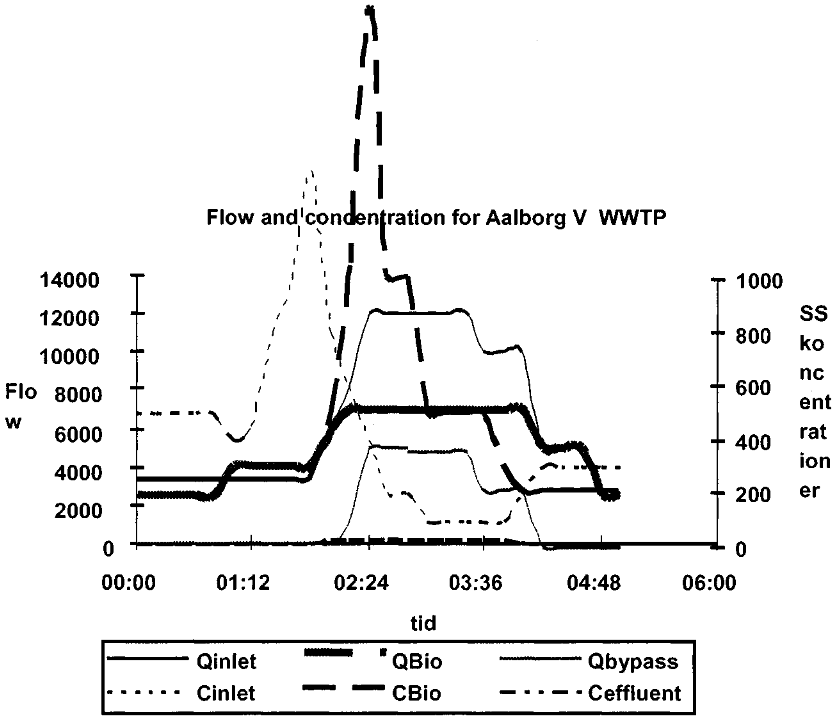


Figure 23 Flow and concentration at strong first flush conditions

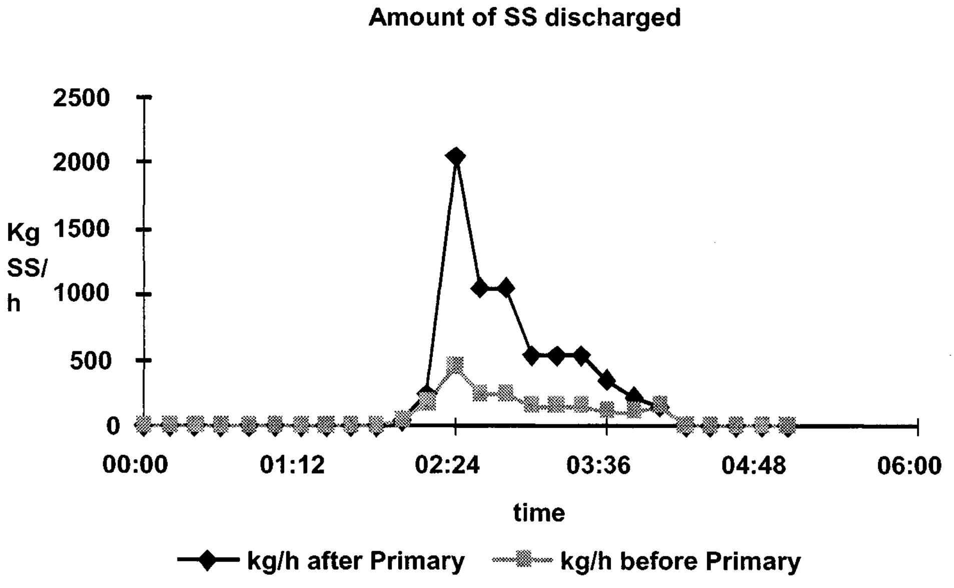


Figure 24 Discharge with or without bypass of primary clarifier

The more concentration dynamic in the sewer the more effect will be available for control.

Statistics must be considered to decide which flow and for how much time these controls are of value to the local flow distribution. An example from Skive WWTP is shown in Figure 25. Here the mean flow for each hour during a year is registered, and multiplied with mean concentration distribution after daily dilution measurements.

The shaded area in the figure illustrates the operation area where control can make improvements, dependent on plant conditions.

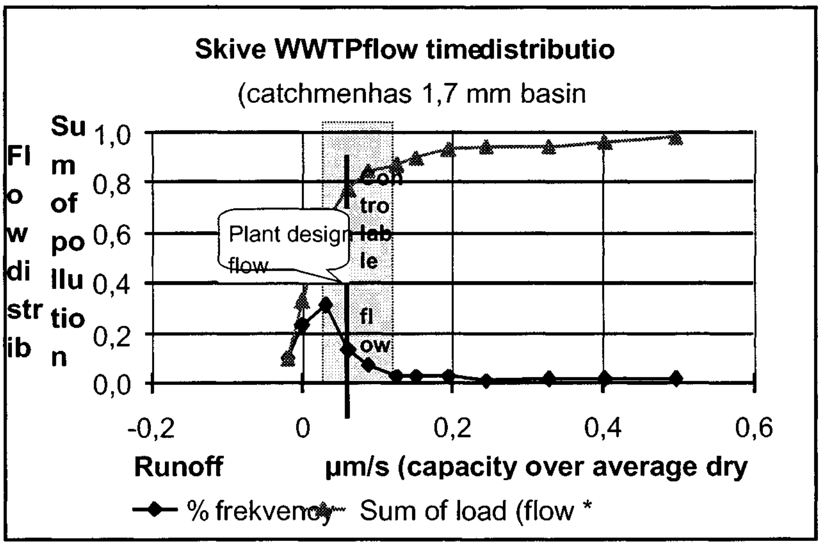


Figure 25 Flow frequents over 1 year for Skive WWTP

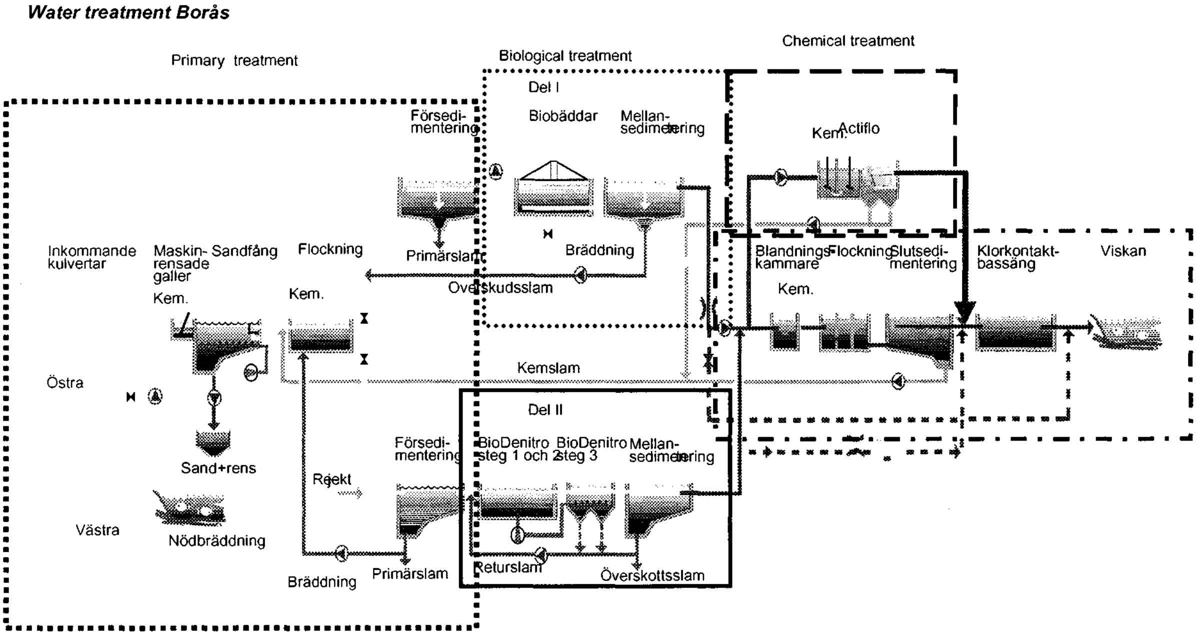
It is seen that although the control is solving the problems in a small flow variation (shaded area), it is however a flow area which contains most of the pollution discharged from the system today, as shown in the sum graph.

The different countries have different attitude to how to discharge CSO, but from a total pollution reduction point of view, control is important, especially when an integrated evaluation of plant and sewer system is implemented.

In periods with bad settleability or low return sludge, the max capacity needs to be reduced compared to design load. Inversely during good settleability and reasonable sludge distribution between clarifier and aeration tanks, the capacity is higher than design capacity, and after introducing ATS or step feed, the capacity is higher. Just using this information might improve the situation considerably. Further improvements are discussed in chapter 9.2.1.

9.2 TOTAL PLANT CONTROL

The operation of total plants is to make all control optimise to the maximum performance at the lowest possible total cost. Hence the optimal control leaves the cleaning to the most efficient step at any time, taking performance and economy into consideration. To do so, it is today necessary to examine how the dynamic of the different steps will affect each other, and then try to introduce the control slowly and empirically find the optimal performance combination. In Boraas the performance of the water treatment part is divided in 5 unit operations shown as different frames in Figure 26.



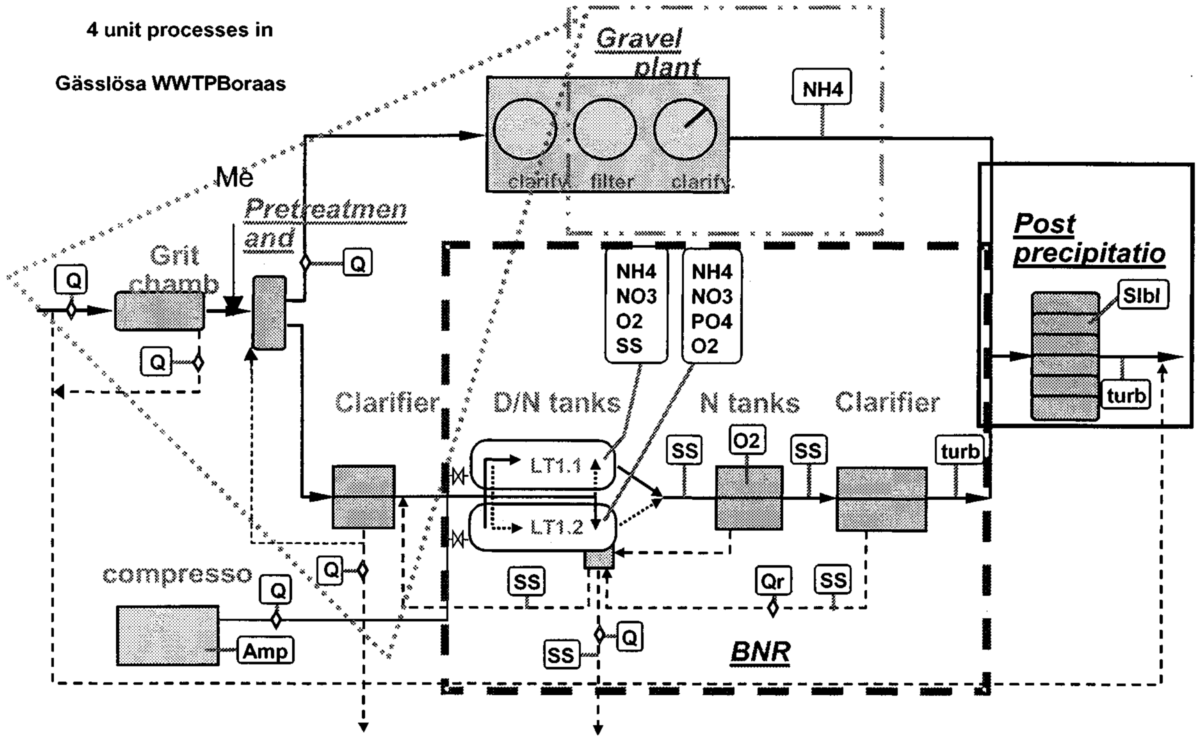


Figure 26   Functional unit operation at Boraas WWTP and instrumentation

Primary precipitation must ensure that the activated sludge plant is not overloaded, but also that there is sufficient C for denitrification. Further the primary precipitation must ensure that the post precipitation is able to meet the demanded 0.3 mgP/l. This last task is most relevant when much water is treated by the biofilter in Figure 26 because it does not remove as much P as the activated sludge plant shown in Figure 33.

The consumption of different chemicals and energy must be minimised, as well as the cleaning efficiency and stability must be maximised.

The difficult selection is to balance the need for constant operation and possibilities of cheaper and more sustainable operations.

Looking at the historical dynamics, it is easy to see that making expensive pre-precipitation is not optimal. In periods where sufficient capacity is available to handle the load in the following biological plant and hereby creating a need for extra carbon addition is not optimal. The control task is to find a useful measurement to decide how efficient a pre-precipitation is needed. The criteria are that the later plant part has the needed capacity, and the removal is cheaper by these processes. Also the P removal can be so efficient that P level will be too low in the following bioprocess. (see Figure 33 , 35 and 45) Equally, post-precipitation is often not necessary to keep the P level in effluent during normal load, but necessary to be able to handle the peek loads during rain situations.

Another example of co-operating unit-processes is when parallel plant with different operation characteristics is available.

It is a general operation problem to identify the sensitivity and the delay of the possible control. As an example, we here consider the Fredrikshavn WWTP where a pre-precipitation is followed by an activated recirculation plant parallel with a submerged aerated filter for N removal.

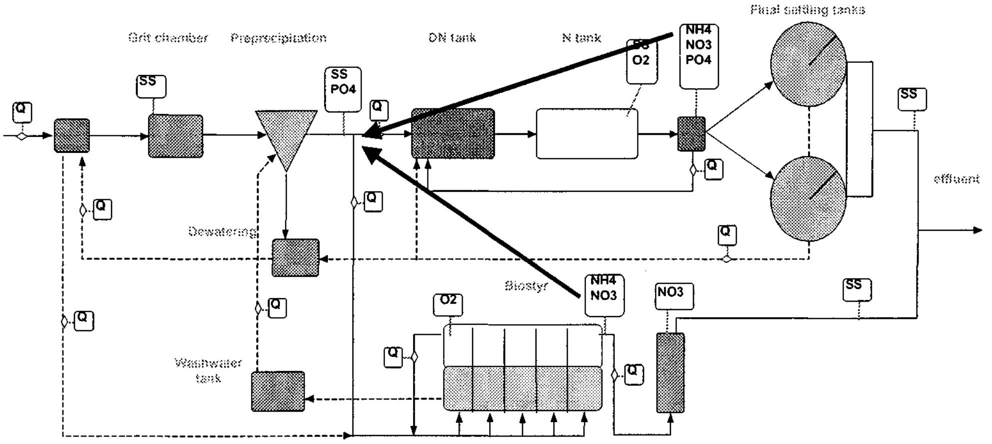


Figure 27 Flow distribution controlled by Nutrient

The control task here is to make the operation strategy to use the capacity robustness of activated sludge for organic substrate and the hydraulic capacity of fixed films during peek loads, and distribute the load to the cheapest processing plant at low loads. This criterion is dynamic dependent on actual load situation.

The objectives could be to obtain minimum nutrient in effluent, so NH3 and NO3 from the two plants are relatively good indicators for how to redistribute the flow. However, the time constants in the two plants are quite different, and the response in effluent from re-distribution at the inlet is too late for direct control; hence the experience learned one day might be used the next day. However, the control delayed one day is often useless, but the pattern from one day to the next is often useful. The best control is based on an identified daily variation, adjusted after immediate measurements and corrected dependent on the actual total load and relation between the two plant performances. This can be adjusted according to actual nutrient measurements.

As the daily load variations are very important in the control described above, the ability to include variable pre-precipitation efficiency might be useful. This ability is important, as the filter plant does not remove much P, so when the filter plant is used, the pre-precipitation must secure low P as well as needed COD removal. During periods with mostly activated sludge in operation, the pre-precipitation can be limited or totally stopped.

The N removal is normally the critical process to adjust to make sure the effluent standard is meet. The primary demand on load-distribution is originating from the N relations between the 2 plants, as indicated by the arrows in the Figure 27. Likewise, the primary precipitation is controlled for NO3 and PO4, as indicated in Figure 32.

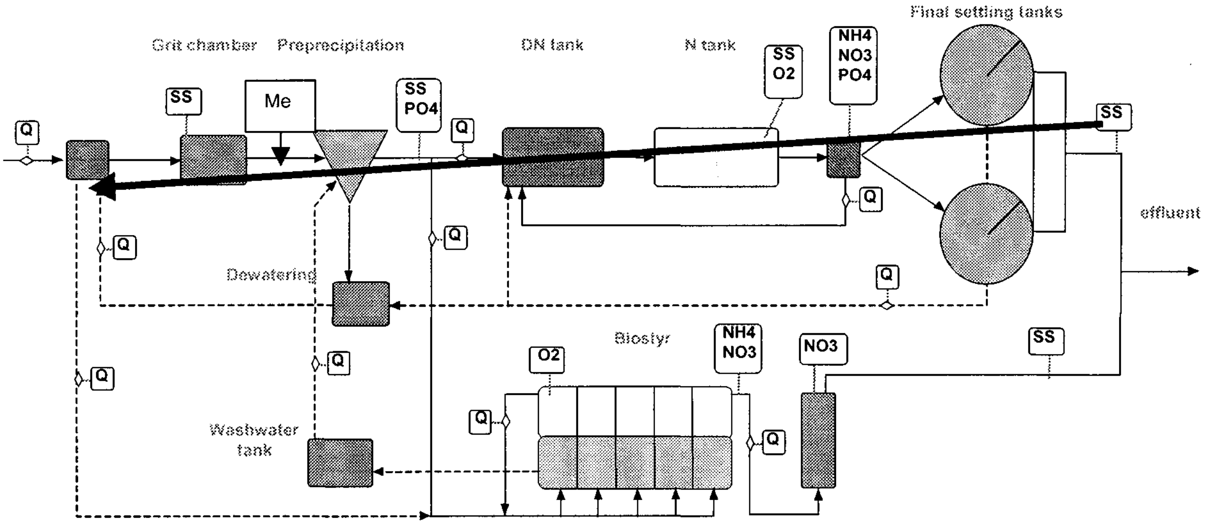


Figure 28 *Control of excess hydraulic flow after suspended material in effluent.*

At many plants, the capacity of inlet is accepted to be constant, although the physical capacity is dynamic dependent on previous load and operation of return sludge and SVI in activated sludge. To be able to determine the hydraulic capacity, the suspended solids in effluent is a relevant measurement. In above control, the delay is relatively short 5-15 minutes, because the level variations are relatively small compared to concentration variations, which are connected to hydraulic retention time and reaction rates. At this plant in Figure 28, there is an extra possibility to bypass some raw wastewater during high load to the filter plant. This extra capacity is obtained by reconfiguration of the filter plant to parallel operation during extreme peaks. Also here the SS in the effluent and the SS in the influent are the most important operation indications for maximum total plant performance.

9.2.1 Extending hydraulic capacity of treatment plants

Methods exist that can increase the hydraulic capacity of the biological part of the wastewater treatment plant.

The best known method is inverse step feed operation where the influent (or part thereof) is diverted to an aeration tank section closer to the clarifier in the hydraulic chain (downstream). Since the return sludge from the clarifiers is still pumped to the first aeration tank, the concentration will increase to about the double during 4-6 hours in the tanks upstream of the influent (Buhr et al. 1984). However, this method will deteriorate the cleaning efficiency after some time and it is working slowly, if the flow is not diverted to the last sections before the settling tank.

Another method is the Krüger patented ATS method, which does not deteriorate the cleaning efficiency. This is developed for alternating plants where sludge can be withheld in and shifted between pairs of aeration tanks and still provide the necessary nitrification and denitrification on the relatively diluted stormwater (Nielsen et al. 2000).

The potential of the ATS control is very strong. A doubling in hydraulic capacity for a wastewater treatment plant without any significant deterioration of the effluent quality, due to denitrification is efficient during settling periods in the reactor, as reported by Nielsen 1996.

The ATS principle can be used in recirculating plant types, which are the most widely used plant types for biological nitrogen removal around the world.

The efficiency will be tested in the SMAC project at the plant of Helsingør, 40 km north of Copenhagen.

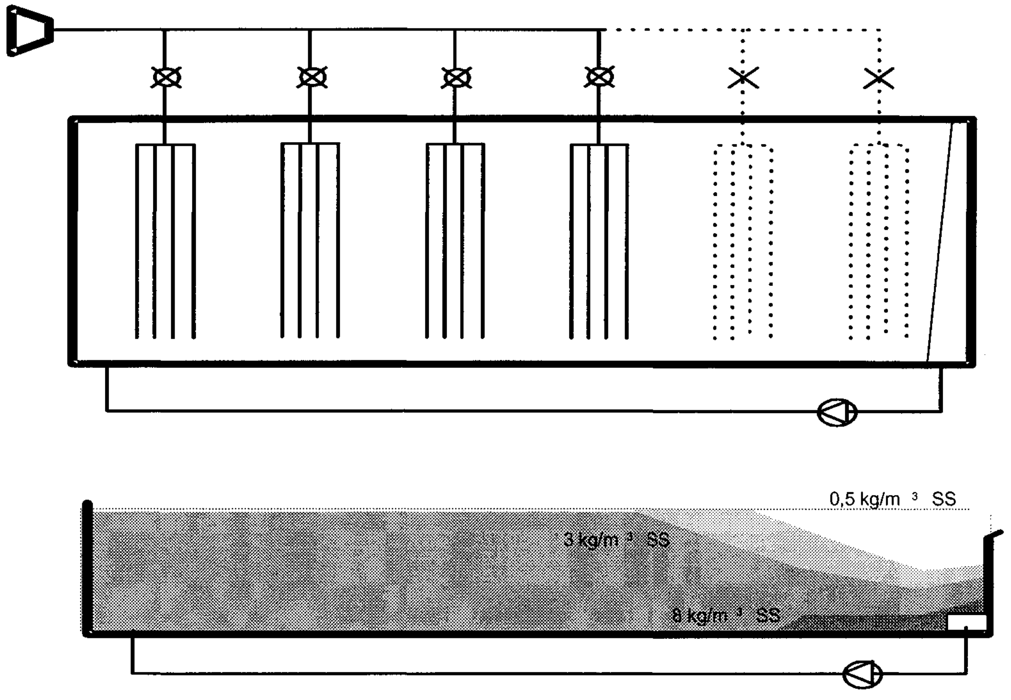


Figure 29 ATS principles for plugflow system

The result of control of the hydraulic capacity must be seen in connection with the possibilities for removing nutrients and saving operation costs. This is discussed by (Nielsen and Strube, 2000). In this paper the possibilities for extending the biological P removal and securing better settleability in sludge is discussed.

9.2.2 Operating series-coupled unit operations

When optimising a plant with two biological units in series, the optimisation aim is to get the best performance and treat as much pollution as possible in the unit with the cheapest handling. As example, an A_B process can be considered as shown in Figure 30.

It is most economic to remove most of the COD in the A process (Biosorption), but if it makes need for Carbon addition in the B plant, it is better to divert water to Bio-P tank or the aeration tanks bypassing the A plant. The condition in the plant is illustrated by the time-graph in Figure 31.

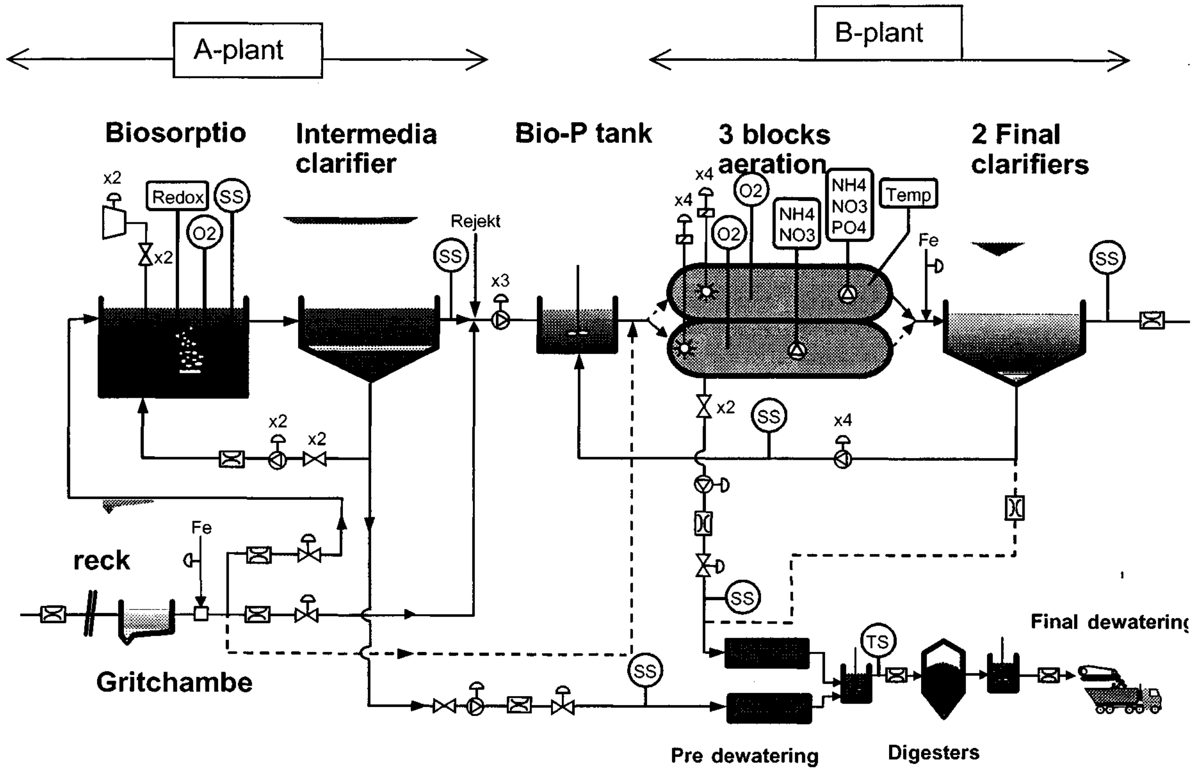
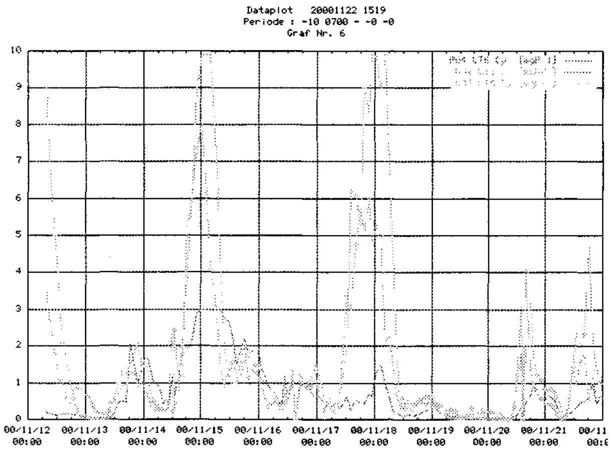
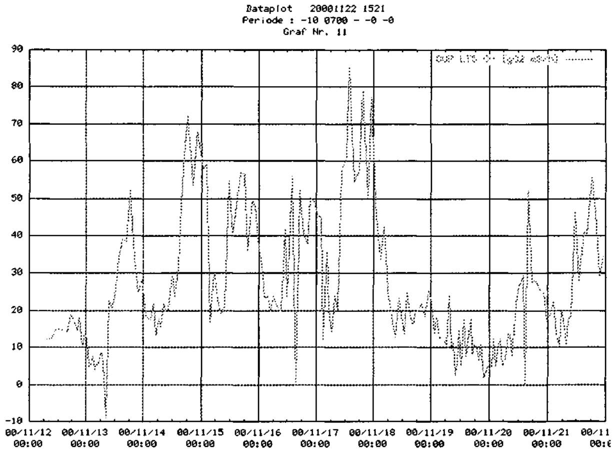


Figure 30 *Skagen WWTP layout with AB process and instrumentation*

As seen, the water can be distributed to 3 points after the grit removal, two via flow measurements and control valve and one as overflow from distribution chamber (dotted line).





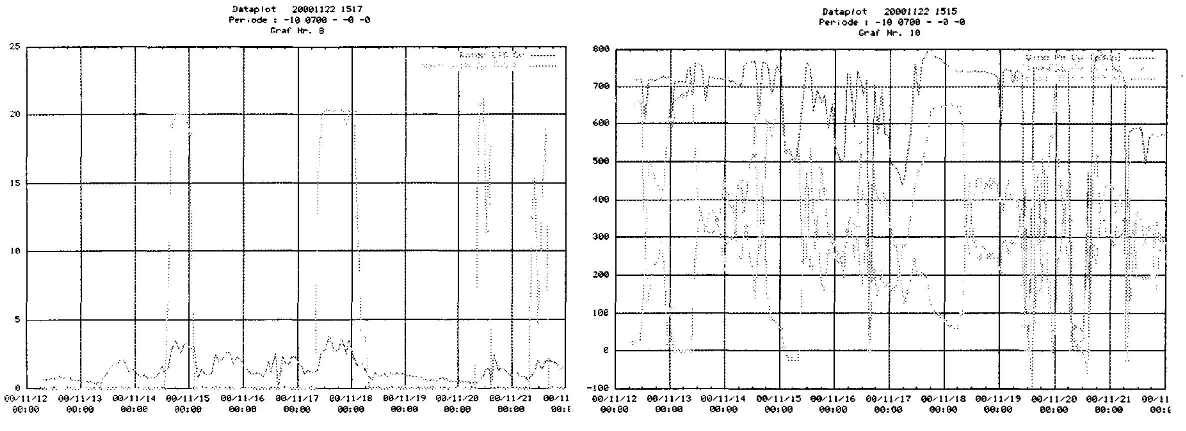


Figure 31 *10 days data from Skagen WWTP.*

In the upper part of Figure 31 is seen how the nutrient in the plant is changing and how OUR follows the load. On the lower left, probably the cause of the variations is seen, the reject water flow from final dewatering device and the use of aeration capacity in the B plant, which follows the OUR above. The lower right graph shows the total flow to the plant, and the distribution of this flow to A and B plant. It is clear that the flow distribution is giving more to plant A during peak loads, but still the nutrient responds strongly. Generally, the P precipitation is only needed during higher loads.

It is still not documented which information it is best to adjust these flow relations. New development in this control is still to come. The present control in Figure 31 is based on total nutrient and the relations between NO_3 and NH_3.

9.3 OPERATING SINGLE UNITS OR FUNCTIONS

9.3.1 Pre-precipitation.

The mechanical cleaning or primary settling is often supplemented with chemical addition and flocculation to enhance the efficiency. The control is normally flow proportional addition of flocculent metal salts and sometimes supplemented with polymers to reduce the electrical charges of the flocks. The chemical need and efficiency is strongly dependent on the water composition especially hardness. Also the aim of the precipitation is different. Sometimes the main goal is to reduce the organic load on later steps, other times it is the P removal that is the main goal. Sometimes these aims are in line, but often in periods of the day the P removal demands efficient removal of the COD and excess Carbon source might have to be added in later process parts for denitrification. Normally the operator must select a mediating dosage, which can be adjusted daily, or weekly.

Typically, there are no control measurements, only adjustments after flow, and if polymer is added, redox or charge measurements are controlled. The proportionality control is often reduced or stopped at extremely high flow.

Traditionally, we accept the design criteria, best possible removal in primary treatment gives cheapest removal of COD, produces most gas and uses less energy. Today the operator may ask: is the needed chemical addition optimal when he later must add methanol to replace the removed

COD, and P removal was not needed maybe 12 hours during the night? This kind of questions can only be answered when the total plant is taken into consideration and are discussed later.

To make different unit-operations in a plant to co-operate, normally the delay is the biggest problem and the relevant measurement is often difficult to obtain. The indicating sensors with correlations to the aim sensor can be used for a cascade control. This is exemplified by adjusting the pre-precipitation before BNR plant, as shown in Figure 32.

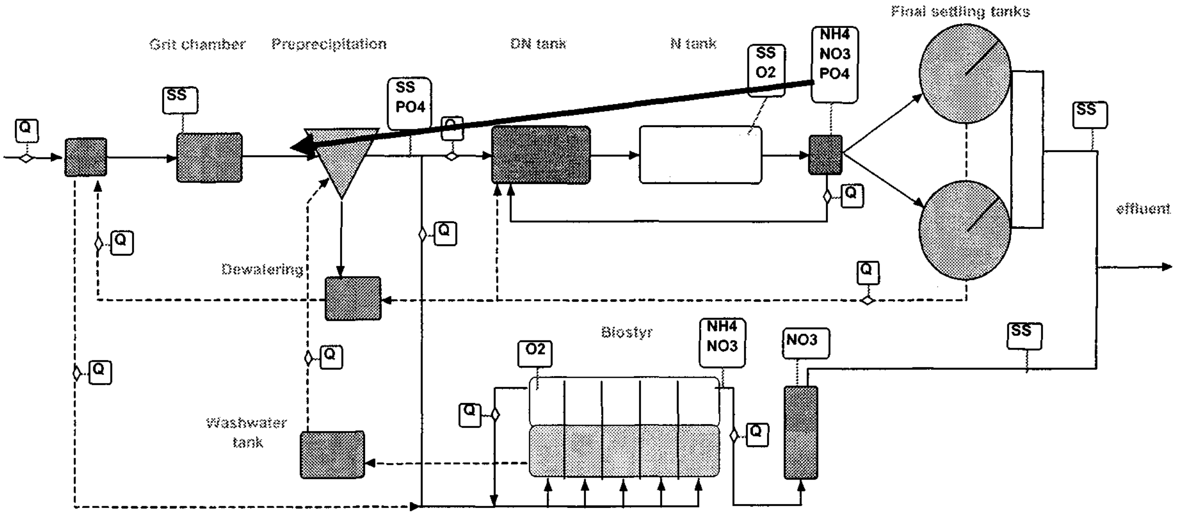


Figure 32 Pre-precipitation controlled by PO4 and NO3 in AS effluent

Pre-precipitation is designed to reduce the organic load to the biological plant or to reduce the P in the effluent. However, often the precipitation efficiency is much stronger than needed.

Sometimes pre-precipitation is even negative, because it is necessary to add external carbon to compensate for the removed C in the influent in certain periods. At other places, the P removal can be so high in pre-precipitation that P is not sufficient for maintaining good sludge settleability in the activated sludge after the precipitation. This situation was experienced in Boraas from where Figure 33 is taken.

During periods where P in the effluent can be controlled by the activated sludge process, the pre-precipitation can be avoided. As the goal measurement here is delayed approx. 6 hours, feed back control is too slow. The periods without dosing need are normally some hours during the night. The solution could be simply to find which hours during the night precipitation is not wanted, but if there are dynamics dependent on industrial load or rain, it is more relevant to find an alternative measurement to control the chemical additions. As turbidity in inlet often follows the COD and TP relatively well, it would be obvious to use inlet turbidity for the dosing control together with the conventional flow control. If the needed measurement is unstable, another alternative could be to use the clarifier effluent turbidity or ortho-P measurements. In such cases the feed back control should be possible, but we must accept the dynamic delay in the control, determined by the hydraulic load at the plant.

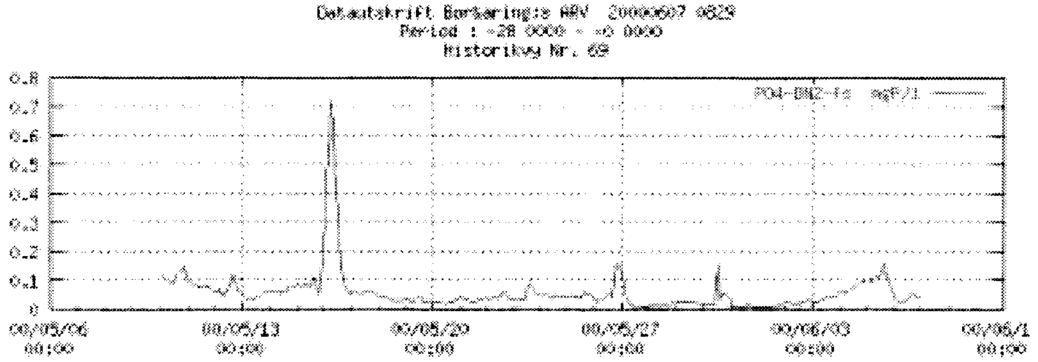


Figure 33 PO4 in aeration tank at Boraas WWTP

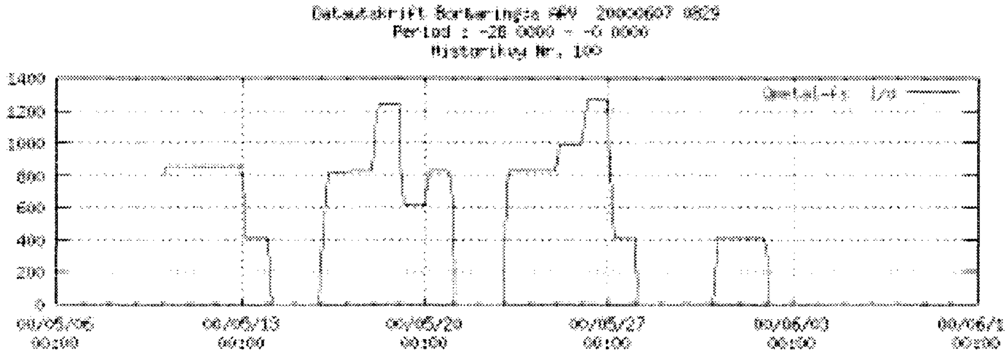


Figure 34 Dosing of chemical in pre-precipitation with above shown PO4 levels

It is remarkable that the dosing in this control was supplemented with a minimum dosing to avoid adding chemical with non flocculating efficiency at the given water quality. Further, the flow-proportional dosing is adjusted after SS out of the primary clarifier, with the objective to keep P around 0.1 in the biological step.

In the example shown on Figure 34, the pre-precipitation is reduced so P in the effluent after biological treatment is sufficiently low during night-time. This control is not feasible as feed back, because the response on changing dosing will be seen many hours later. Hence the control experience from one day may be used the following day, or the correlation to a wanted value of SS or PO_4 out of the primary clarifier could be established and slowly adjusted in cascade control from experiences from the objective control aim effluent PO_4 in activated sludge. As the pre-cipitation is taking place in a plug flow system, even the output from the clarifier might be too delayed measurement for sufficient control. The retention time from dosing to measurement is typically 1-3 hours due to the retention time in the clarifier at different flows. Therefore, a better solution would be to find a correlation to SS in influent and dose according to this. However, the stability of SS measurements in the influent at certain raw sewage types is problematic, with to-day's technology. It is not certain that the optimal precipitation is constant so the set point for the feed forward control must probably be added a diurnal variation to be close to optimal.

The practical best solution at a given plant may need testing, but any of the mentioned operation strategies are often an improvement, because the daily variation is often the most important disturbance at the plant.

9.3.2 Biological step

To reduce the volume of this presentation, we only discuss activated sludge plants with nutrient removal.

The biological step is here defined as including necessary clarifier, as they are an integrated part of the operation of the reaction tanks in activated sludge systems, and in fixed film systems the clarification is often incorporated in the unit.

The biological step has two important functions to control:

1. to keep the activated sludge in the reaction tank during all flow conditions and
2. keep the best concentration in the reactors of substrate and O_2 in contact with the micro-organisms. Figure 54 gives examples of relations of manipulated variables.

To be able to evaluate the possibilities the distinction between hydraulic capacity and organic or nutrient capacity is the first operation decision. A description of the evaluation criteria is described in Nielsen and Strube 2000. The main task is to balance the need to distribute the sludge between clarifier and reaction tank and the need to optimise the Nutrient removal. Further the need for creating the best sludge over longer periods is important.

The storage of sludge in separate reactors (Yuan 2000) is proven to considerably reduce the deactivation of nitrifiers. This storage can be made in the reactors by allowing the sludge to settle and hereby store the sludge without supply of substrate or O_2. The reduction of O_2 load on high loaded sludge is proven to give higher sludge production in the O_2 range of 2-6 mgO_2/l (Abbassi 2000). His data indicates that the sensitivity to lower O_2 levels gives higher effect on sludge production. This phenomenon is explained by the gradient of penetration of substrate and oxygen into the flocks. Hence it must be expected that the mechanisms described by Nielsen 2000a+c are active. The quality of sludge is adjustable by control, of settling in the aeration tanks, return sludge flow, and recirculation flow and oxygen level.

Further, the concentration gradient produced in the settled sludge is of the same size as the gradient often produced in selectors. For selection of the non-filamentous sludge, high concentration gradient is needed. If this effect is used in practical control, maybe not only the filamentous and foam forming micro-organisms can be controlled, as reported by Andreasen (2000) and Chua (2000), but also the carbon source for Denitrification and Bio-P removal will be made available.

Another question to be addressed in control is if the control affects predators, as discussed by Luxmy (2000). So far the experience from WWTP Poznan indicates that optimal control of population and C-pools also enhance the growth of shell amoebae at low loaded periods. Shell amoebae might grow up to disturb both the Bio-P removal and nitrification efficiency for a shorter period. So far only SRT is useful for control of amoebae, and it is a very slow control, so it must be a feed forward control from the load indicators, and often this is left for manual control.

For Nutrient removal, the time scale in phase control and settling is normally half an hour, while the sludge redistribution is 2-6 hours, and finally the build up of C-pools in the sludge is days and selection of biomass has months as time constants.

There is always more control actions, which will be in conflict, so it is important to choose the right priority when selecting which control is most important at the present situation Thornberg 2001 shown in Figure 2. Normally the nutrient removal is by far the most important control aim as it also optimises settling chemical and energy consumption as well as sludge production. The hydraulics take over, as the most important control criteria during rainstorm, and when these process needs are almost fulfilled, the weight is moved more to the C-pools and the sludge population as the important control criteria, as discussed by Nielsen 2000b.

9.3.2.1 Sludge waste control.

Traditionally, it was accepted that optimal values are constant values. It was believed that the design parameter F/M ratio or SRT is very important during operation. This is correct in the long run, but even this value must be manipulated to adjust to the right population for the chosen processes and load variations in amount and digestibility.

Optimal conditions cannot be calculated, only by operating the plant under the given conditions is it possible to come close to understanding what optimal control of F/M is. Hence the operator always ought to adjust a little to move the waste rate to keep an optimal population in sludge.

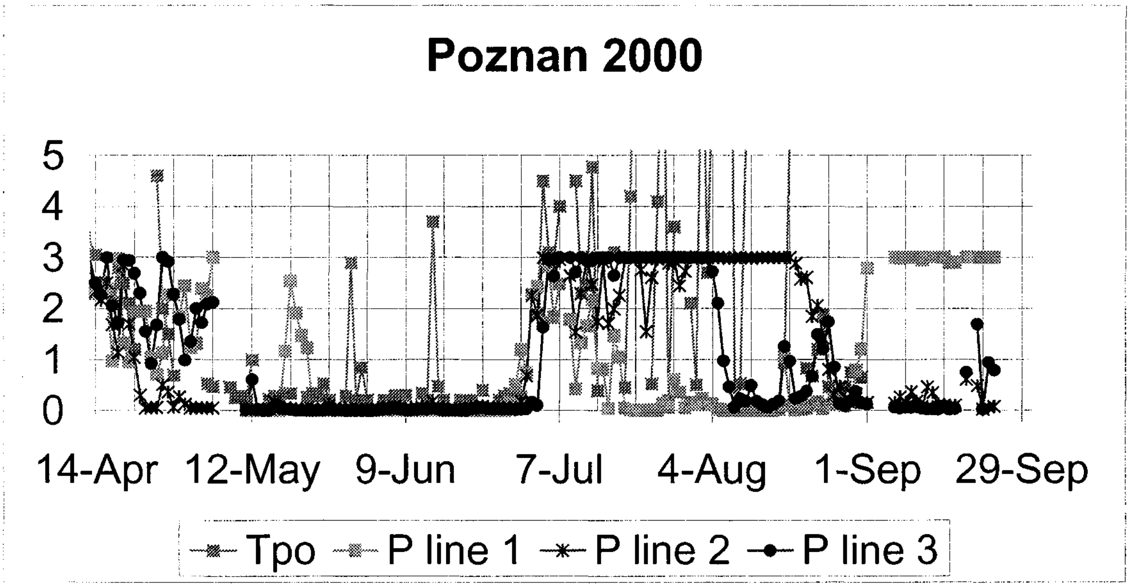


Figure 35 Online daily mean PO4 and sample outlet Total Pout from Poznan WWTP

The most important in sludge waste control is to react slow as the response time will be in the range of a sludge age say 6 – 20 days, so weekly adjustments are often sufficient. Online control is not normally required. The effect of SRT is discussed by Nielsen 2001, and the effluent P form 3 parallel lines as shown in Figure 35, disturbances are pointed out to be affected by the sludge population.

Normally, it is favourable to operate at lowest possible SRT. This will give the smallest power consumption, the best sludge settleability, the best SS in effluent and finally the best Bio-P removal.

However, the nitrification demands a certain SRT to be stable. But during low loaded periods maintaining a relevant SRT is also needed to avoid deactivating the nitrifies and over grassing of Shell Amoebae as experienced in Poznan.

9.3.2.2 Aeration control.

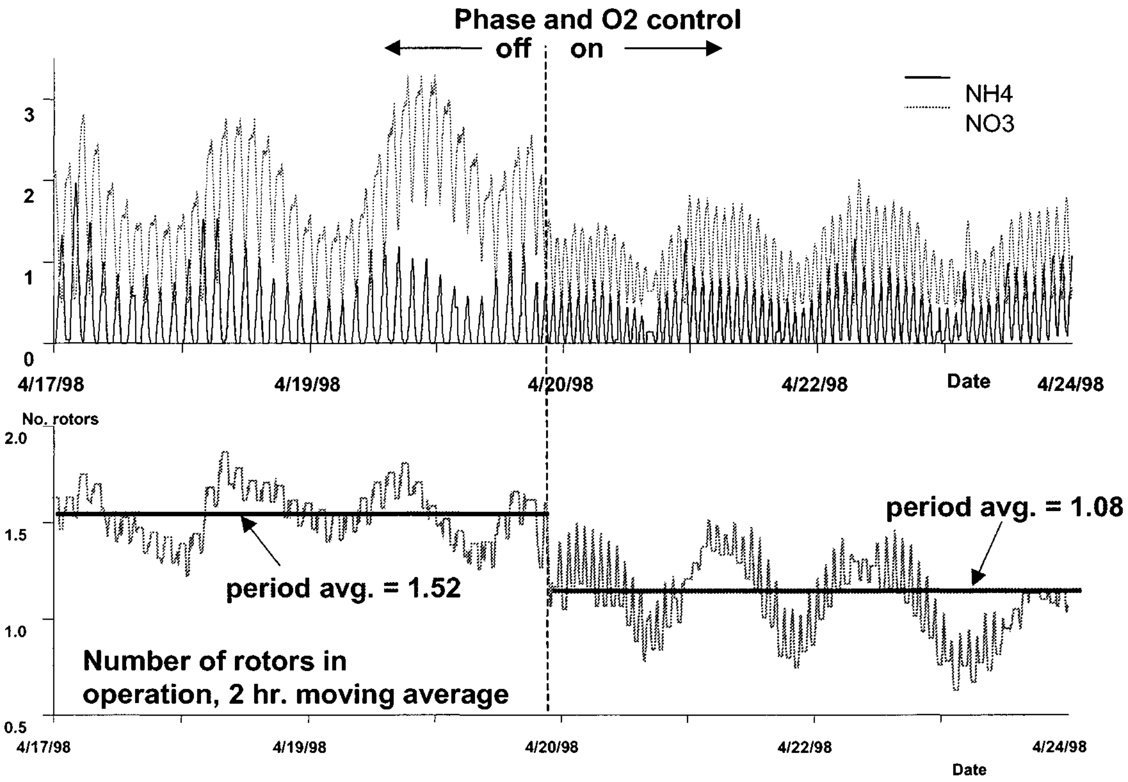


Figure 36 *N and O_2 relations with and without advanced control Aalborg East.*

It is remarkable that the control not only improves N removal and lower O_2 set point, but it also reduces the needed operation of the aerators and saves approx. 30% energy.

In recirculating plants, the aeration part is often designed in more zones aerated from same blower station of more blowers, then the control is divided into valve control and blower control. Generally, the blower-station has to supply the needed amount of air to the different sections and hence keeps a given pressure in the supply pipes and the valves control the O_2 level.

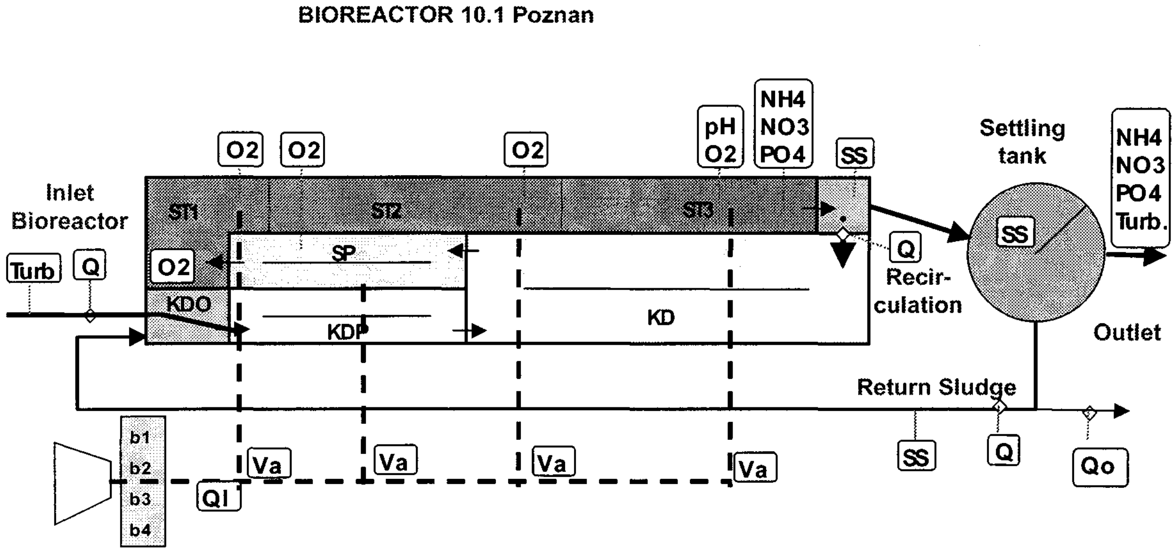


Figure 37 *Aeration tanks layout and instrumentation.*

Figure 37 shows 4 btanks in series for aeration. The optimal O_2 level in the various sections must be adjusted to the need for nitrification, and it must be ensured that no carbon is burned off when no NH_3 is reduced. If we accept that the optimal O_2 level in the bulk sludge depend on uptake rate of O_2 in the sludge particles OUR, and the needed penetration depth of O_2, as illustrated on Figure 54. Then we must adjust the O_2 level according to the OUR-distribution through these sections over the day. Typically we will expect a variation approximately as shown in Figure 38.

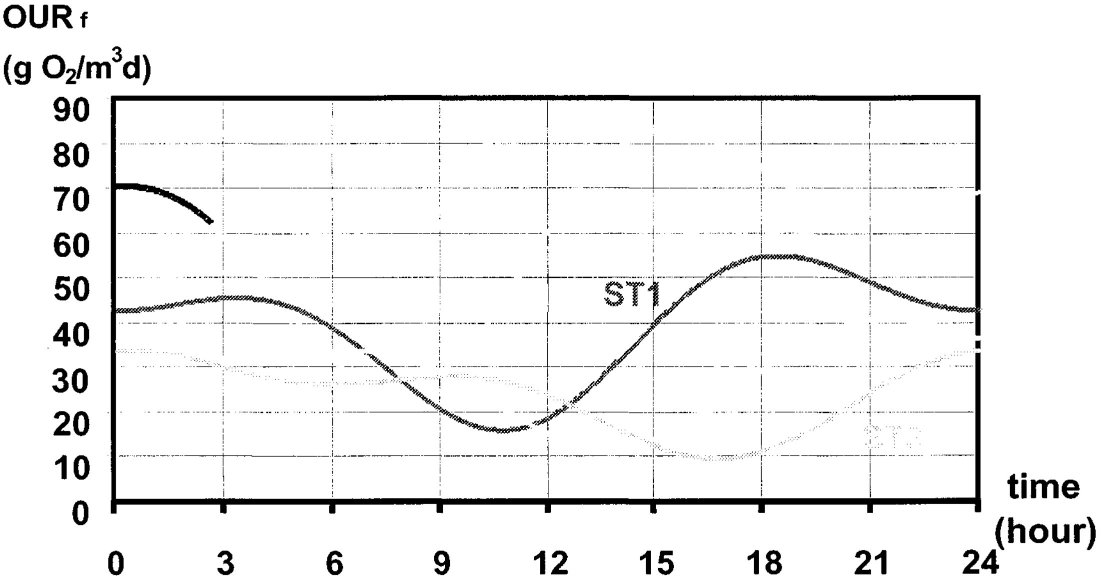


Figure 38 Theoretical oxygen uptake rate distribution in serial tanks

In theory, a need for reduction of O_2 is to be expected, however, practice does not follow often theory and therefore, deviations must be accepted as discussed by Nielsen 2000c.

9.3.2.2.1 Blower control

The blowers are operated at the lowest possible pressure. The energy consumption is proportional to P *Q where Q is airflow. Often the manifold pressure is kept constant at the minimum pressure to supply the maximum airflow, but it is more advantageous to let the pressure follow the flow required to save energy. By doing this, however, the control pressure drops over the control valves. The small pressure drop will reduce the efficiency of the valves in control. The acceptable variations in O_2 will limit how low the acceptable pressure drop over the valves can be. Figure 7 shows how much the intermitting aeration in ST1 tank in Figure 8 affects the O_2 levels in the SP tank. A careful calibration of the distribution system for the aeration sections is therefore required which unfortunately, is very often forgotten in practice causing many difficulties in managing the aeration system.

9.3.2.2.2 Valve control

The valves are normally controlled directly on the basis of the O_2 measurements. The control must be dampened to avoid ringing due to the delay time in the process and O_2 sensor response, after a control action has taken place.

As the oxygen demand varies between the sections it is difficult to avoid valves going into saturation, which may summarise serious faults if a PI controller is used. On the other hand, operation with all valves in nearly closed position will cause a serious loss of energy, so the valve control strategy must be to operate with at least one valve close to or fully open at all times.

During low loaded periods in the nitrifying plants the need for aeration is often so low that the mixing in the tank is so low that the O_2 measurement is not representative for the tanks. If this is the case, periodic over-aeration must be accepted or/and introduction of intermitting aeration will be necessary, to avoid serious over aeration.

9.3.2.2.3 Oxygen set point tuning

When looking at biological N removal the control has a new aim as aeration during periods without NH_3 available will reduce the efficiency of the nitrification process and reduce the ability to perform denitrification.

Therefore, it is not sufficient to keep a constant low O_2 level; the level must also be varied dependent on the load conditions and the sludge capacity in order to get the best effect of the plant.

When a strong plug-flow configuration is applied a special task is to design the right O_2 profile down the line. In Poznan the Nutrient measurements are only available in the last section ST3 as shown in Figure 37. The data are shown in Figure 39 It was experienced that the use of the same nutrient measurement for O_2 control in all 4 aeration sections was too dynamic. This is due to delays between the various sections. Therefor the set-points in the first 2 sections were fixed at a daily variation, while the set-point in the last 2 sections was adjusted from the nutrient measurment. The O_2 variation over a week is shown in Figure 40. details is shown in Figure 44-41

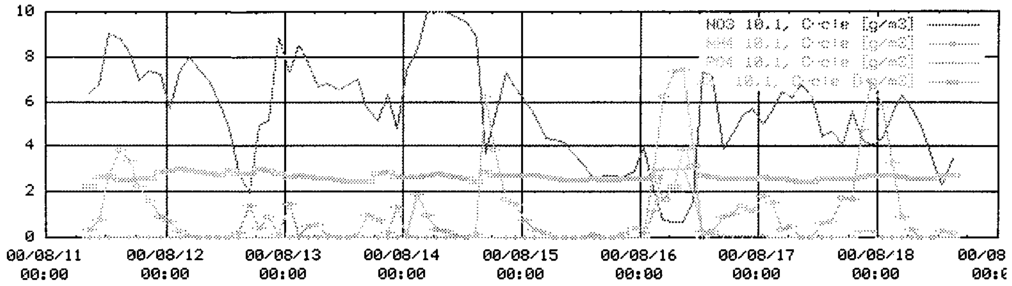


Figure 39   Nutrient in 4 aeration tanks in Poznan

The O_2 levels are normally controlled by STAR. The level in the first 2 sections follows a daily fixed variation and in the 2 last sections the NH3 measurements adjust the O_2 level. Observe the O_2 control overshoot after the blower drops out 16/8 in the morning

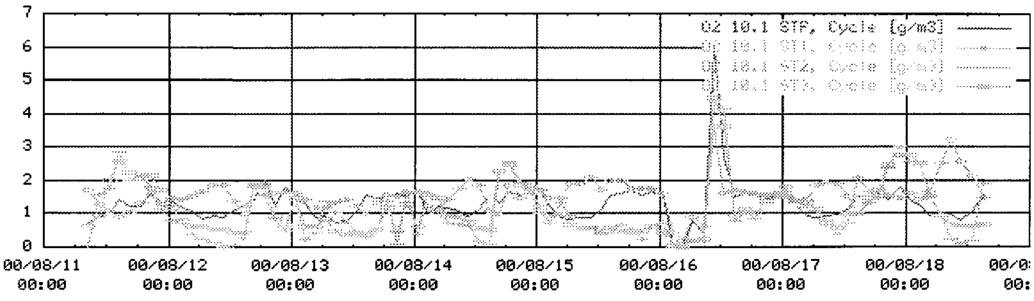


Figure 40 O_2 level in 4 sections in Poznan.

It appears that the O_2 level in sections ST_2 and ST3 in general follows the NH_3 in Figure 40 except when there was a blower disturbance in the morning of 16/8. It is remarkable that the delay and the use of two aeration sections induced a dynamic NH_3-N as in alternating plants. Therefore, the NH_3 level in the last section of a plug-flow system is rarely kept at zero for longer periods. Due to the balance between aeration and load, the plant is able – with this control - to keep the P shown in Figure 39 at nearly zero except during the situation of a blower failure. Details of the O_2 set-point and the actual O_2 are shown in Figure 44 to 41.

9.3.2.2.4 Intermitting control/Phase control

The intermitting control is a strengthening of the O_2 control. When a low O_2 supply is necessary, this can be ensured without distributing the aeration supply in periods instead of to low setpoint that might be unstable to maintain. This is an advantage for both the Bio-P and denitrification at the same time it saves energy.

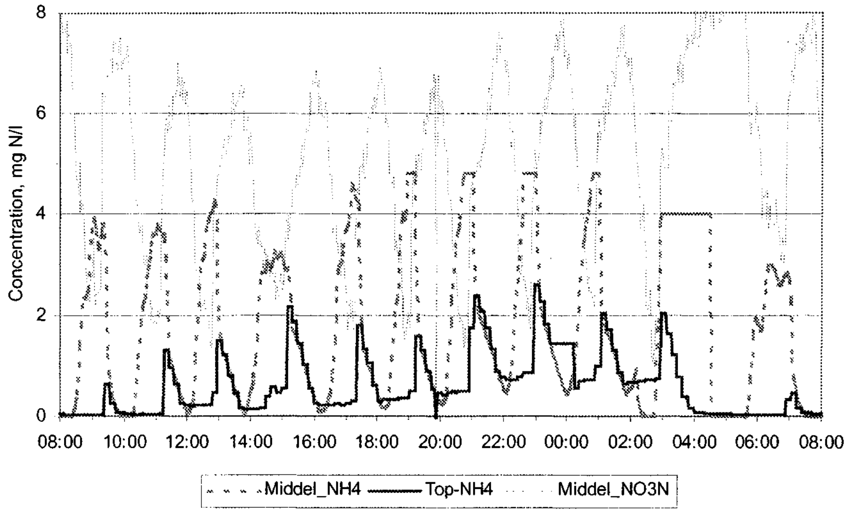


Figure 41 N measurement at various depths during intermittent aeration

It is remarkable how serious the measurement error would be if the measurement was placed in the top or the middle of the tank depth. To get realistic data it is necessary to calculate the representative value by excluding the measurements from the settling period, and only use the measurements when they are representative during aeration as shown in Figure 41 for the two NH_3 measurements. A method to handle this kind of problem is described by Isaac 1999 and shown in Figure 42

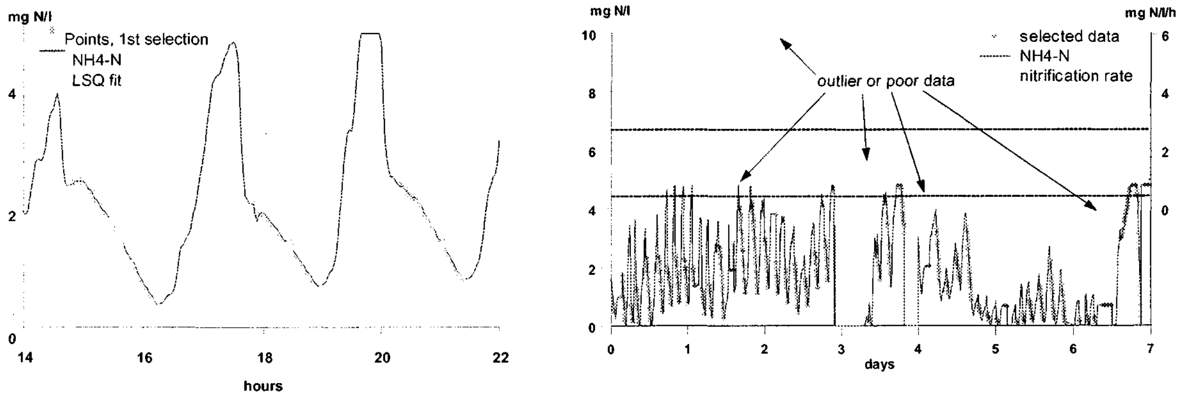


Figure 42 Data quality assurance during intermitting aeration.

When we have the correct measurement of nutrients, we can adjust the aeration to provide the wanted relation between e.g. NH3 and NO3. This control is very important for Bio-P removal as shown by Siegrist (1999) and Nielsen (2000a). The above Figure 42 is taken from this paper.

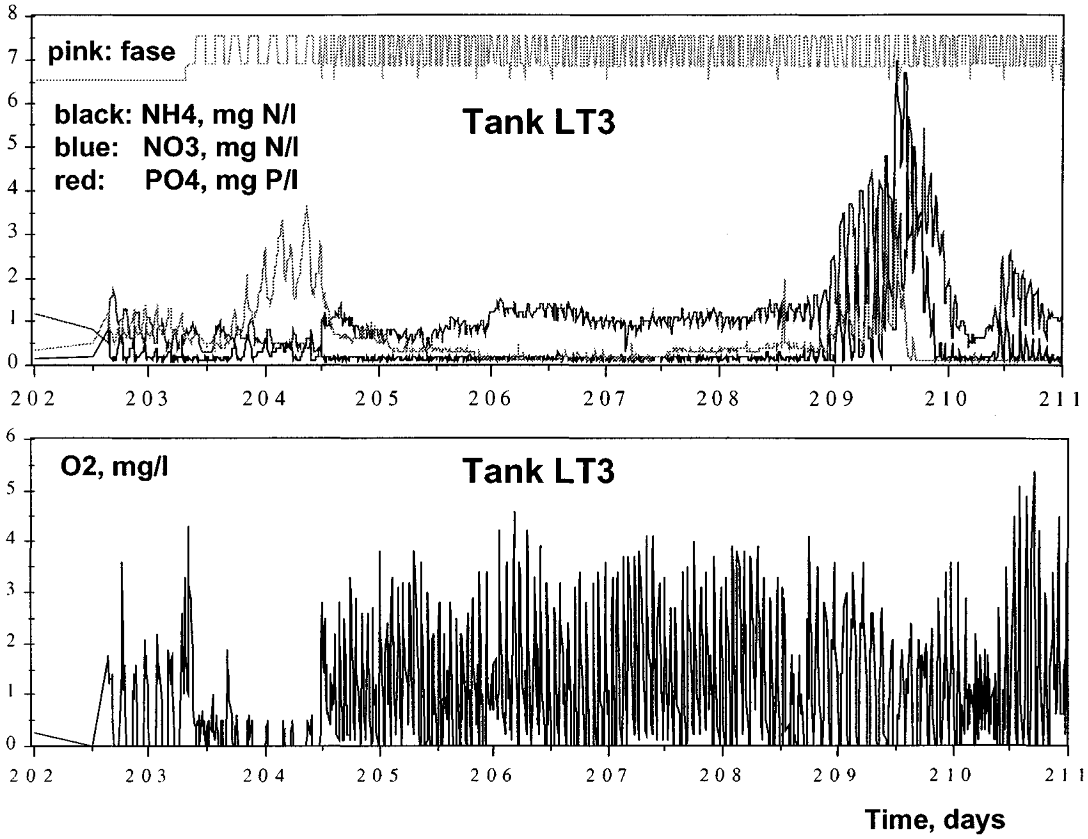


Figure 43 Adjusting the minimum level of NO3 in alternating Bio-P removal

During start-up of new control in Harboere on day 203 data from another plant was used which resulted in under-aeration due to extreme low N values so that P was released, as NO_3 was kept very low as seen in upper part of Figure 43 . On day 204 the criteria was adjusted to keep NO_3 above 1 mgNO_3-N/l even during low load, and hence the PO4 was kept low until the overload was applied on day 209. The change of the O_2 set-point level shown in the lower part of Figure 43shows a significant change in the O_2 level which is needed to make this minor adjustment of the NO_3 level in the tanks.

Figure 44 to 41 shows the combination of a fixed daily dynamic O_2 set-point in 2 first sections. The NH_3 dependent O_2 set-point control in the two last section is integrated with the NH_3 and NO_3-determined intermitting control in the 3 last sections at the Poznan WWTP, as shown in Figure 45

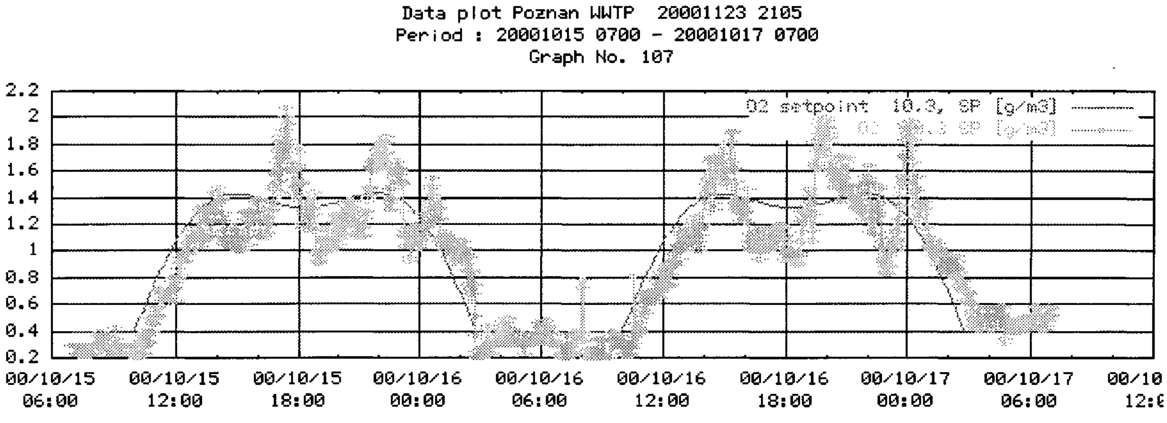


Figure 44 *O_2 set-point and measured O_2 in the first aeration section*

The peaks in Sp tank's first section is due to the pressure variation created by the intermitting control in the last 3 sections. In this section the load is so high that no problem representative of the O_2 measurements occurs.

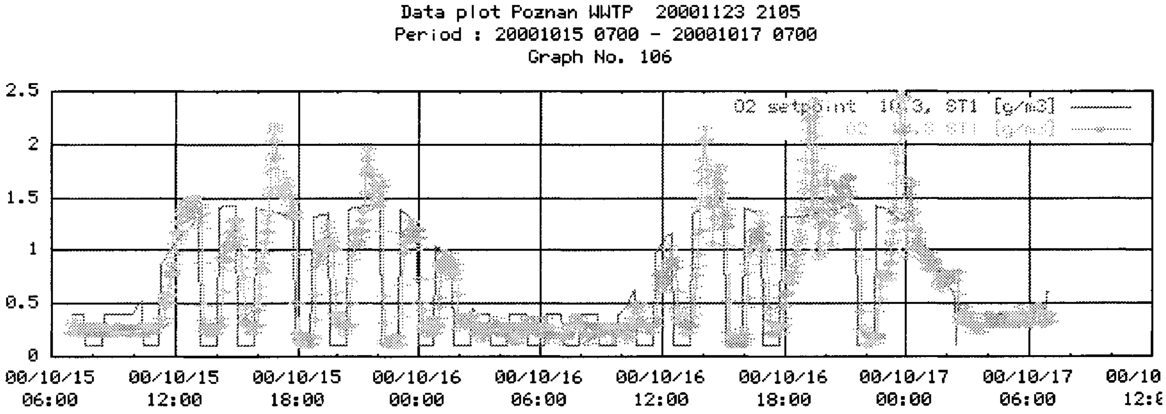


Figure 45 *O_2 set-point and measurement of O_2 in the second aeration section*

In the ST1 second section we see that the O_2 measurement follows the O_2 set-point in section SP, also when O_2 level control is combined with the intermitting aeration. However the intermitting aeration is not efficient during periods with low set-point due to the O_2 level control of the SCADA system below has a dead band of 0.4 mg/l.

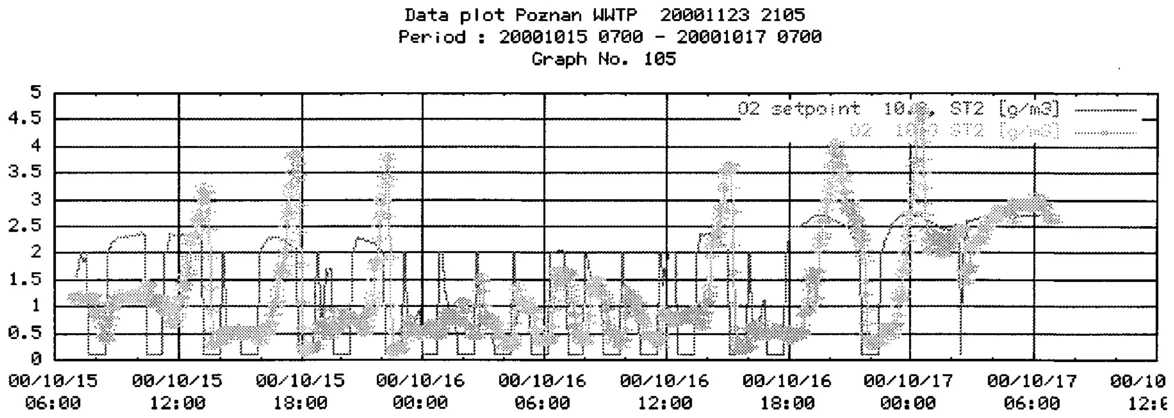


Figure 46 *O_2 set-point and measured O_2 in the third aeration section*

In sections ST2 and ST3 the O_2 set-point depends on NH3 level in section ST3. When the NH_3 level is increased as seen in Figure 47 the O_2 set-point will increase, and we see that the aeration system takes some time to reach the set-point due to the higher 0_2 demand. But when it reaches a low NH_3, an overshoot is observed. This is due to the rapid drop in OUR, and the delay in the measuring system and the process.

The figures also shows how the periods of high load reduce the anoxic time.

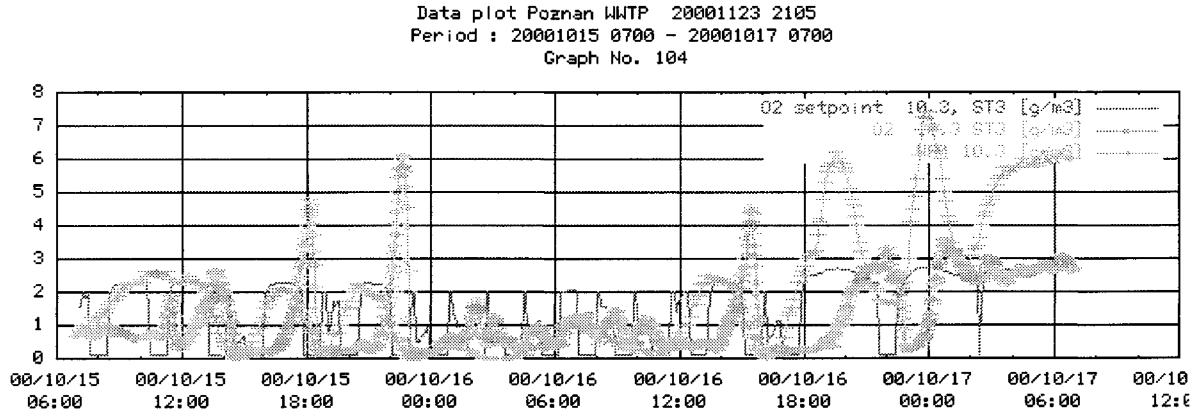


Figure 47 *O_2 set-point and measurement of O_2 in the fourth aeration section*

9.3.2.3 Sludge return control

Earlier, the aim of the return sludge was to keep the MLSS constant, later the aim was to keep the feed/micro-organisms ratio constant. Today we know that variations might be favourable due to the fact that a very significant part of the plant load originats from internal or adsorbed loads in the sludge. Therefore, the load can be adjusted by storing sludge in the clarifiers during periods of high load, and returning the stored sludge during periods of low load. Another aim could be to obtain a higher concentration in the excess sludge, which is withdrawn in different periods of the day. However, the main objective of the return sludge control is to keep the sludge in the plant, therefore, the first rule for efficient return sludge control is to change the flow slowly. The second rule is to keep maximum inventory of sludge in the clarifier to maintain the best possible settling of sludge. This can be obtained by controlling the return flow % from the SSr in the return sludge slowly as shown in Figure 48

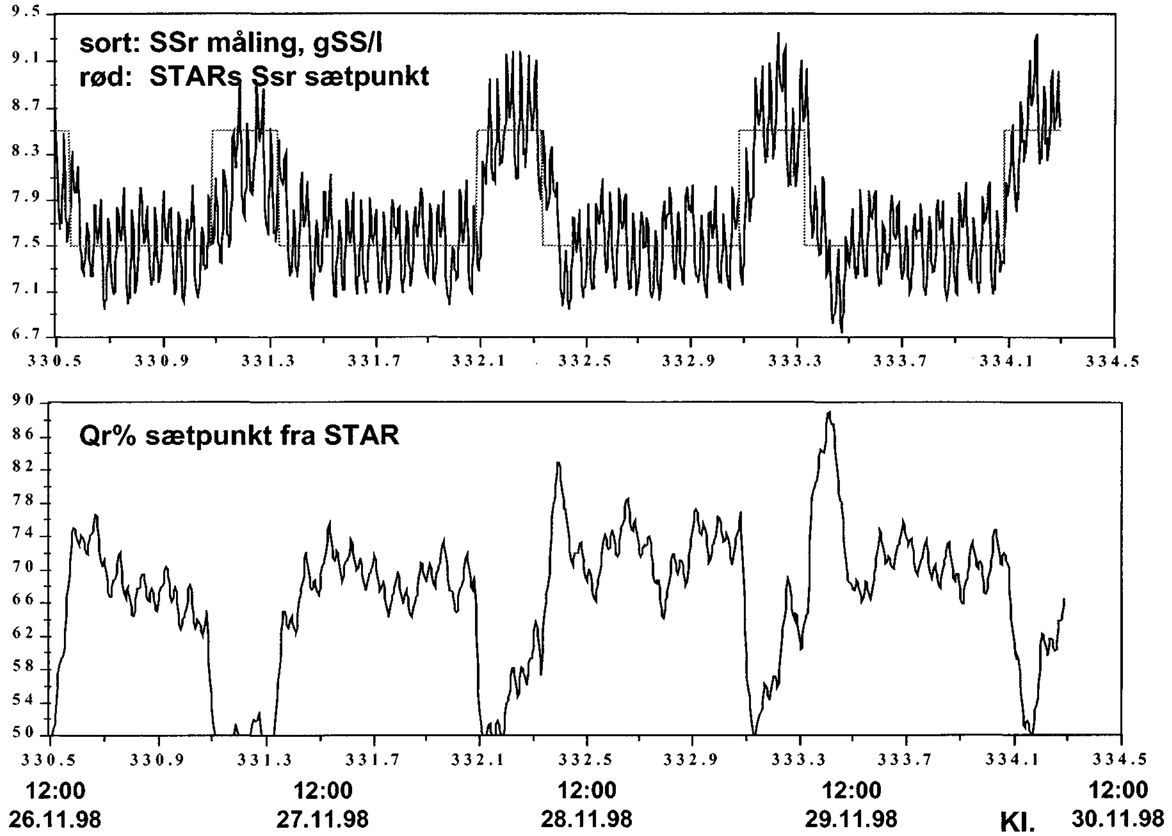


Figure 48 Return sludge control Boraas WWTP

It can be seen that the SSr set-point is reached within a few hours and even with this slow response, there is a single overshoot on 29/11 after declining the SSr set-point. This shows how important the slow response time is for the returnsludge control.

9.3.3 Post precipitation.

The post precipitation process was traditionally introduced as the safe P removal process without sensitivity of what ever problem might be arise in the biological process. Today the simultaneous precipitation has taken over at many plants due to lower costs for chemicals; however, the costs have changed considerably over the last years, so the process is still feasible in many places with soft water.

Post precipitation is used to obtain the best possible effluent and stability by means of flocculation. The introduction of electrical charge control has been successful at some plants. The control rarely takes into account the inlet concentration, as the flocculation often demands a certain amount of chemical to be efficient. Alternatively, a determination of the chemicals required for P-removal should be evaluated as efficient control strategy in soft water areas.

In general, a flow-proportional control of chemical addition, adjusted by rain and charges of particle, is used. In the future it will be a question, whether it is optimal to reduce the precipitation efficiency in certain periods in the precipitation. Probably the amount of chemicals used to day is too high and stopping the precipitation during periods could reduce a large part of the sludge production, where sufficient effluent quality from previous step of the treatment process is available. This evaluation becomes more relevant when biological P removal is enhanced in the biological step.

As the process requires a certain amount of chemicals to create a good flocculation, a reduced dosing control will often be an add-on control. It might often be an on-of control that will be efficient. Whether it in the future it will be possible to reduce the amount of chemicals and the sludge production by minimising the post precipitation efficiency to the required efficiency, is still to be seen.

10 TRENDS IN MODELLING AND CONTROL OF WASTEWATER SYSTEMS.

The trends in control according to recent international modelling and control conferences (i.e. 7th IAWQ Workshop on ICA of Water and Wastewater Treatment and Transport systems, 1997, and Spec Conf. Sensors in WasteWater Technology, Copenhagen 1995) can according to Steffens 1996 be distributed in two categories:

1 Inferential/ indirect control and

2 direct quality control.

Inferential control refers to strategies aimed at controlling process intermediates, such as OUR, DO, NADH and MLSS. As described above these types of control are referred to as tuning when these are very superior. The tuning is normaly an addition to the direct control discussed in section 2 of this STR report. While direct quality control refers to the direct regulation of quality variables such as effluent COD, ammonia phosphate and nitrate. The challenge is to interpret and balance the direct and indirect measurement to operations the give the best performance.

In the future we also want to chose controls which will affect population dynamic as well as pools of Carbon in the sludge mass, this will improve settleability and hydraulic capacity of the plants as well as reducing operation cost through more biological Nutrient removal. These controls are of a more inferential nature, as they will be integrating all levels and processes in the plant, and will have a long response time.

These controls will need a combination of many balanced sub-goals to be operative for on-line use. This approach will be tested in Smart controls project (SMAC) supported by EU fifth framework program as discussed by (Thornberg 2001) from where Figure 49 is taken.

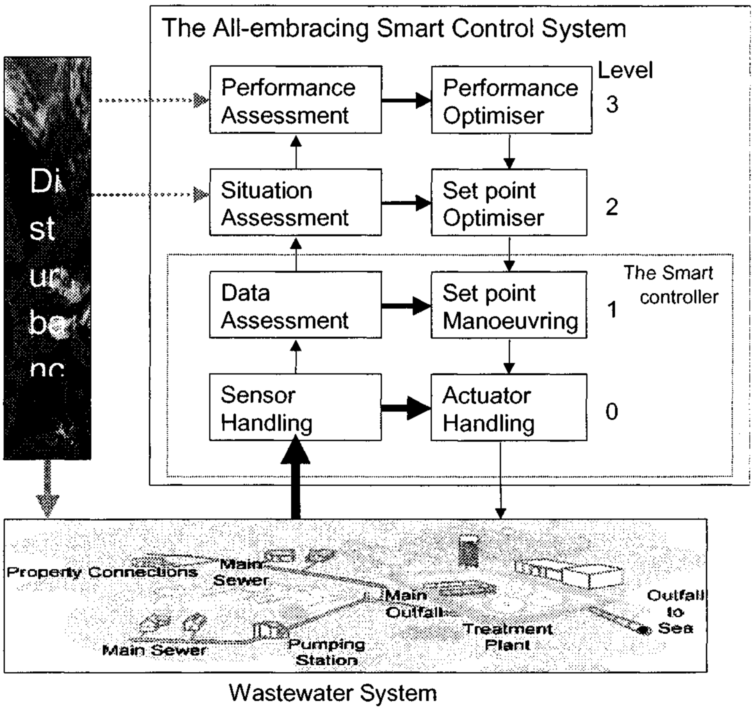


Figure 49 Proposed control hierarchy for total system control.

Until TAR appeared with level 1 control in above figure, it was mostly single input/single output controls that were used. There were very few examples of robust operation of multiple on-line instruments used in the control of a single final element (handle). The reasons were the cost and lack of stability of available on-line measurements. To day the quality description of the data, make it reasonable to use more IT power to maintain these needed quality index for the measurements and use them for optimal control

However, the bottleneck caused by instrumentation has now been overcome. There are several examples where the `new generation' of on-line instruments has been established (Nyberg et. al, 1993; Thornberg et. al, 1993, Thomsen and Kisbye 1995). While the capital expenses for and maintenance of these instruments may be significant, the returns could easily justify the expenses, when used correctly. For example, Nielsen 2000b , Önnerth 1995 and Thornberg et al (1993) reported that the improvements in the N & P removal capacity resulting from on-line biological nutrient control (using on-line SS, NH_3 , NO_3 and PO_4) can result in reductions of aeration tank and clarifier volumes of up to 30%.

How do we achieve a more efficient process operation?. I.e. how do we use the on-line information to improve the process operation further?

The first demand is to integrate the available off-line as well as on-line data. In the off-line level 2 in the below Figure 50 Data are often available for adjusting or calibrating the internal relations in the on-line data in level 1.

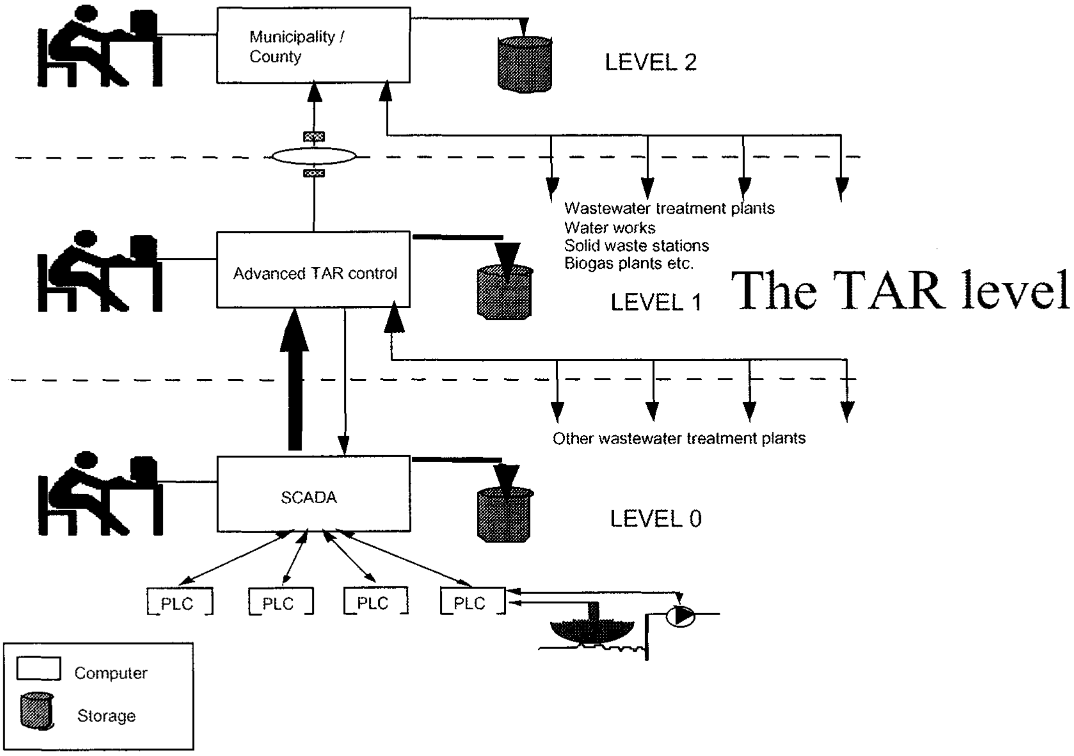


Figure 50 Levels on which to integrate on-line and off-line data.

Apart from the on-line data from more plants and water supplies, level 2 also obtains the data from economics of the system and the registered consumption of chemicals, energy etc.. Also any internal or external laboratory data from different points in the sewersystem may be included. These data will often be sufficient to calibrate relations (small models) for developing any missing information for objective control optimisations. Even cost benefit evaluation of operating different parts of the system at tested strategies might be quantified on-line.

When these correlations are fed back into the on-line level 1, the system becomes a self-documenting on-line control system. When the methodology has proven its robustness the correlation could be made adaptive from integrating all available data on-line and off-line into the ICA systems of the future.

It is only through a more efficient process operation that significant investment in ICA Figure 9 can be justified. While direct quality control (namely the direct control of effluent quality, consumption and capacity variables) offers the only means by which process objectives may be added together.

The inherent nature (and inflexibility) makes the need for the reporting facilities of the process necessary. These have previously made this hard to achieve the goals, or even objectively quantify the improvements. This is particularly true for complex nutrient removal systems, and is reflected in the small number of contributions of practical implementations in this area seen in the literature.

Several authors have dealt with this issue by operating the activated sludge process intermittently (e.g. Sorensen et al, 1994; Zhao et. al, 1994; Thornberg et. al, 1993, Carucci 1999, Yuan 2000, Chua 2000). In doing so, they introduce an additional manipulatable variable, namely phase lengths. This enables further improvement for nutrient removal to be achieved by control.

10.1 EDUCATION AND EXPERIENCE SHARING.

Apart from the technology development, it is also important to consider the logistic in exchanging experiences and advising operators to get the best out of the systems. In general most plant operators are reluctant to adjust on the controls when the experts have left a plant.

This situation is damaging to many controls and limits further development. In order to make discussing the issue with other colleagues to get the confidence that they can actually improve the control by adjustments. Also, the extent of improvements the operator can expect to gain from on his own plant from a given adjustments, is a need the must get from trying in praxis. Many operators expect that small adjustments are very significant, because other conditions change when they adjust one parameter. If this occurs the first time, an operator adjusts his plant, he will be reluctant to make the necessary adjustments when required later. To improve this situation an on-line user group and newsgroup, if possible, on relevant topics could be of great value.

Today, such a tool is available at www.smac.dk. The public information is limited while the user group part is open to all the available key themes. The structure of the site is illustrated on

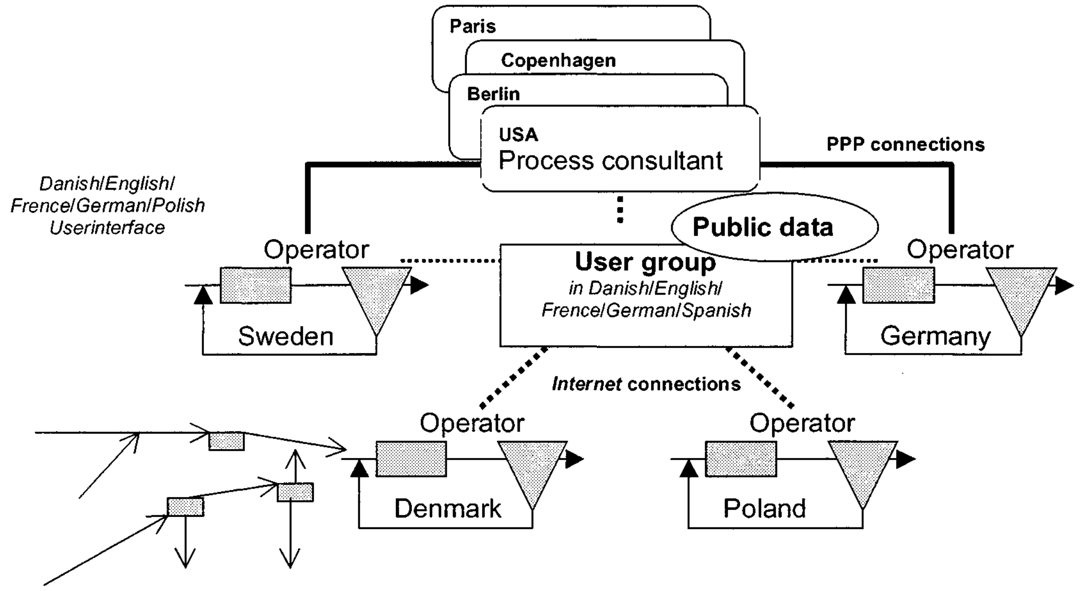


Figure 51 *Internet and PPP support and exchange of experience for operators.*

Previously the support was limited to a few local experts. Today, the data can be made available anywhere, and presented in whatever language needed, so the operator can call in any top expert, by giving him the access code and addresses to his plant. This will give the expert all available information on his screen within an hour, and the costs of expert support will be reduced. Whether these facilities are best managed directly from the controlling server or rather made available via a back-up server for several plants. This will depend on the necessary co-operation between IT expertise and process expertise, by the people operating the systems. It is assumed that in the future all off-line data will be made available via the Internet, so that - seen from the outside - the on-line system and the off-line system will melt together seamlessly.

10.2 NEED FOR FURTHER RESEARCH

10.2.1 Knowledge on correlation between rain, flow and pollution.

Rain intensity prediction from sewbr flow and/or meteorological information.

Stability of the correlation's, run-off number, unit hydrographs etc.

Measuring of pollutant dynamics in the sewer.

10.2.2 Generic control algorithms for storm water incident start-up and ending (for plant and sewer)

Sludge distribution

Empty tanks and pumping stations/pipes

10.2.3 Link between off-line data, on-line/grey box results and improved design.

The on-line data can be calibrated against actual values measured at the same point; often a good correlation can be made to other parameters at the same spot, so good estimates of correlated values can be available for online use; when data quality is maintained trough the calculations.

The grey box facility can also make good predictions to correlated values at other points in the plant by use of the available online meters and available operations and report data. The basis is that the previous off line data from the different point are used to calibrate and validate the applied correlation, so the accuracy of the estimated values is known.

It is a tedious job to identify which data are relevant for different correlation; an example from the Borås plant on the activated sludge plant is shown in Figure 52. The result will develop into that all information or good estimates are nearly available online, so environmental accounting and management report data are always updated. And as the economy of removing the pollutant in different points or Unit operations are known. The result can be feed back to the top-level control of the system as described in Figure 49

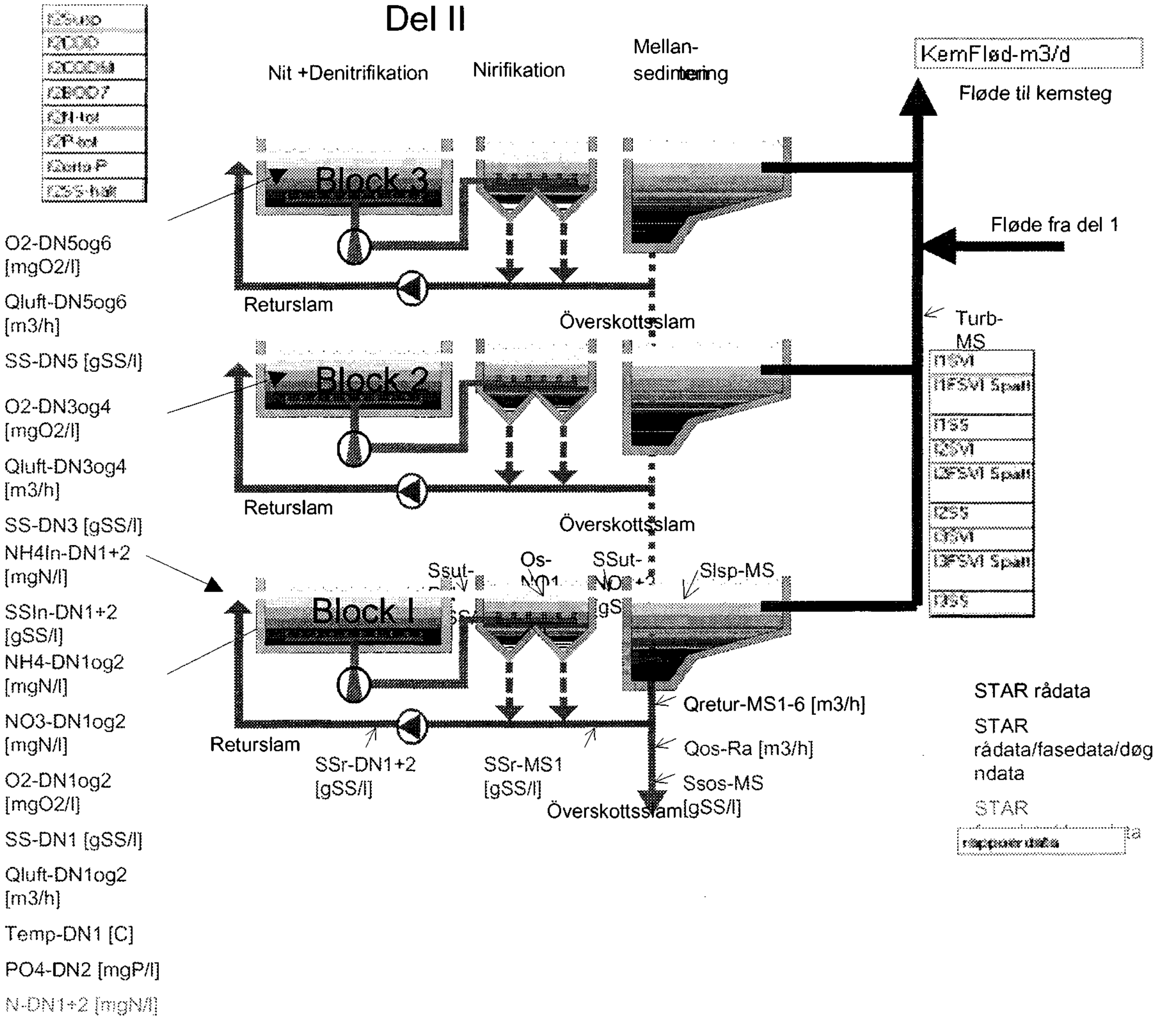


Figure 52 Online and of line report data at Borås

Robust methods to adapt simple models from few off-line data is needed, the models should include expected variance quantification, to be an important improvement of to days situation.

Analyses of the critical pollution component correlation. (COD, N, P, toxicity, bacteria, metals, etc. linked to acute/accumulative effects on different types of recipients) is another possibility to get extra benefit from the enormous amount of data we to day gets from our systems.

10.2.4 Simple model development

Many of the currently available wastewater treatment process models and sewer system models are necessarily complex to provide an adequate representation of the process and system. While these may be suitable for design or 'what if' studies, model-based controllers do not need this level of complexity. Model reduction plays an important part in the controller design (Olsson and Jeppsson, 1993). Techniques developed at IMM at the technical university of Denmark (Carstensen et all 1993) called grey box estimations are an important step in the direction of developing simple transparent models with parameters which are all identifiable from available on-line data.

If we introduce many constants in a model we can make it fit any calibration data, but it gets more complex and as it cannot be updated, the model loses its validity as shown in Figure 53.

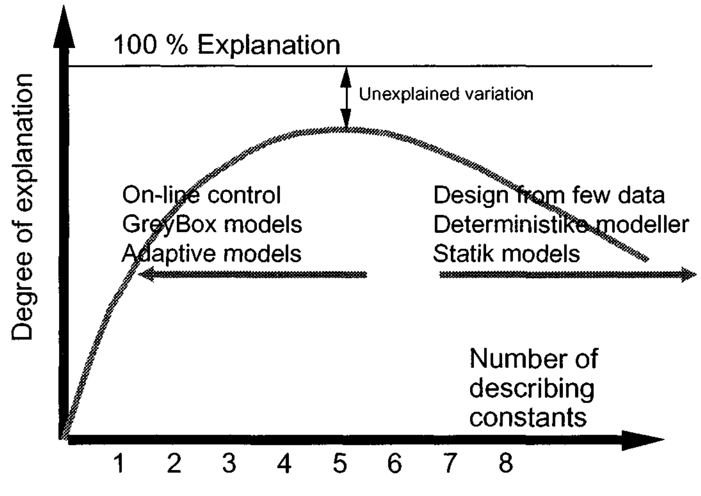


Figure 53 Principle for selection of models for different use.

The constructive use of data are still in the future using the old rule:

Keep It Simple; which we might extent with a new addition. If you can not keep it simple at least Keep It Structured.

10.2.4.1 Concentration gradients and their use.

Another approach that needs more attention is to develop smaller models, to describe the concentration gradient phenomena. These phenomenas are not covered by the normal comprehensive models, like the IAWQ model no. 1-3.

The correlations between O_2 penetration level and yield of sludge, have been modelled by Pochana 1999 and Abbassi 2000. While Siegrist 1999 correlate activity versus anoxic/anaerobic and aerobic conditions. The mechanisms are relevant, but will complicate the existing comprehensive models out of a realistic range, to include the size distribution and penetration depth in sludge particles.

The operational use for this is not only to reduce the sludge production by keeping a higher O_2 level; but more important to evaluate how much better the denitrification and Bio-P removal will be available when a lower O_2 level is maintained in the bulk liquid etc. These mechanisms can be modelled assuming that film theory is used on the single flocs in activated sludge as shown in Figure 54.

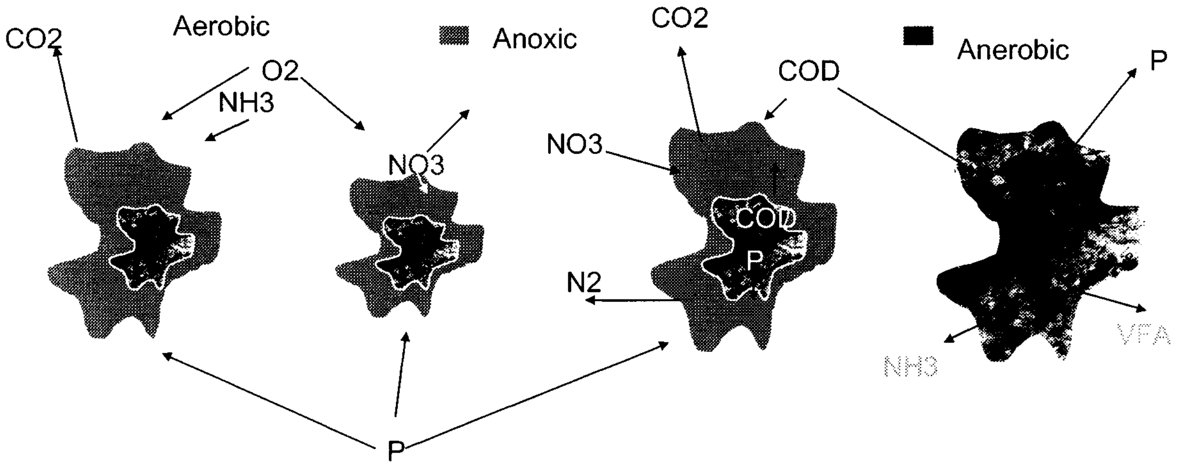


Figure 54 Transport of substrate in and out of sludge particles (Nielsen 2000a)

The location of the zones described above will strongly depend on substrate. Especially the easily degradable substrate will reduce the O_2 penetration despite of the O_2 level in the bulk. Also, the composition of the suspended substrate is important. It will give different hydrolysis rates, which will depend on the surface of the particles, as described by Terashima 2000. These relations cannot be deterministically included in the models. In this area very little is quantifiable, but may bee the value can be disclosed by analysing full-scale data.

The result of such development will make it possible to make co-operation between laboratory results from research and feed back of new relations from full-scale plants, as illustrated in the information flow circle below.

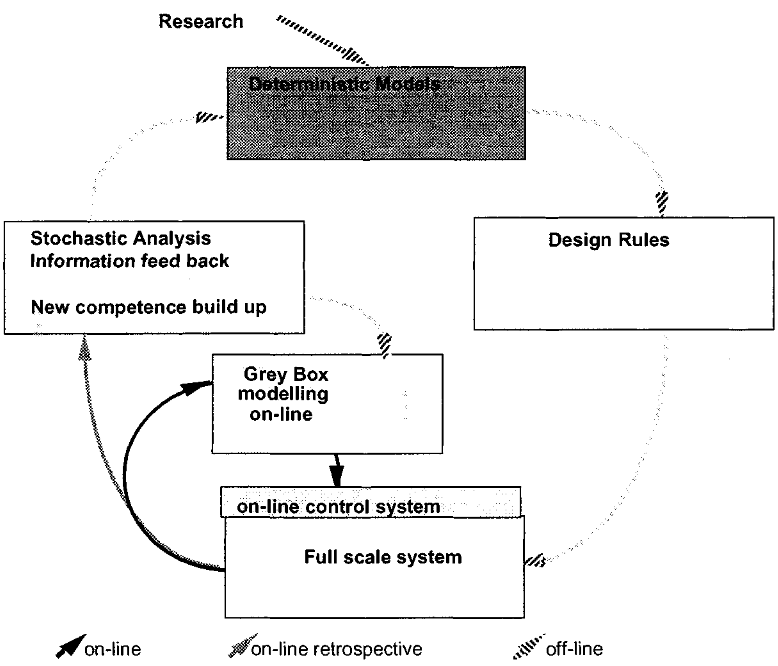


Figure 55 *Information flow cycle between research and praxis*

The use of simple quantitative criteria - in which a direction given control modification will change the process approach – allows for handling more quantitative relations as described above (Nielsen 2000a). The operation task is to adjust the criteria from the available data, as information from actual concentrations and distribution of processes inside the flocs as reported by Okabe 2000, will probably not be available in practice, but methods for estimation should be within reach.

11 CONCLUSION

ICA system for wastewater systems must be reliable and robust, so it can be argued that the increasing demands upon wastewater treatment processes in the future will be more of the tradition for safe over-designs of processes as the penalties of failing is increasing. This attitude will be promoted by the selection of traditional single-process, single-loop control. However, the coordination of many processes and loops, together with the reporting capacity, has increased the need for more integrated control, where overall evaluations form the basis of control decisions during. This development has proven it viability.

The economic demand will drive the control of processes harder, and force plants to operate closer to constraints by using the relevant measurements and other data.

There are still many possibilities that have not been investigated in practice. At the same time it is necessary not to make the systems too complex, so that the transparency and understanding are lost. To solve this paradox, it will probably be necessary to maintain the information structuring in the control hierarchy as proposed by including a TAR level.

It is inevitable that there will be an increased dependence on ICA in the future. The next step must be a growth in the TAR level process control systems for improvement of the process regulation and support of decisions for the process management including off-line data. While on-line instrumentation such as nutrient analysers, suspended solids and even multiple parameter sensors will grow because of the economic advantage, i.e. using them for reduction in investments and operation costs; as well as more reliable performance as well as documentation of load and capacity.

The remote monitoring together with laboratory and economic data will provide the necessary increase of understanding of the data background that will - faster and faster - bring new understandings of the processes involved. The process understanding will create a need for new control, which again will – faster and faster - form ideas into practical operation. The optimal development will require more university research directly connected to full scale operating plants.

Finally, by means of modern IT systems remote experts can support any plant on full data background owing to the use of the Internet technology, i.e. experts can support any plant all over the world and perform special and complicated analyses, if required.

This part of the report has summarised several process ideas and analytical tools, which have been developed and are now implemented in the TAR level control to address this issue.

Finally, it should be noted that the acceptance of increased ICA will require a cultural attitude in the wastewater industry, with a greater dependency on commitment of trained and educated operators to be cost effective.

The basic rule for control is:

Keep It Simple.

If this is not possible then

Keep It Structured,

With Love
Marinus K. Nielsen

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