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STATE OF THE ART IN SEWAGE TREATMENT PLANT CONTROL

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ABSTRACT

In this survey the state of the art of wastewater treatment system control is presented. Instrumentation, dynamical models and identification applications are reviewed. Current practice in control is described and computerization of wastewater treatment plants is discussed. Biological treatment systems have been emphasized. The interactions between unit processes and between the sewage treatment plant and the sewer network are also considered.

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ACKNOWLEDGEMENTS

The author is indepted particularly to two persons, who have strongly influenced the ideas behind this paper. The work on dynamical models of wastewater treatment systems has been heavily influenced by the collaboration with Professor John F. Andrews, University of Houston, Houston, Texas during the fall semester 1975. His advice and comments during many discussions have been invaluable. In the control area, Professor Karl J. Åström, Lund Institute of Technology, Lund, Sweden is a never-failing inspiration source for new ideas and constructive advice. The work on the Käppala plant identifications has been performed together with Olof Hansson, Datema AB, Nynäshamn, Sweden, and the staff of the plant under Dr. Kjell Ivar Dahlqvist, Lidingö, Sweden.

1. INTRODUCTION

Wastewater treatment is a relatively new field for the application of control theory. Quite recently there has been an increasing interest in questions concerning automation and on-line instrumentation of wastewater treatment systems. Special symposia on instrumentation and automation have been arranged [7]; [29] [66]. In the USA a special Instrumentation and Automation Advisory Committee for Wastewater Management has been formed recently under the Environmental Protection Agency (EPA) [65].

The concern about environmental quality has naturally contributed to this interest, and more strict regulations have been stipulated by regulatory agencies. The investment costs for wastewater collection and treatment systems are enormous and it is desirable to use the systems as efficiently as possible. The operational costs for the plants have risen due to increased costs for power, chemicals and manpower.

As most wastewater treatment systems are public systems, they lack the incentive of a profit-making process. This is one reason why the development of these systems have been slower than that of the chemical process industry.

It is important to remember that the contaminant concentrations in wastewater are very small. Domestic wastewater is 99.95% water. For most uses, however, the water must contain much lower levels of contaminants. Wastewater technology, therefore, must phase the problem to extract very small concentrations of different pollutants to very small levels. There is also a great diversity of contaminants. In fact, this diversity is so great and the concentrations are so low that only a few substances exist at a measurable level. This makes much of the instrumentation a major problem.

In order to characterize the influent and effluent water qualities, some gross measures are used such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total phosphorus, nitrogen and suspended solids concentrations. In addition, there are several more relevant parameters, such as heavy metals, trace organics, pesticides and viruses. The problem for the operating or control engineers is to find the most relevant measurement information for estimation and control purposes. The great problem is, that one has very little control over the influent "raw material" but all the time has to produce an acceptable "product" of the plant.

Wastewater treatment should be considered as a part of a larger water quality system if an adequate systems analysis should be successful. Basically one can distinguish between four sub-systems of a water quality system:

(i) potable water abstraction, purification and distribution
(ii) water collection system, including the sewer network, and urban run-off
(iii) the wastewater treatment plant, including both wastewater and sludge treatment
(iv) the recipient

The main object for this paper is the treatment plant, but because of the strong interaction from the water collection system, both those subsystems will be considered from a control point of view.

In section 2, some of the typical problems for wastewater treatment control are summarized. Some of them also appear in other processes, but taken together they define the unique features of wastewater treatment control. The collection systems are considered in 3. Some of the problems in modeling and the current practice in operation are reviewed. The most used and important unit process in biological wastewater treatment is the activated sludge process. It is also the process where control theory may be most profitable. The dynamics of the process is reviewed in section 4, and current practice in operation of activated sludge plants is discussed in 5. The general problems of identification of biological systems are discussed in 6. Some applications are mentioned and a study of the dissolved oxygen dynamics in an activated sludge plant is described in more detail.

Chemical treatment is applied widely in wastewater treatment. Settling or sedimentation is discussed in section 4 in connection with the activated sludge process. In 7 the process of phosphorus removal by chemical clarification has been chosen to represent chemical treatment processes. In 8, instrumentation and measurement problems are discussed. The application of process computers in wastewater treatment is reviewed in 9. In 10, some overall problems for plant design and control and process interactions are mentioned. Some personal thoughts about essential control problems and the future development are made.

2. SOME TYPICAL PROBLEMS IN WASTEWATER TREATMENT CONTROL

Control theory does not, in itself, pay any special attention to the system's physical or chemical nature; the plant is just a set of differential equations or transfer functions. In the design of control systems for a wastewater treatment system, there are, however, some special features which must be considered. Some of them are also typical for other process control problems. Added together, however, they define the special type of approach which it may be necessary to take for the control of a wastewater treatment plant. In a workshop on Research Need for Automation of Wastewater Treatment Systems held at the Clemson University in 1974 [29] problems were listed and researcl priorities were set up. Here we will look at some of the problems from the control engineer's point of view.

(1) Disturbances

The usual regulator task in process control is to keep certain variables or time-averages of variables constant despite external disturbances to the plant. In chemical process control these disturbances are often related to the influent feed stream. In contrast to many chemical processes the influent disturbances in a wastewater treatment plant or a collection system have a significant amplitude, both in flow rate and in composition. In a small plant with a concentrated sewer network the ratio of peak to minimum flow can be as much as ten. In a large plant with a more distributed network, this ratio may be 1.5 or 2. The flow changes are both regular ones - like diurnal variations - and sudden chock loads - like the hydraulic load after a rainstorm. Diurnal concentrations changes are often in phase with the flow rate changes, which amplifies the total load variations to the plant. Also, concentration and composition can change rapidly, for example caused by industrial effluents of either high concentrated organic nutrient material or toxic substances. As opposed to flow rate changes, concentration and composition variations are very difficult to measure. For example, heavy metal or other toxic disturbances to the plant most often cannot be observed until they have affected the process output.

(2) Flow Rates

The flow rates in a wastewater treatment plant ought to be compared to that of chemical processes. A very large oil refinery may have a daily output of 100,000 barrels, i.e., some 0.2 m^3/sec. A medium sized wastewater treatment plant has a flow rate of 1.5 ÷ 2 m^3/sec., while the largest plants have flow rates of about 50 m^3/sec. Because of this fact, flow equalization is unrealistic in many domestic plants, and the incoming variation has to be accepted. In industrial wastewater treatment plants, however, flow equalization is more common.

(3) Transportation Lags and Measurement Lags

As in many chemical processes, flow transports create time lags which can cause stability problems. There is also a significant time delay in the instrumentation. Because many measurements are based on analysis, the control action can be delayed. The time delay not only creates stability problems; sometimes it creates total process failure. Examples of this are toxic materials entering an activated sludge process or a wrong pH value in an anaerobic digester.

(4) Sensor Problems

Only a very small fraction of the interesting variables can be measured. In order to define the influent stream a large amount of highly sophisticated measurements should be needed. Even for a large plant, it would be impossible to do this. Even if it were economically possible, the time delay from the measurement to the process might be too large, so the damage has already been made. To measure biological parameters is an awkward task. Mostly, they have to be measured indirectly by physical and chemical parameters. Often the measurements can be misinterpreted or obscured by unaccountable effects, and therefore, all measurements have to be carefully analyzed before they are used for control. One example may suffice here. Dissolved oxygen (DO) is consumed due to biological activity. The DO concentration can increase because of two completely different mechanisms. Either the substrate concentration in the feed can go down or toxic material can enter the plant. The real cause of the disturbance must be judged based on, for example, time scale and location of the DO change.

There is certainly a severe limitation in equipment and sensors. Due to the lack of dynamical models it is also difficult to identify which are the essential process variables and the needed process instruments.

(5) <u>Time Constants</u>

There is an immense difference between the smallest and largest time constants in a typical biological treatment plant. The word 'time constant' may not be adequate in a strongly nonlinear system like a wastewater treatment plant, and the word response time may be preferred. The response times for equipment like pumps and blower systems are of course fast, less than a minute. Also, chemical flocculation is in the order of less than a minute. The oxygen transfer of gaseous oxygen to dissolved oxygen in an activated sludge process takes place in about 15 minutes. The hydraulic time constants for a typical plant are several hours. The biosorption process - when the bacteria cells first capture the substrate - take place within 10-30 minutes. The biological synthesis is a process over days and the endogeneous respiration is even slower. Anaerobic digestion of sludge typically operates over almost a month or several weeks. On top of this, there may be strong seasonal variations, primarily depending on temperature. As biological species are temperature sensitive, the control problem may look quite different during summer and winter in many countries.

(6) Nonlinearities

This is, of course, not unique for wastewater treatment processes, but it must be emphasized here. Linearizations are seldom adequate because of the large amplitude disturbances. Moreover, the control problem is not so much a setpoint regulator problem, but is more to control the plant for large size disturbances in concentration or flow rate. Very often the task is simply to save the plant.

(7) Couplings

Couplings in each unit process often play a large role, but still no multivariable control has been implemented in any plant. Often the wide span of time constants can be used to decouple the control loops. The interaction between different unit processes has been considered to a very little extent, even if this possibility and problem has been recognized for a long time. The relation between sewer network operation and plant control is important, if the plant size should be properly designed and operated. The coupling between sludge and water treatment is very significant. The energy saving possible from anaerobic digestion methane gas production is important and is used in many places.

(8) Spatial Distributions

Spatial distribution problems are common in wastewater treatment plants. In a sedimentation basin the spatial distribution of the concentration is essential to understand, both from a design and a control point of view. One example is the settler for biological sludge, following the aerator in an activated sludge system. The spatial distribution of settled sludge concentration must be known so the total stored capacity of sludge could be calculated. This is directly related to the control authority of the return sludge flow rate. In an activated sludge process, the spatial distribution of oxygen uptake can be used as an information to estimate the biological activity. As in other processes spatial dependence creates theoretical problems of different kinds, i.e., where to place instruments, how many sensors are needed, etc.

Another kind of spatial problem is the geographical distribution, especially in water collection systems, but also in large treatment plants.

(9) Process Changes

In a biological reactor the process itself may change character during a time period of some days. Due to substrate composition or dissolved oxygen changes the composition of the bacteria culture can change and consequently the whole dynamics of the system is changed. One example is when the floc bacteria are limited by substrate and filamentous bacteria take over. A toxic material can also kill certain species but save other. This type of problem naturally makes it sometimes difficult to reproduce experiments successfully. It also demands regulator parameter changes and sometimes even structure changes in the control system.

(10) Control Objective

The apparent control objective for a wastewater treatment plant is to produce an acceptable (for the regulatory agency!) effluent quality to minimal cost. The real difficulty, however, is that so little is known about which parameters, variables or even unit processes will affect this quality dynamically. Therefore, there is a clear need for better understanding of basic principles as well as of accurate dynamical models, useful for control purposes.

(11) Control System Structure

There is a multitude of control structures possible for the control of a wastewater treatment plant. It is by no means clear à priori which control variables to use and what to measure. Different control variables have different control authorities and are useful in different time scales. Before the control law even can be formulated the problem of dynamical models and control objective must be tackled.

(12) Process Design and Control Design

A substantial progress would be possible if process design would be more integrated with control system design. Sanitary engineers are in general designing processes from steady state calculations with insufficient attention to dynamic behaviour and controllability. The lack of communication should not only be blamed on the sanitary engineers. I believe, that the control engineers have a great responsibility to educate process engineers and to get deeply involved in real applications to show what is possible to achieve. Too much work and time have been devoted to develop control strategies for over-simplified models. This has a tendency to turn off sanitary engineers instead of encourage them to try better control.

(13) Non-Profit Industry

The incentive to build an 'optimally designed' process is too small. One reason is, that governmental grants are given only for investments and not for operating costs. Therefore, there is a tendency to overdesign the process in order to minimize operating problems, and the trade-off between design and operation is seldom analyzed enough. Another problem is that designers have little incentive to minimize the construction cost, as the profit is often related to the total construction cost. Because of the guarantee rules few designers dare to minimize the design and compensate it with a more advanced operation.

There is also a lack of incentive for instrumentation manufacturers to develop new instrumentation. The lack of fundamental knowledge concerning benefits vs. costs of automated treatment is a major obstacle to a general application of more elaborate control.

3. WASTEWATER COLLECTION SYSTEMS

The operation of wastewater collection systems is often overlooked in wastewater treatment systems, despite the fact that the cost of the sewer network is a major part of the total investment. It is, therefore, natural that the design and operation should be performed in such a way that the costs and the undesired effects of a overloaded sewer system network would be minimized.

From a homeowner-taxpayer's point of view the sewer system should be operated and designed in order to avoid stoppage, inadequate capacity and discharges of untreated polluted water. From the treatment point of view, the collection system should be operated such that flow rate or water quality changes could be early predicted and the flow rate to the plant could be controlled within certain limits.

The problems of wastewater collection system control can be split up into the two subproblems:

- the determination or prediction of inflow to the sewer network from urban run-off and municipal usage
- the routing of flows across the sewer network to outfalls and wastewater treatment plants

In terms of a variable and controllable transportation delay some of the necessary storage flexibility may come from several potential locations within the sewer network and buffering wells at the treatment plant.

3.1 Models For Design, Flow Prediction and Routing

Not unnaturally, the problems of sewer network modeling and control are similar to those of a river system for hydroelectrical power generation. A sewer network has a large number of input flow sources and is generally distributed over a large area. The flows are collected into few or maybe only one large trunk sewer, that enters the treatment plant. The input streams to the system can be quite different in flow rate and in water quality. From municipal consumers there is generally some periodic diurnal flow variations, and the composition of the pollutant does not vary significantly. Industrial effluents are more diversified, both in flow rate and composition. There is a higher potential risk for toxic materials in the streams from industries. Rainstorms, melting snow and infiltrations can cause major changes in the flow rate. In a big sewer network the local variations in rainfall must be taken into account in order to make the proper operations.

In order to predict urban run-off several models have been developed during many years. The models are generally extremely complex and deterministic and consider a multitude of properties pertaining to the surface topography and cover, e.g., asphalt, turf, etc. Also, processes like infiltration, surface retention, overland flow and gutter flow are mostly considered. Examples of models for storm water run-off can be found in Chen and Shubinski [33] Papadakis and Preul [92] and Offner [86]. The complexity and the amount of physical details is remarkable to say the least. There are, of course, considerable difficulties in establishing the parameters which characterize such a model. The part of the model that describes the travelling time and the routing through the network is not less complex, as the flow rate is calculated with the traditional hydraulic differential equations in depth and flow velocities., see e.g., Harris [60].

Despite their complexity models of the mentioned nature have been successfully applied for the design and operation of sewer networks in two cities which will be considered here, Seattle, Washington [78] and Cleveland, Ohio [1], [94]. In order to find a suitable design of the collection system, a number of rain events were dynamically simulated. These events represented the spectrum of local rain over a period of years. Typical hydrographs were then generated and the actual mass balances calculated for the network. Those values were used as inputs for the design programs, in order to find suitable capacities of pipes and storage volumes.

The mentioned models have the obvious drawback, that no stochastic element is included. An alternative approach to the sewer models would be to derive input/output stochastic dynamical models for the different sections of the network.

Maximum Likelihood identification techniques, see Åström-Eykhoff [11], has been applied to establish input/output relationship between wastewater treatment influent flow data and rainfall data for the Käppala wastewater treatment plant at Stockholm, Sweden, see Beck [17]. The Box-Jenkins [25] identification techniques have been applied in a similar manner to model sewer flows by Goel and LaGreda [51] as well as Berthoeux et al [22]. It must be emphasized that it is very difficult to achieve accurate flow rate data and representative rainfall data. The data given by the meteorological institutes are often daily accumulated data and do not necessarily represent the rainfall over the actual sewer network area.

For the prediction of flow rate in different subsystems the flow rate can of course be considered as a stochastic process with more or less structure, depending on the à priori knowledge of the inputs. As the parameters in the stochastic process model are slowly varying, an adaptive predictor can be a useful tool for sewer flow prediction. Beck [17] has applied a self-tuning predictor, developed by Wittenmark [123], based on the Åström-Wittenmark self-tuning regulator [12]. A few attempts to approach the sewer network system as a hierachical system for control have been made, e.g. by Labadie et al [77]. For another approach, see Bell [20].

3.2 Current Practice in Operation

There is a tremendous difference in the operation between different wastewater collection systems. Most of them are not operated or controlled at all, except some local pump control stations.

In an advanced system for water collection control there are some natural goals that should be satisfied:

- the storage capacity of trunk and interceptor lines within the network should be utilized so that overflows caused by storm inflow are reduced or eliminated
- the daily flows should be regulated for the best operation of the treatment plant
- overflow points should be selected to cause the least harm to receiving waters, when overflows cannot be avoided
- early warning of exceptional water quality or toxic materials should be given to the plant operators

The Seattle system [78] represents one of the most advanced operations of a sewer network today, and may represent the state of the art. The system is equipped with a central computer data acquisition and control system, connected to the many remote control stations in the network. These stations are either pumping or regulator stations. The essential control variables for the system are pump speeds and gate positions.

Obviously the most interesting measurement variable in the system is flow. Other pertinent parameters, more or less essential for the operation of the sewer system, are meteorological, atmospheric and water quality parameters. It is not at all trivial to measure flow rates in open sewer channels. Even for such a fundamental process variable as flow rate, the limitation of sensors is still a serious problem (see further Ch. 8). The actual flow rate can for example be calculated from pipe configurations and depth information. The calculations, however, can be complicated by upstream or downstream backwater and submergence effects.

Rainfall is the minimum meteorological data to be collected and supplied to an automated system. Rainfall data from each subsystem will allow the analysis of infiltration and will provide some predictive information for control functions in a combined sewer system. Typically, 10 minute readings are desirable. Some systems are now looking for an improved rainfall prediction. An increasing interest in the use of radar as a predictive device for short-term pattern has been shown, and even a special conference on this topic has been arranged in December, 1975 [117].

Continuous monitoring of water quality data within the system are of great value and is done in the most advanced systems, typically on an hourly basis. In a control decision to select a point of overflow for example, it is essential to know the impact of receiving waters. Some important parameters are dissolved oxygen, suspended solids, temperature, pH and biochemical (or chemical) oxygen demand. Some of these measurements are made with instream sensors. Others have to use automatic water sampling equipment, which is installed at many places.

The systems mostly work under supervisory control, so the human operator has to recognize the situation before he takes action. Local stations can sometimes be switched to automatic control, when desired.

4. ACTIVATED SLUDGE SYSTEMS

During the last few years much work has been performed to develop dynamical models for biological wastewater treatment processes. Still the understanding of dynamical behaviour of these processes is far from complete. Gross process failures are all too frequent and even when these are avoided, it is not unusual to find significant variations in process efficiency, not only from one plant to another, but also from day-to-day and hour-to-hour in the same plant. The available space does not permit to review all available biological treatment processes, so the problems will be typified by the activated sludge process. This is by far the most important unit process for wastewater treatment in large systems and will probably remain so for many years. It is also the most challenging biological process from the control engineers point of view.

4.1 Process Description

In the activated sludge process microorganisms react with the organic pollutants in the wastewater and with oxygen dissolved in the water to produce more cell mass, carbon dioxide and water. The aerobic environment is achieved by the use of diffused air or mechanical aeration or even by pure oxygen. In the latter case, the tanks are covered. The effluent of the reactor flows to a sedimentation basin, where the activated sludge is separated from the liquid phase, Fig. 4.1. A portion of the concentrated sludge is recycled in order to maintain enough mass of viable organisms in the system and a reasonable food to mass ratio. Part of the settled sludge is wasted. The process effluent consists of the clarified overflow from the settler tank.

Because of the recycle of sludge the biological reactor is inseparable from the settler. The recycle serves the purpose of both increasing the concentration of microorganisms in the aerator and maintaining the organisms in a physiological condition, such that they will readily flocculate. However, recycle also results in difficulties in understanding and modeling

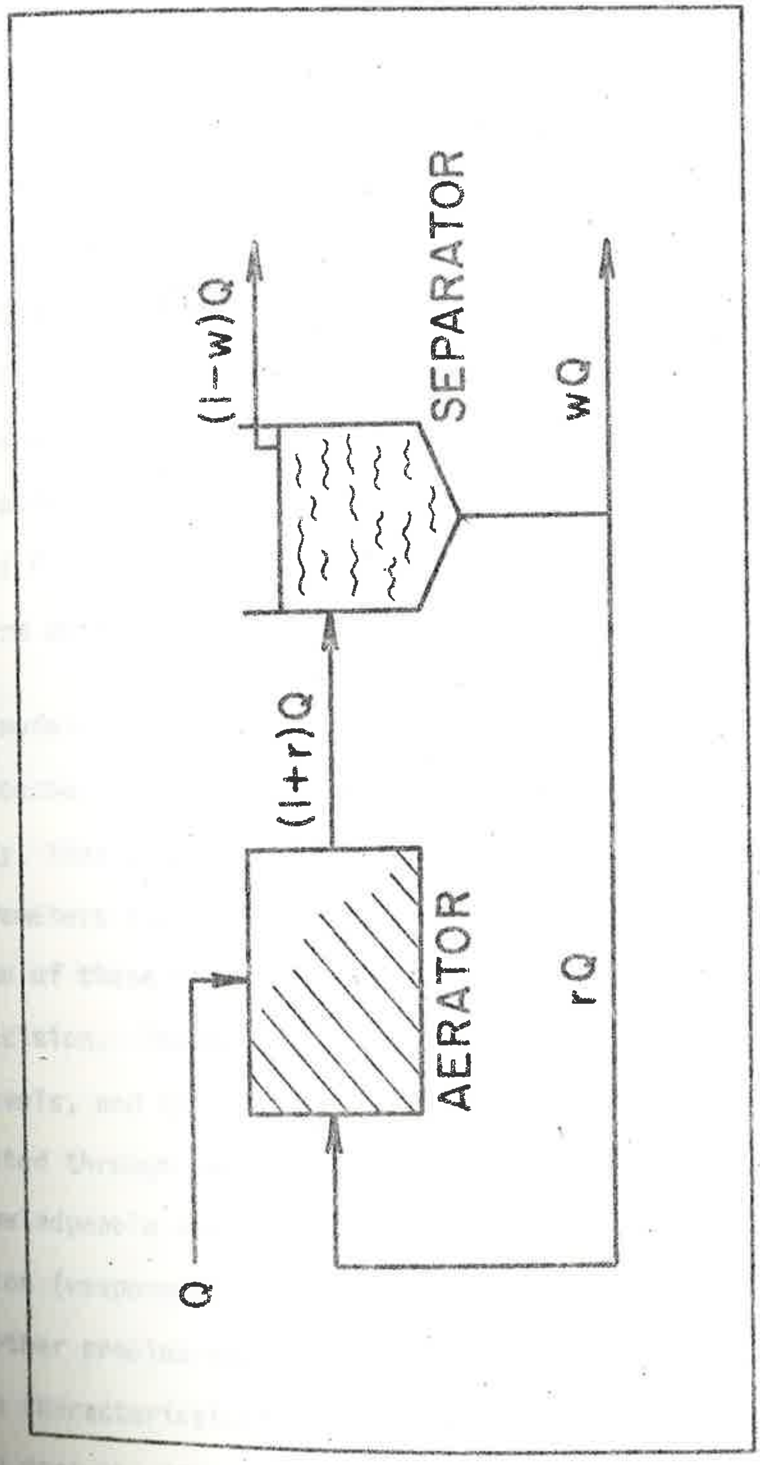

Fig. 4.1. The activated sludge process.

the process since it creates a feedback loop, thereby causing a strong interaction between the aerator and the settler.

4.2 Dynamical Models

During the last six or seven years dynamical models for the aeration chamber have evolved to relatively structured status. Smith [106] should be credited with one of the earliest attempts to model the complete wastewater treatment process, later followed by other models [107]. Under the leadership of Professor John Andrews at the Clemson University, S.C., a great research program on dynamical modeling of different parts of wastewater treatment systems has led to sophisticated models presented in a series of PhD theses [24,28,31,32,96,108,112,113,119]. For a more detailed review, we refer to Andrews [3,4] and Olsson [89].

All the models mentioned are complex dynamical models, which describe the unit processes with deterministic equations in a mechanistic fashion. Typically, they are non-linear, multivariable and space dependent and contain many parameters such as kinetic rate coefficients and mass transfer coefficient: The value of these kinetic parameters are sometimes difficult to determine with precision. The models still lack verification at both the pilot and full scale levels, and this remains an awkward problem. Hitherto, they have only been tested through laboratory experiments, literature searches and discussions with knowledgeable operations engineers. This is, at best, a semi-quantitative validation (responses in the right direction and right order of magnitude). But, another problem may be even more significant. One easily accepts the idea that the characteristics of the sewage being treated are not constant, that not only does the BOD change with time but also that the composition and the biodegradability of organic material feed probably change in time. The physiological state of the microorganisms upon which we depend for treatment may be time varying as well and their response to changes may reflect past conditions as well as present. In other words, the state vector of the system not only must include present organism concentrations but also some variables, that reflect how these concentrations have been reached - the history of the organisms. This fact has been discussed for several years by biochemists, see e.g. Powell [97].

The time series approach is more open in the sense that we do not start with an à priori model of the system, and stochastic modeling will be discussed separately in Chapter 6. Some important cause-effect relationships can be verified in order to get reasonable control models as well as more knowledge of the internal parameters. The verification of internally descriptive models can thus be approached piecewise by drawing inferences from black-box results, as in [91].

4.3 Properties of the Biological Reactor Models

In a structured model it is assumed that substrate (or pollutant) is degraded in the following steps:

(i) the substrate penetrates the cell membrane by a purely physicochemical process. The removed substrate is thus "stored" in the floc phase. This process can take place within 15-30 minutes if the sludge is in the right condition. This initial rapid uptake is encountered in the so called contact stabilization process where as much as 90% of the soluble BOD can be removed in 10-20 minutes and be captured in the floc phase.

(ii) The pollutants stored in the sludge are metabolized to give viable organisms. This synthesis phase is a process which has a response time of the order days.

(iii) The organisms are degraded to inert mass through endogeneous respiration and decay. Typical time scale for this process is several days.

It can thus be observed, that the relative rates of these processes are different by an order of magnitude. The steady state profile of substrate and stored mass in a plug flow aerator can demonstrate what happens. Fig. 4.2 shows when sludge in the proper condition has been recycled from the settler. A proper condition means that the content of stored mass in the floc is low at the tail end of the reactor, and there has been enough time for metabolism of the cells. As Fig. 4.2 indicates, there is a relatively high transfer rate from liquid phase BOD (soluble and collodial BOD) to floc phase BOD (stored mass). Most of the soluble BOD is consumed already after travelling time of about 15 minutes. Later in the tank the stored mass is consumed through the metabolism process along the tank.

If the sludge is not in the proper condition, the biosorption process is much slower, Fig. 4.3. There has not been enough time for the metabolism so the recycled sludge, which is brought into contact with the substrate has still a relatively high concentration of stored mass. Therefore, the concentration of soluble substrate is decreasing relatively slowly and the synthesis rate determines the rate. This type of behaviour is further analyzed in Olsson [90].

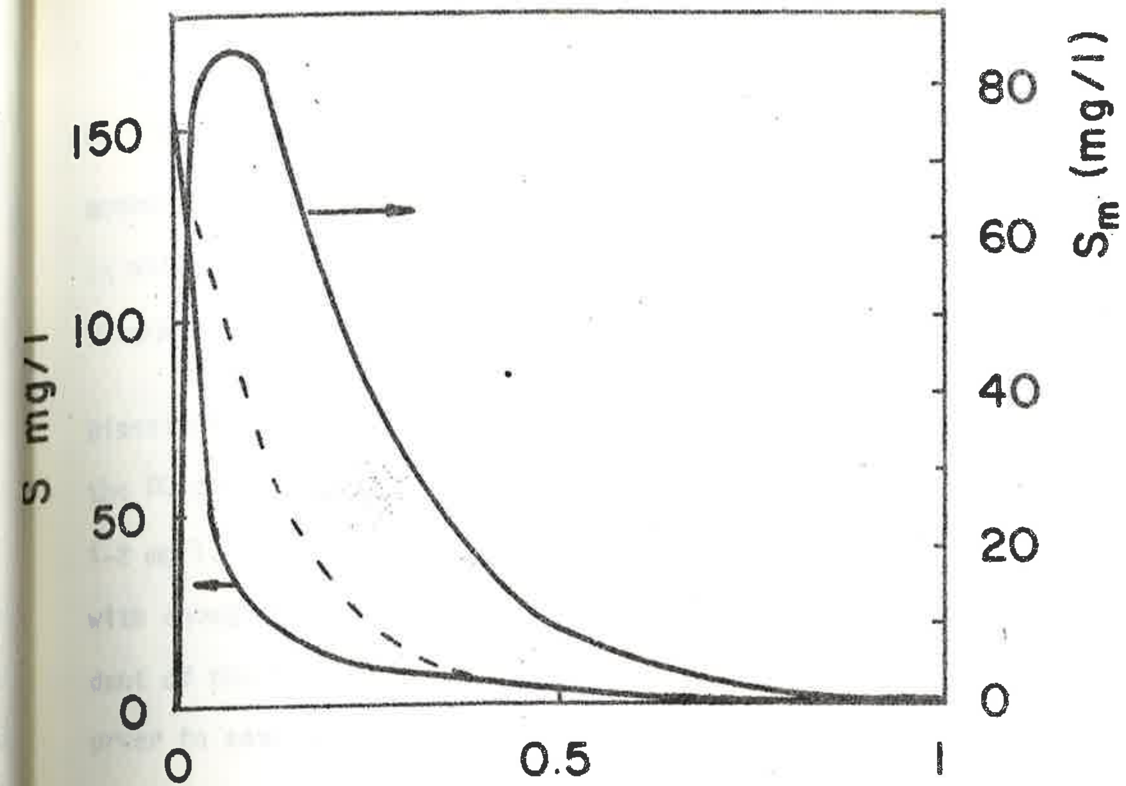

Fig. 4.2. Profiles of liquid phase substrate (s) and stored mass (s_m) in a plug flow aerator. The substrate is rapidly captured by the cells at the head end. Later in the tank the stored mass is consumed by metabolism. The travelling time in the aerator is 3 hours. From [90].

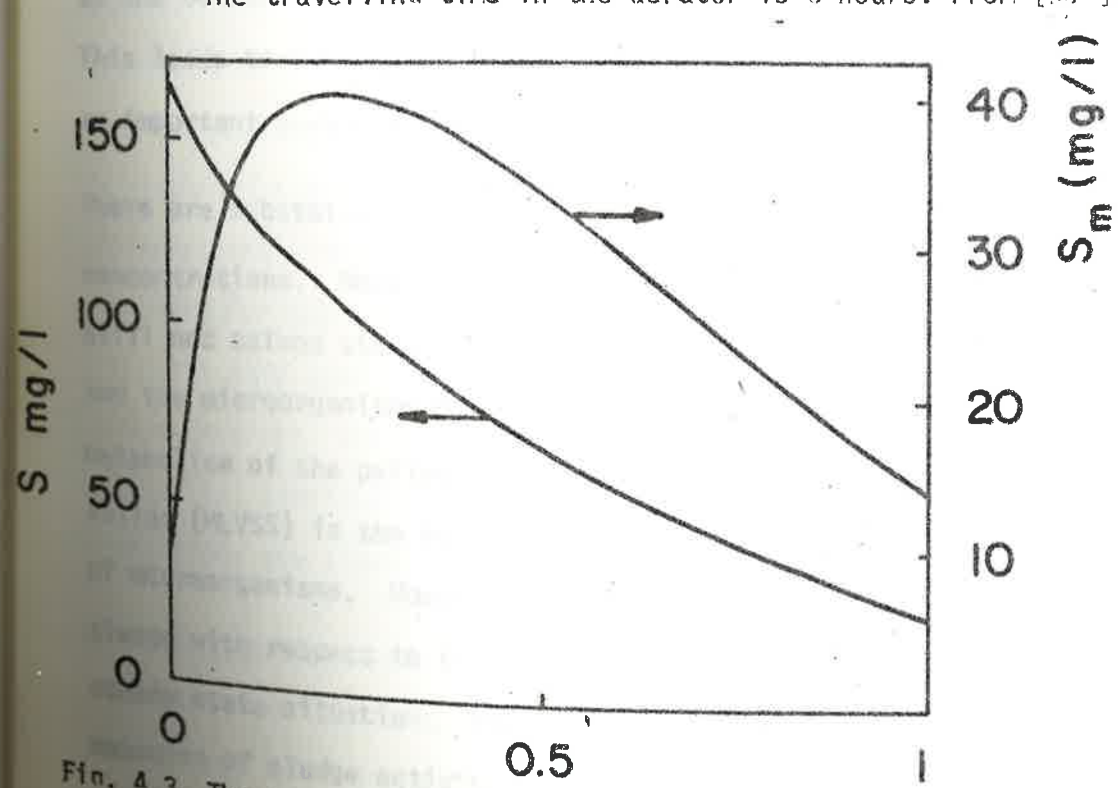

Fig. 4.3. The same reactor as in 4.2, but here the mass of sludge is smaller in relation to the substrate concentration. The recycled stored mass concentration is high in the head end. Consequently the cells cannot take up new substrate fast enough. From [90].

On top of the biological dynamics the hydraulics must be taken into account. It has a response time of a few hours and can be widely varying in nature, depending on the construction of the plant, all the way from complete mix to the plug flow extreme.

Dissolved oxygen (DO) dynamics is important for two major reasons. First, the DO concentration has to be kept above a certain critical level, some 1-2 mg/l, in order to supply the synthesis and endogeneous respiration with enough oxygen. For higher concentrations, the metabolism is independent of the DO level. Therefore, it is important to keep the DO level low in order to save aerator power costs. Secondly, the DO concentration is related to biological activities. A reliable DO dynamical model can be used for the estimation of biological parameters and organic loading, particularly as the DO sensor is one of the few reliable on-line instruments available. This leads to the concept of specific oxygen utilization rate (SCOUR) as an important parameter to estimate organism activity [8].

There are substatial difficulties to measure both pollutant and organism concentrations. Moreover, even if they can be measured the problem is still not solved since, for example, the pollutants may be nonbiodegradable and the microorganisms may have a low biological activity with respect to metabolism of the pollutants. Measurements of Mixed Liquor volatile suspended solids (MLVSS) is the most common index used for measuring the concentration of microorganisms. However, this gives no indication of the activity of the sludge with respect to the metabolism of pollutants especially not in a non-steady state situation. There has been considerable work devoted to other measures of sludge activity such as ATP and DNA concentrations (see further Ch. 8) and dehydrogenase activity. However, none of these analyses seem to be adapted to on-line analysis. There is considerable disagreement in the literature of their value as a measure of sludge activity. However, there seems to be an almost universal agreement that the specific oxygen utilization rate (SCOUR) is an indicator of biological activity in aerobic systems. The SCOUR can be defined as mass of oxygen utilized per unit of sludge per unit time and has been explored as a parameter for control purposes by Andrews et al [8]. SCOUR is intimately related to the growth rate or organisms. When the rate at which oxygen is utilized for organism decay is also known, the SCOUR variable can be used to calculate the amount of pollutants present or indicate when the reaction has gone to completion.

The concept of SCOUR thus can solve a serious dilemma and relate a complex biological variable to measurable quantities like dissolved oxygen. Research is in progress to relate not only space independent measurements of oxygen to biological activity, but to make use of the spatial distribution of the oxygen. Especially in long tank reactors, which can resemble tubular reactors, the knowledge of the profile of dissolved oxygen can substantially increase the knowledge of the biological activity and give better understanding for the type of control which is needed. Hitherto, steady state concepts have been used to find relations between organisms and pollutant concentrations, and these concepts do not make sense at all in a dynamical situation, particularly in a wastewater treatment system where influent variations are significant.

4.4 Settler Dynamics

The behaviour of the settler is crucial for the whole activated sludge operation. The settler has three important tasks of different nature in the process chain. An ideal settler should give:

- a high underflow concentration (a good thickener)
- low suspended solids concentration in the overflow (a good clarifier)
- a large buffer volume of sludge

The ultimate goal of the treatment should be to produce an effluent with minimal BOD and suspended solids content. Therefore, the whole biological operation should be maintained in such a way as to produce a sludge of desirable settleability properties. Actually, very little is known how to produce such a sludge under dynamical conditions. It is known that the condition of the floc determines the settleability and thickening properties. The load condition also determines both the clarified effluent and the underflow concentrations. On the other hand, a change in the underflow velocity through a recycle flow change will change the underflow concentration and consequently the organism concentration in the aerator. This will in turn change the settling characteristics, which are depending on the specific growth rate of the organisms among other things. It is therefore crucial, that an activated sludge process model also contain the settler dynamics.

The primary purpose of a dynamical model of the settler is to predict:

- concentrations of solids in the underflow
- solids blanket height
- solids concentration profile in the settler
- concentration of suspended solids in the overflow

Dynamical models for the settler/clarifier have not yet attained the same level of sophistication as the biological reactor models. Most of the models developed hitherto for the thickening process are based on the theory developed by Kynch [76]. Basicly, Kynch proposed a theory of sedimentation which lead to the conclusion that the various thickened sludge concentration layers rise at constant velocities, i.e., the settling velocity of a layer is a function of the particle concentration within that layer only. Even if the thickening theory contains a number of contradictions and disagreements, it appears that the Kynch theory can be used as a rational basis for design, see e.g. Dick-Ewing [38], Dick-Javaheri [39]. Dynamical models based on the Kynch theory have been developed during the last few years by Bryant [28], Tracy [112], Tracy-Keinath [113] and has been used in plant models e.g. by Busby [31] and Stenstrom [108]. For more details see Keinath [72], Fitch [45],Vesilind [114].TheKynch theory is not suitable for a dynamical model. It cannot predict such a fundamental variable as the sludge blanket height and can only predict steady state changes in the underflow concentration. Therefore, a more sophisticated model is needed in the dynamical case. The Kynch theory gives only mass balance equations. On top of this momentum balance equations are needed . [A]

Even if better models would be available for the settler, it must be recognized that the parameters are time variable. For example, the settling characteristics and solids flux velocity must be measured on-line in order to update the parameters. Here it is certainly a need for real-time identification before a successful automatic control could be implemented.

As the return sludge flow rate is an important control variable, it is important to understand how it interacts with the settler. Its control authority depends on the stored buffer volume of sludge in the settler and also of the concentration of the recycled sludge. The latter in turn is determined by the flow rate of the return sludge. A simple measurement of sludge blanket height and underflow concentration would not be sufficient information. The concentration under the sludge blanket is not uniform and can be strongly affected by the underflow rate. Moreover, it is not always desirable to operate the plant to keep the sludge blanket height at a constant level. There are two reasons for this. Some operational experiences indicate that with a high sludge blanket level the suspended solids concentration in the effluent would be much better. Then by a purposeful variation of the sludge blanket the buffer storage could be operated to be optimal when it is really needed under high load conditions.

5. CURRENT PRACTICE IN ACTIVATED SLUDGE PROCESS CONTROL

Hitherto, there has been no application of any control based on some of the structured models mentioned previously. Instead, most control schemes in current practice are either very simple conventional controls of local loops, or are based on steady-state or quasi-steady-state assumptions. Examples of this are found in Flanagan [46], Burchett-Tschobanoglous [30], and Smith [107]. A more detailed literature list is found in Andrews [3] and Olsson [89].

In a conventional activated sludge process there is quite a limited choice of control actions, mainly:

- air flow rate

- o recycle sludge flow rate
- o sludge wasting rate

These controls will be considered in 5.1 - 5.3. A fourth type of control - step feed control - will be discussed in 5.4.

The activated sludge process thus is multivariable. The control, however, is simplified by the fact that the inputs act in different time scales, which makes the couplings between the variables relatively small. The air flow rate is used for controlling variations in dissolved oxygen (DO) concentration, and the response time is of the order 10-15 minutes. The recycle flow rate can be used primarily to transport sludge and cannot affect the process faster than a few hours. The wasting rate is used primarily to affect the average loading conditions to keep the daily or weekly average food to microorganism ration at a desired value.

5.1 Dissolved Oxygen Control

The air flow rate is primarily of importance in controlling process economics and does not appear to have much effect on process efficiency as long as the dissolved oxygen concentration remains above a minimum level, some 1-2 mg/l. There are exceptions to this rule, when filamentous organisms should be controlled or when pure oxygen is used instead of air.

In the cases the air flow rate has been controlled there are basically two simple control schemes applied. In one the air flow rate is ratio controlled to the influent wastewater flow rate, without any other measurement being made. In the other scheme the dissolved oxygen concentration is controlled around a setpoint with a simple P or PI controller. There are several commercially available DO control systems available today. Generally, they consist of a dissolved oxygen probe connected to a PI controller.

Air to flow rate control (without any DO measurements) is applied at some plants in Los Angeles County Sanitation District [49], while setpoint control is made in a couple of other plants in the same district. Other examples are plants in Renton, Washington [99] and Reno, Nevada [46]. An extensive study on dissolved oxygen control has been preformed in Palo Alto [121]. [109], [93] as a joint project between EPA and Systems Control Inc. Current studies are performed at the Kappala plant at Stockholm, Sweden. The Achere plant in Paris is further referred to in 5.3 [27].

In no present DO control scheme, the distribution of DO concentration or air flow along the aerator tank has been taken into consideration. Only the total air flow rate has been regulated according to one representative dissolved oxygen concentration measurement.

The air flow is of course limited by the compressor capacity. If the plant is properly designed this limit should not be any severe problem. The air flow must not be too low either, because the diffusers or mechanical aerators must also mix the liquid. Too low air flow may lead either to clogging of the diffusers or to insufficient mixing. During low load periods, this may lead to dissolved oxygen concentrations much higher than necessary. An example of this is shown in Fig. 5.1 from DO control experiments at the Kappala plant in Stockholm.

5.2 Return Sludge Flow Control

If the recycle flow rate is controlled at all, the most common control is to vary the sludge recycle flow rate in proportion to the wastewater flow rate. This control strategy is not perfect as could be expected. It does

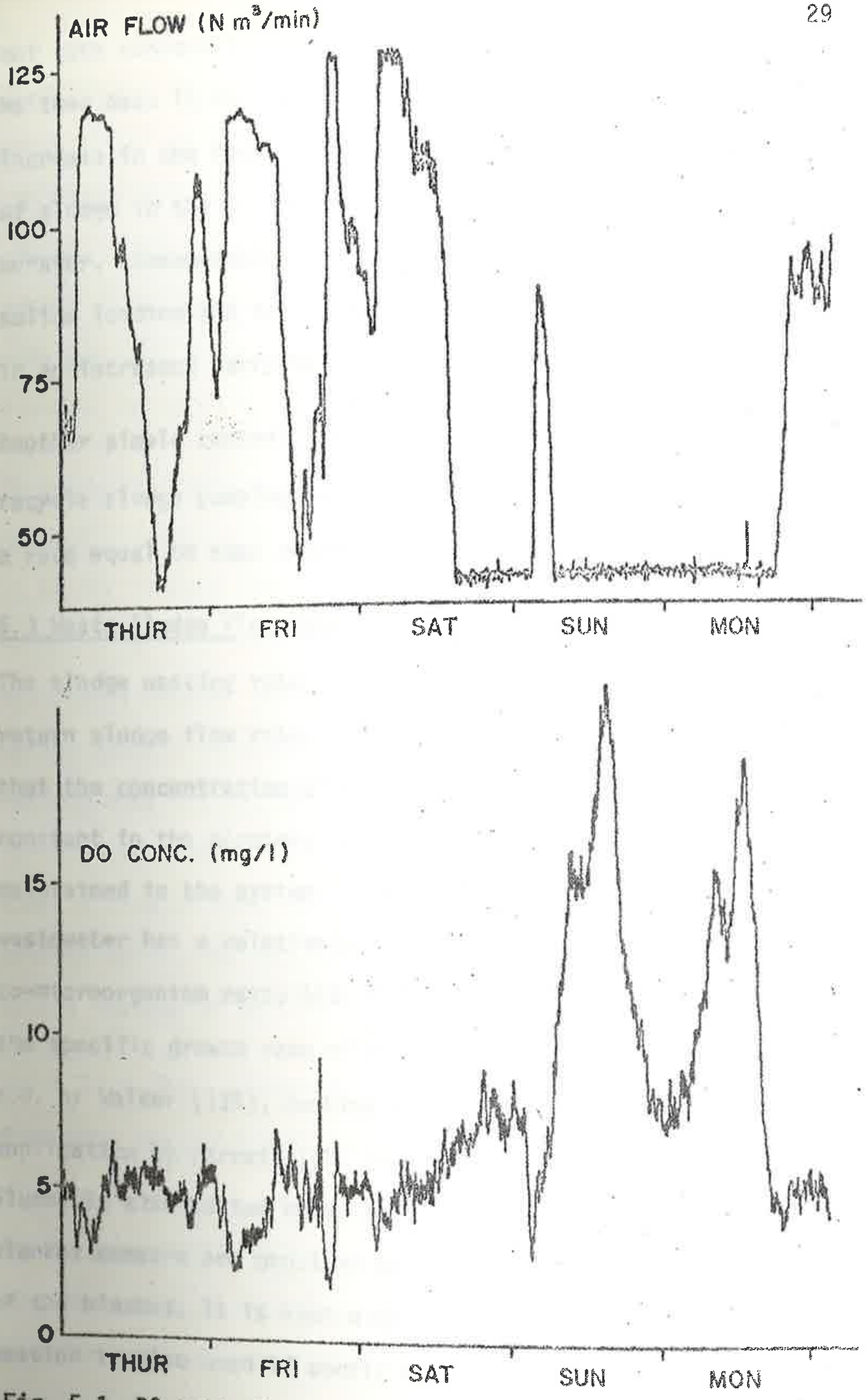

Fig. 5.1. DO control experiments from the Käppala plant, Stockholm, Sweden April 17-21, 1975, showing the limited control authority of the air flow. It reaches its lowest permitted value during late Saturday due to low loading, and the DO level rises. The upper limit of the air flow (125) is obtained at early Saturday. No big rainstorm occured during the actual time period.

not take concentration variations of the influent water into consideration. Neither does it consider changes in the recycle flow concentration. An increase in the recycle flow can, within limits, increase the total mass of sludge in the aerator. However, it also increases the loading to the aerator, consequently, to the settler. With the combination of increased solids loading and additional turbulence in the settler this can result in an increased carryover of solids in the process effluent.

Another simple control scheme is suggested by Klei-Sundstrom [73]. The recycle sludge pumping has been manipulated in a feed forward manner at a rate equal to some constant fraction of influent wastewater TOC content.

5.3 Waste Sludge Flow Rate Control

The sludge wasting rate is controlled in a slower time scale than the return sludge flow rate. In one control scheme the sludge is wasted so that the concentration of mixed liquor suspended solids (MLSS) is kept constant in the aerator; in other words a constant mass of sludge is maintained in the system. Such a control is only possible if the incoming wastewater has a relatively constant concentration. Otherwise, the food-to-microorganism ratio will fluctuate considerable and consequently also the specific growth rate of the organisms. This type of control is described e.g. by Walker [115], Jenkins-Garrison [68], Flanagan [46]and a special application by Garrett [48] in Houston.

Sludge is also wasted based on sludge blanket height measurements. Sludge blanket sensors are provided to give information about the high and low levels of the blanket. It is kept within these limits by on-off control. Sludge wasting is also used if poorly settling or bulking sludge is encountered.

in order to prevent the sludge blanket level from rising in the settler until sludge is discharged into the effluent. To waste sludge under bulking conditions may be a wrong control action, if the bulking sludge is caused by process overloading. By wasting the sludge, the total sludge mass in the system is further decreased, thus resulting in still further overloading with possible process failure. Here step feed control (see 5.4) would be a proper action.

To keep the sludge blanket height constant may often be undesirable, which is easily realized by dynamical studies. The time when the sludge blanket is at its highest (and the waste sludge pump will tend to switch on) is not necessarily the best time to withdraw sludge. If such a scheme is combined with ratio control of the recycle flow some undesired results may occur. During diurnal variations of the inflow the sludge blanket tends to have its maximum when the inflow is highest. Then also the return sludge flow has its maximum and consequently the underflow concentration is small. If the waste pump is used at that time, the waste sludge tend to have the smallest concentration during the day, which tends to maximize the volumetric sludge withdrawal instead of minimizing it.

There is a large difference between the control authorities for the recycle flow rate and the waste flow rate. In a typical plant the long term average waste flow rate is only about 3 % of the return sludge flow rate. Some of the proposed control schemes keep the recycle flow rate constant but vary the waste sludge flow rate in an attempt to keep the food to microorganism ratio constant. Because of the small flow rate of the waste sludge flow such a strategy will have only a marginal influence in a short time scale on the sludge content of the aerator. The influence is exerted in a slow time scale measured in days.

Therefore, to manipulate the ratio between food and organisms on an hourly basis, it is necessary to manipulate the return sludge flow rate, which gives a better control authority.

An idea of estimation has been used in the control at the Achère plant in Paris as described by Brouzes [27]. The DO concentration is kept constant with a separate controller. It is assumed that the oxygen transfer rate is constant. Then the biological oxygen uptake rate can be calculated from the known oxygen transfer. Using empirical relationships, the oxygen uptake rate can be related to cell growth or sludge production rate. Then the computer calculates and controls the rate of sludge wasting in order to maintain a constant specific growth rate of the sludge. As an extra control the sludge blanket is measured and is not allowed to exceed a certain limit. As the remark in last paragraph shows, this control is quite a slow control. The same type of idea has later been applied at the Palo Alto plant mentioned previously [93].

5.4 Step Feed Control

In the step feed activated sludge process, Fig. 5.2 there is an additional control action possible. The points at which the wastewater is added along the aerator can be regulated. This control action was first analyzed by Andrews [6], and further by Busby-Andrews [32], but had been used in full scale by Torpey [111] in New York City at the Bowery Plant already during the 1940's. This control is basically a long-term action with typical response times of several hours up until a day. Basically what happens is that sludge is transported to different parts of the system, where it can be most efficiently used. This gives an important control tool to take action

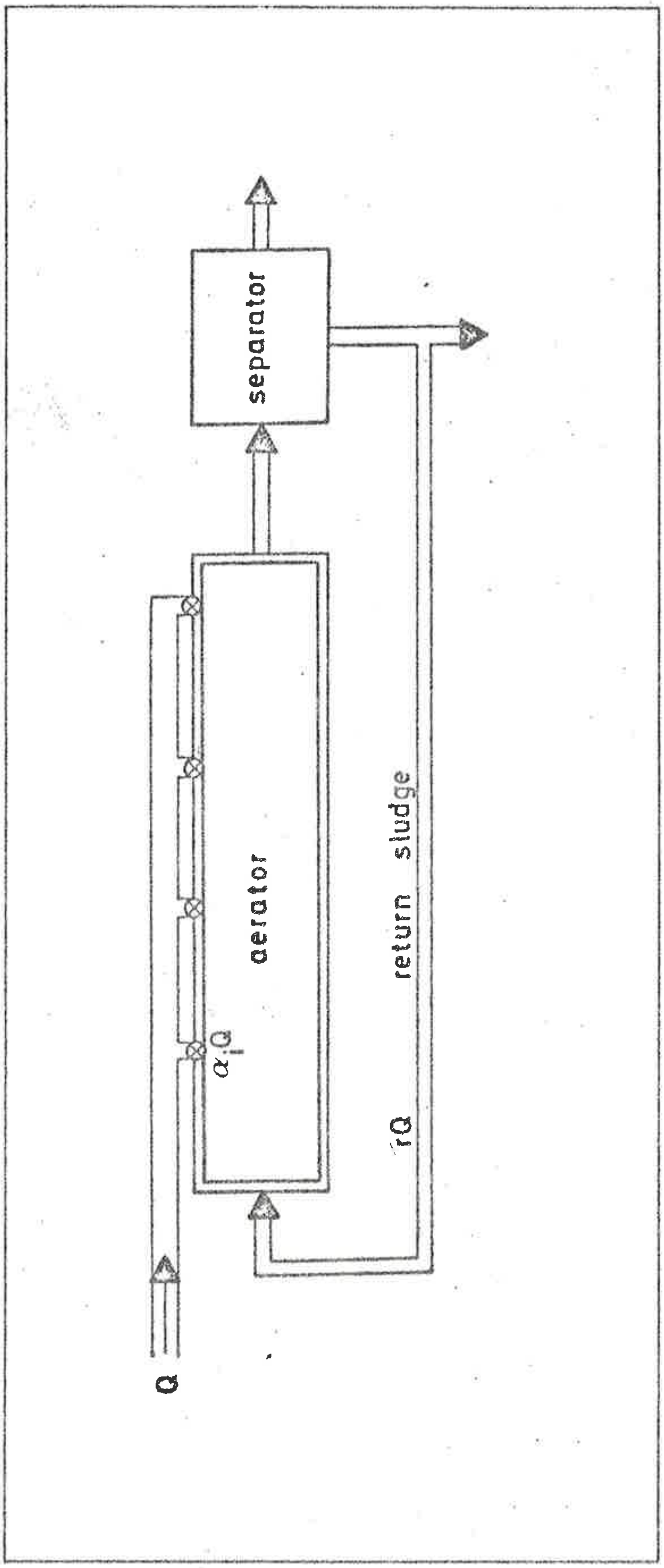

Fig. 5.2. The step feed activated sludge process.

against sudden hydraulic shock loads, or to prevent process failure due to poorly settling sludge or bulking sludge. Step feed control can also be applied to avoid the consequesces of toxic influents as analyzed by Busby [31]. Although several plants are constructed with the step feed facility, the author is not aware of a single plant, where this strategy is used regularly in the operation. Still it has a great potential for activated sludge plant control.

6. IDENTIFICATION OF BIOLOGICAL SYSTEMS

The field of system identification and parameter estimation has been proved to be useful in water quality and wastewater treatment system modeling. Hitherto there has been few applications reported, but the applicability of the techniques has still been demonstrated.

6.1 Special Problems in Biological Systems

In a superficial manner many wastewater treatment plants can be resembled to any industrial process and many ideas from process identification can be directly applicable to the wastewater treatment field. Practical considerations as discussed e.g. by Gustavsson [58] are mostly valid also here. There are, however, some major differences in the applicability of identification techniques to the wastewater field. Mainly they can be summarized as follows:

- o the flow rate, composition or concentration of the influent stream can seldom or never be manipulated
- o instrumentation is a major obstacle
- o the level of understanding the underlying phenomena is often poor

Unfortunately, it is a characteristic of water quality systems that only natural excitations of the process dynamics can be observed in general and artificial disturbances are precluded. This tends to mean that normal operational records exhibit just one particular mode of process behaviour. There is a low signal/noise ratio, and the routine measurement sampling rate may obscure some of the most important time constants for the system. This is particularly true in a river system, see Beck et al [18]. In a wastewater treatment system there are better possibilities to perturb the process. Sometimes even the flow rate of the influent stream can be manipulated for experimental purposes, see Olsson et al [91], but still the influent stream concentration is not controllable. This fact plus the fact that the concentrations and compositions cannot be recorded with the frequency and accuracy desired can easily obscure the results.

In the majority of cases the observation of water quality variables is very much a labour intensive affair of manual or automatic sampling followed by laboratory analysis. To get truly representative field data sets the identification of biological processes somewhat apart from the average industrial process modeling problem. Even when we can be sure of measuring the desired process variables, it is probable that many current experimental studies of biological systems will be inadequate, simply because there is so little à priori information of the dynamical behaviour that we wish to examine. Frequently, subsequent attempts at modeling show, that the experiments should have included measurements of additional state variables.

When examining the identification and dynamic modeling of biological processes, one problem which faces the systems analyst is his level of understanding of the fundamental theories which govern the process. Indeed, this is a problem which occurs with embarrassing regularity. A typical problem in the experimental design is the feedback structure coupling between the aerator and the settler of an activated sludge process (see section 4). A disturbance not only affects the aerator, but also the settler and is thus fed back at a later stage to the aerator. Therefore, it is sometimes difficult to locate the reason for some phenomena, especially as the dynamics of the settler is very poorly understood.

6.2 Applications to water quality systems.

As there are several problems which are common in water quality and wastewater treatment system identification, it is considered pertinent to mention applications from both fields here. In a recent survey by Beck [16] further references are given.

Time series analysis with the Box-Jenkins method [25] has been used to analyze influent BOD data for a wastewater treatment process by Berthouex et al [22]. The authors found, that a first order autoregressive model was adequate for the data. In another paper [21] the same authors have made time series analysis of daily influent-effluent data from a treatment plant, but very poor quality of the parameters were found. For a river stream, the dynamics for dissolved oxygen (DO) and biochemical oxygen demand (BOD) has been identified with a similar type of time series analysis by Huck et al [62]. Beck [15], [18] has described the modeling and identification of DO-BOD relations in a freshwater stream, where both Maximum Likelihood identification and extended Kalman filter estimation has been applied.

Identification of activated sludge process dynamics was performed in the pioneering work by Wells-Stepner [121] and it was followed by further studies by Stepner-Petersack [109] and Petersack-Smith [93]. Mostly models for the DO dynamics were identified. As the plant is close to complete mix the hydraulic pattern was favourable and point models could be derived.

6.3 Identification of Dissolved Oxygen Dynamics

In this section a case study of DO identification will be shortly presented. The experiments have been and are currently being performed on a full-scale municipal wastewater treatment plant at Käppala, outside Stockholm, Sweden.

As mentioned in 4.3 there are two reasons why DO dynamics is interesting:

(1) the economic incentive, and

(2) the relation between DO and biological parameters

The control of DO as a physical parameter is not an advanced control problem, at least not for complete mix reactors. For the estimation of biological parameters, however, it is clear that an accurate model is needed.

The details of these identifications will be presented elsewhere [91], but here some general ideas and spin-offs may be pertinent to mention.

The Käppala plant serves some 300,000 - 400,000 people in the northern suburbs of Stockholm and was completed in 1969. The average dry-weather flow rate is about 1.3 m^3/sec (~30 MGD). The dynamical experiments were performed on one of the six parallel aerators in the plant. Each aerator has a volume of 6000 m^3 and a length of 100 m. Air is supplied by diffusers uniformly along the tank. The raw wastewater is fed at four positions between 30 and 60 m from the head end, in a step loading system, Fig. 5.2. The plant is equipped with a computer data acquisition system. For the experiments three different inputs were manipulated. Except the air flow rate and the return sludge flow rate also the influent flow rate could be manipulated by redirecting the flow to other aeration basins during the experiment.

There are four basic mechanisms that determine the DO mass balance:

(1) the hydraulic transportation or dispersion of DO in the reactor
(2) the oxygen transfer from gaseous to liquid phase
(3) the oxygen uptake due to cell synthesis
(4) the oxygen uptake due to endogeneous respiration

Referring to Fig. 4.1 for the hydraulic flows the mass balance for a complete mix reactor can be written

$$\frac{dc}{dt} = \underbrace{\frac{Q}{V}(c_i-(1+r)c)}_{(1)} + \underbrace{k_1 u(c_s-c)}_{(2)} - \underbrace{k_2 \frac{c}{K_c+c}\,\frac{s}{K_s+s}\,x}_{(3)} - \underbrace{k_3 x}_{(4)} \qquad (4.1)$$

Where c = DO concentration
c_s = DO saturation concentration
c_i = influent wastewater DO
V = reactor volume
k_i = constants
s = substrate concentration
x = microorganism concentration
$K_c K_s$ = rate limiting constants
u = air flow rate
$k_1 u$ = oxygen transfer coefficient

The term (2) obeys Henry's law and reflects that the oxygen transfer approaches zero when the DO concentration goes to the saturation concentration. In (3) it is shown, that both oxygen and substrate are limiting factors for the cell synthesis, while (4) shows that the endogeneous respiration rate is assumed to be independent of the DO level.

For another hydraulic pattern eq (4.1) has to be suitably changed. A dispersed plug flow reactor better reflects the Käppala plant dynamics,

$$\frac{\partial c}{\partial t} = E\frac{\partial^2 c}{\partial z^2} - v\frac{\partial c}{\partial z} + k_1 u\,(c_s - c) - k_2\frac{c}{K_c + c}\,\frac{s}{K_s + s}x - k_3 x \qquad (4.2)$$

Where z = spatial coordinate $c = c(z,t)$
E = dispersion number $s = s(z,t)$
v = stream velocity $x = x(z,t)$

As the metabolism is much slower than the oxygen transfer mechanism, it can be assumed to be negligible during one or two hours. Also the hydraulic time constants are much longer than the oxygen transfer time, which is utilized in the experiments. The oxygen transfer coefficient $k_1 u$ can therefore be determined separately from other parameters. This is particularly important in an on-line situation, as k_1 varies significantly with the operational conditions.

In order to test cause and effect relationships without any a priori assumptions about the structure the canonical Åström structure [10] was used:

$$A(q^{-1})\ y(t) = \sum_{i=1}^{p} B_i(q^{-1})\ u_i\ (t) + \lambda C(q^{-1})\ e(t)$$

where A, B, and C are polynomials in the shift operator q while y and u_i are the output and inputs respectively. The disturbances e(t) is a sequence of independent gaussian zero mean stochastic variables. The parameters were identified with the Maximum Likelihood method. No further comment will be given the identification method as such, as it will be discussed elsewhere in this conference. In this type of identification where relatively little is known about the structure and relationships in the process the feature of an interactive identification program has been of particular value. The program IDPAC, developed at the Department of Automatic Control in Lund, Sweden [57] was used for the data analysis parameter estimation as well as model analysis. With the interactive feature a large number of models and input-output relationships could be tested relatively easily (see also [13]).

Instead of just mentioning the modeling results we will discuss some spin-off effects of the identification. The air flow input is the major input to the DO concentration. A first order model with about 15 minutes time constant would be expected. This time constant should be independent of the location of the probe, even if the profile is not at all uniform. Nevertheless, the time constant for a probe located close to the tail end of the reactor was found to be nearly twice as long, 30 minutes. The only explanation was that the degree of mixing was smaller at this location. Probably the pneumatic resistance of the diffusers around this probe was too large due to clogging. In another experiment it was found a very rapid response of one probe, indicating two time constants, one in the normal range of about 11 minutes and the other 11 seconds. After some confusion it got clear that the DO sensor was sensitive not only to dissolved oxygen but also to gas bubbles. It was shown that the membrane was failing, giving the wrong results. These two relatively simple results show how identification can be used systematically to detect process and instrumentation problems. Due to the different time scales they can be easily identified in on-line operation. In a normal operation they were not at all detected.

The other types of disturbances made were of hydraulic nature, either the influent flow rate or the return sludge flow rate. The influence from these inputs is of an order of magnitude smaller than that of the air flow rate. The parameters themselves may be of minor interest in this presentation, but also here some interesting spin-offs resulted. When a flow rate is changed there are two mechanisms that influence the DO concentration. The first one is the dilution effect caused by the changed flow rate as the volume of the reactor is constant. This is an instant response. The second effect has a larger amplitude, but is slower and is the DO transportation through the tank, and this concentration transportation determines the response time. In a complete mix reactor the transportation is rapid and the major time constant is determined by the oxygen transfer dynamics, i.e. about 15 minutes. For a tubular flow reactor the dominating time constant is determined by this transportation time. Even if the amplitudes are relatively small it was possible to verify this hypothesis. By moving the sensors to different locations different dominating time constants were achieved. This gives a method to estimate the hydraulic dispersion in the tank with the available on-line instrumentation.

7. PHYSICAL AND CHEMICAL TREATMENT PROCESSES

There are a number of physical and chemical treatment processes also in a biological wastewater treatment system. Processes like sedimentation and chlorination are important unit operations and are crucial for the total performance of the plant.

Some problems of secondary (biological) settling were mentioned together with activated sludge dynamics in ch. 4. In this chapter one process will be emphasized, phosphorus removal by chemical clarification. It is crucial from an economical point of view. At the same time it reflects some of the typical difficulties in chemical treatment in wastewater treatment.

Of course there is a minor treatment of physical nature in all systems including flow routing and equalization, screening and degritting. They will not be considered here, as they do not create essential control problems. Other operations, like pH control are purely chemical operations which are not unique for the water and wastewater field. The operation of deep-bed filters will be mentioned in connection with the operation of the whole plant in 10.4.

It is to be noted, furthermore, that this treatise is not meant to be an exhaustive review of the pertinent literature. Rather literature citations have been made only to illustrate the general scope of research currently being conducted. By purpose unit operations like chlorination and carbon adsorption are omitted because of space limitations. For a recent survey the reader is referred to Keinath [72].

7.1 Phosphorus Removal by Chemical Precipitation

In most circumstances the only possibility to get a high phosphorus removal from wastewater is by chemical clarification. Phosphorus forms essentially insoluble precipitates with a number of substances. High rate of phosphorus removal thus can be obtained when the right chemicals are added in proper doses. Because of economical reasons the use of salts of aluminum and iron or lime as chemicals is dominating. Both metal salt and lime precipitation are very complex reactions. The major reactions taking place when metallic ions or lime are added to the wastewater are the formations of insoluble phosphates. The distribution of phosphates depends strongly on pH and about ten different phosphates can occur in raw wastewater. Lime, on the other hand, also reacts with the bicarbonate alcalinity of the wastewater to form calcium carbonate. This illustrates that part of the chemical added does not remove any phosphorus primarily. Therefore, the necessary dosage tends to increase over the stochiometric relation in the dominating reaction.

It is beyond the scope of this paper to describe the details of precipitation chemistry. More of this can be found in standard books like Weber [118] or Culp [36] or the surveys by Kugelman [75], Jenkins et al [67] or Olsson et al [88]. For further information see also the symposium proceedings [95]. Here the main purpose will be to discuss in what way the dosage of the chemicals can be controlled.

The pH is obviously a most important parameter to know for control purposes, especially for metal salt precipitation. In lime precipitation the biocarbonate alkalinity is crucial to know. The phosphorus or phosphate content is also a most desirable information, but is very difficult to get, except in terms of total phosphorus content. As the chemicals most often react also with several of the other constituents of municipal wastewater, the average dosage has to be determined experimentally for each individual plant with its special wastewater composition.

From a process control point of view, the most essential measurement information to get is therefore the following,

- o flow rate
- o pH
- o bicarbonate alcalinity (for lime)
- o phosphate content
- o organic pollution load (e.g. BOD or COD)

A reasonable control law thus should be based on pH and flow rate as a minimum requirement. Yeaple [125] has made a model to evaluate some control strategies for phosphorus removal.

7.2 Current Practice in Chemical Dosage Control

The control strategies applied can be divided into two basic groups. In one group the control is flow proportional with manual updating of the dosage rate. This is applied often in phosphorus precipitation and in sludge conditioning with chemicals. In the other group the control is flow-proportional with on-line sensor-based feedback updating such as pH controllers, analog or digital. In phosphorus removal control some additional check is made, e.g. the turbidity and the phosphorus content of the effluent.

Automation of lime dosage has been demonstrated in some plants, e.g. at the Blue Plains Pilot Treatment plant in Washington, D. C., see Schuk [103]. Another demonstration in pilot scale is described by Schmid [102]. Lime addition was paced by an automated pH control system with instrumental monitoring of plant effluent turbidity and orthophosphate concentrations. The pH control system philosophy in the lime precipitation is also applicable to other pH control systems, such as recarbonation, prechlorination and breakpoint chlorination. This is also reported in the mentioned report by Schuk [103]. For further information of pH control in general, the reader is referred to Shinskey [105].

8. INSTRUMENTATION

One of the major problems in achieving reliable operations except sufficient process knowledge is the lack of adequate instrumentation to improve plant performance. The automation of wastewater treatment systems can be compared to other industries and can be found to need further development. The non-profit character of the process was discussed in 2 (13). Often it is also an insufficient appreciation of the benefits of instrumentation and automation and the consequence is an inability to provide a strong incentive based on a strict cost/benefit analysis.

Some general trends and special problems pertinent to wastewater treatment will be described in this chapter. The instruments will be classified into the groups physical, in-stream sensors, analytical instruments with automated wet chemistry and finally a special group for biological activity measurements.

8.1. Recent developments and general trends

A vast amount of literature has been published on instrumentation during the last few years. Molvar-Roesler [83] published a collection of about 600 abstracts summarizing technical articles related to instrumentation and automation of wastewater treatment plants. These articles are published between 1967 and 1973. Other surveys are found in Roesler-Wise [100,101]. A special symposium on instrumentation and automation of wastewater treatment systems was held in London 1973 and is published in Andrews, et al [7]. The EPA has published a handbook [59] containing reference information for use in the planning and operation of industrial waste monitoring.

EPA recently announced an expenditure for fiscal year 1975 of $4 billion [41] for the construction of municipal WWT plants in the USA. Assuming an average "control equipment" investment of 5% approximately $200 millions of fiscal year 1975's $4 billions may reasonably be expected to be spent for instruments and other control equipment

According to another survey by Heckroth [61] the biggest increase over the next 10 years will be in the installation of process stream analyzers. An increase of over 1100 percent should be shown for dollars spent on both municipal and industrial water and wastewater process stream analyzers.

8.2 Special problems in wastewater instrumentation

Since most measuring devices in wastewater treatment interface directly with raw sewage, mixed liquor or thickened sludge, these devices are subject to continued fouling from solids deposition, slime buildup and precipitation. Accordingly, they need more frequent cleaning and calibration. Poor mechanical reliability, interferences, and a lack of established measuring principles are also responsible for the unsatisfactory state of some analytical sensors.

Although most plants have reasonably well-qualified instrument maintenance staffs, any plants that call for the addition of sophisticated instruments and automatic control devices must provide for upgrading the staff's qualifications. In a recent survey of about 50 US installations of municipal and industrial wastewater treatment plants Molvar [84] has remarked that unreliable sensors accounted for most of the difficulties experienced with automatic measurements and control. The operating experiences showed, that wastewater instruments require more maintenance than their industrial counterparts.

Hitherto there has been too little sensor requirement studies in parallel with modeling, simulation and control system design investigations. There is today a lack of definition of necessary need of instrumentation, such as what measurements are really needed in order to exert effective control over the plant. Because of poor understanding of the dynamics there is also insufficient knowledge about how frequently these measurements should be made, how accurate measurements are necessary,and how much time delay between the sample is taken and the time when the results are known is tolerable for effective control.

The possibilities to systematically use estimation theory in order to overcome some of the instrumentation limitations has only been explored to a very little extent, see Chapter 4. Especially for measurements of biological activity, estimation seems to be a promising way to progress of control. One example is the SCOUR concept, see 4.

8.3 Physical measurements

According to the survey by Molvar [84] flow and level measurement devices account for nearly half the instrumentation employed in treatment facilities, while position, speed, weight and other mechanical type measurements add up to about 15%. Instruments for these physical measurements generally do not create any big problems, as long as they are properly maintained.

A special word may be said about stormwater flow measurements (see also chapter 3). Accurate and reliable flow rate monitoring for storm water does pose special problems. Highly transient flows, large operating ranges, high suspended solids, and frequent collisions with large debris are only some of the obstacles that an acceptable storm-water in-sewer flowmeter must overcome. Consequently, a suitable stormwater flowmeter needs to be developed that will produce the accurate flow rate data required for sewer regulation.

Sludge level and sludge solids concentrations are important to measure. Since sludge disposal accounts for approximately 40% of the cost of sewage treatment, any means of minimizing the volume of sludge passing forward from the settlement tanks for further treatment is worthwhile. Sludge density meters have been field tested with varying success, see Briggs [26]. Conductivity, ultra sonic and turbidity measurements for diluted samples are used. A sludge density meter, based on cross-correlations techniques has been developed, see Wormald, et al [124]. The method is based on the measurement of conductivity fluctuations within a turbulent flowing stream. Control of sludge withdrawal based on viscosity measurements has also been applied, see Richards-Kirk [98]. Devices based on gamma absorbtion or gamma back-scatter have been used as well, see further Molvar-Roesler [83].

Turbidity measurements for suspended solids concentration are widely applied. The instruments make use of the optical properties of the suspension. As a rule, these instruments will operate reliably, provided the optical surfaces are cleaned automatically at least once daily and provided they are calibrated empirically with a frequency dependent on the particular size and the nature of the solid material.

8.4 Analytical instruments

The very nature of pollution control facilities demands the use of various analytical measurements. The processes which are basically fermentation, chemical or a combination thereof, have a much more complex chemistry than most industrial processes. We are dealing with a variable quantity and variable quality of raw material. It is necessary to know the characteristics of both the influent and the effluent for control of the process as well as evaluation of the results. The result is that analytical devices and systems are of paramount interest to this field.

The analytical instruments can be divided into two major groups

- in-stream sensors or electrodes which generate an analog signal of the variable measured

- automated wet chemistry, which samples a quantity from the flow stream. The sample is subject to an automatic laboratory procedure, requiring reagents. Although the procedure may be rapid, a certain amount of time elapse before the measured value is recorded.

Many of the in-stream probes or the automatic sampling system use well-established principles, that are suitable for wastewater monitoring and control activities. Still they require so much maintenance that many users are dissatisfied with them. These instruments need improved maintenance characteristics before they will become widely used.

8.5 In-stream sensors

At present the most widely used and successful systems are the simple electrode systems for pH, conductivity and certain selected ions.

The electrode system for pH; designed for continuous process operation, have improved greatly in the last few years. The reliability of this basic instrument has reached very high levels. The pH measurements are essential for the chemical dosage (see 7.2) as well as for characterization of influent and effluent. It is also an indication of changing conditions of the anaerobic digester. Despite the good properties of the pH probes many pH control systems in the survey by Molvar [84] showed a poor performance, because of faulty system design and installation.

The dissolved oxygen (DO) probe has been used successfully in several installations and is considered one of the few reliable on-line sensors for on-line activated sludge control, see e.g. Jones et al [69] and Briggs [26]. The DO probe and ion selective systems are basically electrode systems as are pH probes. These are developing at an enormous rate and are available for a number of different ions and radicals.

8.6 Automated wet chemistry instruments

The second group on analytical devices on which work is being done are those of the automated wet chemistry. They are used for measurements of organic loading, nitrogen and phosphorus content of the stream.

The biochemical oxygen demand (BOD) is one of the most widely used- and most fundamental- determinations of organic loading. It is, however, a notoriously awkward variable to measure, since it takes five days (or more) to carry out the test. Indeed, almost by its very definition, it is a measurement which defies automation. Today alternative means of monitoring organic pollution levels are available for use in the field. The advantages to monitor organic loading by total organic carbon (TOC) or total organic demand (TOD) or chemical oxygen demand (COD) has been pointed out by numerous authors, e.g. Arin [9], Briggs [26], O'Herron [87] and McDonald [81], Andrews, et al [7].

Nitrogen pollution control of both organic and inorganic forms should be part of the functionality of wastewater treatment plants. This requires quick-time parameter determination of different forms of nitrogeneous materials in waters. The Total Nitrogen Analyzer when coupled with certain specific ion selective probes for nitrates and ammonium give relatively quick measures of total oxidizable nitrogen (TOxN).

Analyzers for phosphorus (phosphate) analysis are also available. Usually the analyzers measure total phosphorus.

8.7 Measurements of biological activity

Information of the rate of consumption of oxygen by activated sludge can be of considerable value in the operation of aeration units. Depending on the location such a unit can be used both for the control of the ratio between food and microorganisms and as a warning system for toxic loadings. The biological activity in an activated sludge unit is strongly correlated to the consumption of oxygen (see 4.3). Therefore dissolved oxygen probes are invaluable in the operation of activated sludge units.

The problem to measure the percentage active mass in activated sludge is a most advanced problem. Luminescence measurements have recently generated considerable interest as a potential tool for rapidly determining the percentage of active biomass. The biochemistry and basic applications of both chemiluminescent and bioluminescent reactions have been described by Seitz and Neary [104] and Chiu, et al [34].

Adenosine Triphosphate (ATP) measurements of viable biomass have been used to control the flow of return sludge at two fullscale municipal treatment plants [23]. ATP concentrations responds rapidly to cell viability and changes with population shifts and the cell growth phase. Therefore it could be a useful variable in process evaluation and control. The sources of error in measuring ATP were also emphasized by Seitz et al [104]. Wise [122] and Chiu, et al [34] made a survey of commercially available and relatively inexpensive ATP analyzers.

9. THE ROLE OF COMPUTERS

Most plants being built today or recently finished are equipped with data acquisition systems. It is estimated that over the world there are some one hundred installations presently in operation or being built. Still computerization in wastewater treatment is in its infancy, and not enough operating experience has been accumulated to assess its desirability in many plants.

Today several of the major process control manufacturers can offer computer systems with hardware and software specifically developed for wastewater treatment systems. The software is based on what is developed for chemical process control. Advanced man-machine interfaces like colour CRT displays are available. The standardization of instruments for computer use, however, is still not at all satisfactory.

Instead of giving an exhaustive list of computer installations some specific examples will be discussed here, wastewater treatment systems in 9.1 and wastewater collection systems in 9.2.

9.1 Wastewater treatment plant computer systems

The new John Egan plant, operated by the Metropolitan Sanitary District of Greater Chicago has been put into operation recently, and consequently no operational experiences are yet reported. Despite its moderate size (30 MGD $\approx$ 1.3 m^3/sec) the plant is of particular interest. It is constructed with an unusually great flexibility so that new operational procedures can be tested out. Experiences from this plant will provide a basis for modernization of the big 1.2 billion gallons per day ($\sim$50 m^3/sec) plant in Chicago. The plant and the computer system has been described by Lynam [79] and Graef, et al [52]. The computer system is a dual processor system. One processor is the normal on-line processor, while the other one is a back-up machine and also serves as an off-line computer for engineering and program development. The primary tasks for the computer are supervision and data acquisition. Some analog setpoints are also controlled from the computer. Then the computer controls the logic for operations like backwashing of deep bed filters, and sampling procedures like measurements of profiles of dissolved oxygen and mixed liquor suspended solids concentrations in the aeration tanks.

The Achere III plant in Parish serves about 3 million people and is probably the biggest one in Europe. A computer system is installed that makes data acquisition and direct digital control of some essential loops (cf ch 5), [43] [44]. Another good example are two activated sludge plants in Bridgeport, Connecticut [40]. Also there a steady state calculation is made to compute the biological oxygen uptake, based on dissolved oxygen concentration measurements. Other computer systems are found in Atlanta, Georgia [64], Norwich, England [70], Arakawa, Japan [110], Palo Alto, California [93], San Jose, California [19], Stockholm and Gothenburg, Sweden.

In Philadelphia a very advanced system for both water distribution and wastewater treatment is planned and partially completed. In a major improvement program for the city's wastewater treatment plants some $225 million will be spent on three major plants. Each plant will be equipped with a process computer responsible for data acquisition but with the capability to take over more and more control loops as soon as enough process knowledge and operational experience have been gained. The idea of decentralization of computer power is attractive in big plants because of the long distances between the unit processes, and therefore dedicated small computers will take care of local control loops. Those "operating and control stations" are located at strategic points in the plant. Except for local control they will also serve as trouble shooting stations, multiplexing, alarm and communication centers, computer-to-process interface connections as well as check points for operating personnel on their rounds. One plant computer will be more sophisticated than the others. In addition to the normal process control tasks it will provide off-line capabilities for data reduction, report generation and program development for all three plants. The three main computers will be interconnected in a computer network and will ultimately be linked to a large management information system computer. The goal is to achieve an integrated total system automation for Philadelphia's water distribution and wastewater treatment facilities. The systems have been described in several publications [14,50,54,55,56] .

9.2 Wastewater collection computer systems

The typical feature for computer systems in sewer networks is the long distances between the sensors and the central computer. Sometimes the public telephone network is used, sometimes special purpose microwave networks are constructed. Most often the computer performs supervisory control (see chapter 3) and its main task is data acquisition and presentation for the operator.

The Seattle system [78] (See chapter 3) is supplied with a central computer system for the operation of the sewer network. To give an idea of the size of the computer system, there is a 48 k internal core and 32 k external core memory, a fixed head disk (1.5 M word) and two magnetic tape units. The central computer room is supplied with eight CRT displays. It communicates with 37 remote stations over telephone lines.

Some other installations are mentioned here too for reference. In Baton Rouge, Louisiana, a computer supervices 120 unmanned pump stations and alert a human operator if anythings goes wrong with the equipment [85]. Detroit has a monitoring system that includes telemetering, rain gauges, sewer levels and overflow sensors [116]. The signals are transmitted to a central computer and data logging facility. In England sewer network supervision and control has been practiced for some time [35]. In San Francisco a real time computer system is developed to predict sewer flows from urban run-offs [53] [82].

10. TOWARDS MORE ADVANCED CONTROL

Some thoughts of the state of the art of sewage control have been presented.

Many problems remain to be solved. Here some areas will be emphasized, where there are strong research needs. In order to be able to formulate suitable performance indices process knowledge is needed. This is discussed in 10.1. The desired interaction between design and operation is emphasized in 10.2. Some areas where estimation and prediction are useful tools are shown in 10.3. Control of the unit processes and the whole plant is discussed in 10.4. Finally, in 10.5 some personal reflections and conclusions are made.

10.1 Control objectives and performance index

There are some obvious objectives for the control of a treatment plant like

- improved quality and a reduction of quality variations in the effluent water
- adjustment of the plant to varying influent concentrations and flow rates
- reduced costs for power and chemicals
- better detection of process problems and failure risks
- a certain quality of the waste sludge in order to save costs for sludge treatment
- preferably no by-passing

Some of these objectives are difficult to quantify, and even the most important one-effluent water quality-cannot be expressed with today's knowledge in terms of a reasonable performance index. There is a great need for improved models, that tell which variables, parameters, unit processes etc. actually influence the effluent water quality. Just an example: is an increased turbidity of the effluent caused by changing settleability properties of the cell mass, on different loading conditions, on inadequate chemical dosage, on backwashing of deep-bed filters or on supernatants from the anaerobic digester? This implicates the need for more structured measurement information together with a more substantial process dynamics knowledge in order to make the adequate control decisions. Needless to say, the performance index should reflex the total system behaviour, that is not even only the plant but the plant plus the collection system. A nice way to improve the plant performance is to allow only a constant influent flow and bypass the rest to the receiving water. The so called "midnight valve" is still a frequently used control variable in some plants.

10.2 Process design and process operation

The integration of process design with control system design is a largely ignored area. This is not unique for wastewater treatment processes, as Foss [47] has discussed in such an excellent way. The process should of course be constructed flexible enough to allow the desired operations, see Andrews [2]. Secondly, there is a trade-off between design investments and operational costs, but this type of calculation is seldom done. One reason is the grant system. Governmental contributions are given only for construction costs and not for operational costs. Some work among these lines to integrate design and operation has however started and notable examples are the cities of Chicago with the John Egan Plant and the city of Philadelphia (see 9.1).

The design of a plant is naturally coupled to the design of a sewer network. If both of them were to be constructed at the same time there is a tremendous potential in saving money by looking at the interactions between the sewer network and the plant. If the collection system can be used systematically to attenuate the flow peaks to the plant, then significant investment costs can be saved. It is more probable that many plants are overdesigned, which means that control actions are hardly necessary. One indication of this fact is found by Berthouex, et al [21]. They showed that the effluent quality variability is very small in a well designed plant, and it is hardly possible to detect any transfer function relationship between the influent and the effluent water qualities. If the plant is large enough the effluent quality is very insensitive to hydraulic or influent substrate changes .

A fundamental problem in all wastewater treatment is pumping of water. Sedimentation basins are extremely sensitive to sudden flow changes. Therefore the flow rate has to be changed smoothly in order not to upset the settling too much. In many plants there are no variable speed pumps, so the available pumps have to be started up stepwise. This can create significant pulses of suspended solids concentration in the effluent. Many good control actions can be spoilt by unsuitable pumping.

Bypassing of sewage should be avoided by all means. It might take many days of good control to compensate for the detrimental effects on the recipient after a bypassing. It is often a matter of suitable piping and reasonably large hold-up tanks to manage to keep storm water flows, so that a peak load can be treated at a later time.

The activated sludge process gives several examples, where an increased communication between control and design engineers is rewarding. The oxygen demand is varying along an aerator, so therefore many plants are supplied with a so called tapered aeration. The air flow is maximal in the head end where the biological uptake rate is great. The spatial air flow distribution however is a design constant and only the total air flow can be changed in order to control the DO content. In most plants, however, the air flow is designed to be uniformly distributed along the aerator. This results in a strongly varying DO profile. This abundance of oxygen is of no biological use, but is a waste of money. It is of course necessary to keep a certain amount of mixing all the the time, and this can motivate a higher air flow rate. As the spatial distribution of oxygen demand will vary with the loading of the plant, it would be desirable to be able to control not only the total air flow but also to some extent the distribution of air flow. Such a control could probably save considerable power costs.

In many plants there is a considerable variation in the plant load at different seasons. Due to inflexible piping, however, it is often impossible to change the water flow pattern to make the plant more effluent during such changes. Especially at low loading periods the aerators may have too dilute substrate in the feed. On the other hand it is always desirable to use as many settlers as possible. If the flow could be redirected from fewer aerators to all settlers the plant operating costs could probably be saved to some extent. Moreover, the maintenance could probably take advantage of this.

It has been shown (5.4) that step load is an important control variable in many situations, especially in a longer time scale of several hours or more. To provide piping and the suitable valves to make step loading possible if desired should certainly be considered in a construction phase.

For many measurements it is necessary to take water samples. To provide the plant with the adequate sampling points in the design phase is naturally of great value.

10.3 Estimation and prediction

This area is probably the most profitable area for control theory applications in the field of wastewater treatment processes. The instrumentation is-and will probably be for a long time - a serious problem. State variable estimation can help to overcome this problem. One type of application was mentioned in 5.3. A more elaborate estimation of the specific oxygen utilization rate SCOUR (see 5.3) still remains to be shown in full scale.

As several parameters are slowly varying there is a need for real time identification. The oxygen transfer coefficient (eq 6.1) is important to update, if SCOUR should be estimated. The specific growth rate varies with the substrate composition. Still another example is the sludge settleability in the secondary settler.

Real time prediction must be much more applied. Rainfall prediction and flow rate predictions in sewer networks ought to be more explored, and the stochastic nature of the flows should be taken into account more systematically. These flow predictions in turn will affect not only the collection system control but also the plant control. By re-routing the flow streams in the plant it is possible to prepare the plant for expected major disturbances in substrate concentration, toxic loadings or hydraulic changes.

10.4 Control

It is my personal belief, that the control algorithms will be simpler than the estimation algorithms in an advanced control system of wastewater treatment. As soon as the processes are well understood and the pertinent parameters and state variables are estimated, the control actions might be of a relatively easy nature.

Four kinds of control ought to be considered in a well working system

- the control of the single unit process
- the interaction between the unit processes in the plant
- the interaction between the plant and the sewer network
- the interaction between the plant and the receiving water

For the control of the unit processes it has already been remarked, that most algorithms are based on stationary considerations. A dynamical formulation of the control problem therefore leads to reexamination of some basic concepts.

As an example, consider again the activated sludge process and the control of the food-to-microorganism (F/M) ratio (or sludge retention time control). It is generally agreed that it is desirable to keep a constant biological growth rate, or F/M ratio, in the aeration system. Further it is often assumed that this may be maintained through maintaining a constant sludge retention time (or sludge age), based on static relationships between the total sludge mass in the system and the flow rate of waste sludge. These static calculations are not adequate in plants with considerable flow variations, but only on some "daily average" basis. The specific oxygen utilization rate (SCOUR) mentioned is a much more fundamental indicator of the biological activity and - more important - it reflects the dynamical character of the process. Once a desired value of SCOUR is established by some method the practical implementation of a SCOUR control would be to calculate the required sludge concentration in the aerator and control this via the return sludge flow rate.

In order to meet diurnal variations the sludge storage capacities should be more systematically used, see 5.3-5.4. This can be accomplished by using the settler capacity for storage together with the step feed control.

There is a misleading tendency for models to be used in ignorance of the practical limitations. This is exemplified in a paper by D'Ans et al [37]. They propose a non-linear regulator for anaerobic digester control. This is suitably discussed by Wells [120] who points out that such a controller is necessarily some distance from being innovated in practice. Fan et al [42] have taken a similar approach to apply linear-quadratic theory for the control of an activated sludge process. Also here the model is too simplistic and consider neither organism recycle or the interactions due to the solids-liquids separation.

As in chemical process control there are essential interactions between the unit processes. Hitherto, however, too little attention has been paid to this problem [47]. In a wastewater treatment plant both sludge disposal and wastewater treatment should be considered together in order to get realistic cost/performance figures for the plant. There is not only a direct influence on the sludge quality from the water treatment but also feedback effects from the sludge handling to the wastewater treatment chain. For example the anaerobic digester supernatant is returned directly to the biological activated sludge process, see Malina - DiFilippo [80]. Sometimes lime is added to the sludge for stabilization. The return water (reject water) can give some undesired disturbances in the biological treatment or at metal salt precipitation due to pH changes. Backwashing of deep bed sandfilters can create significant flow disturbances (often as chock loads) on the wastewater treatment processes. The backwash flow is usually of the same order of magnitude as the influent flow to the plant. Typically the length of the filter run may be 10-12 hours, while the backwashing time is normally 5-10 minutes. In order to avoid the chock load of the returning water the backwash wastes must be suitably buffered and returned at the proper time. Another important interaction comes from the methane production in an anaerobic digester. This is one of the few processes which can be operated with profit. The methane gas can be used to supply power to blowers and heating systems [5].

The operation of a wastewater treatment plant in relation to the state of the receiving water (e.g. a tidal estuary) has hitherto been given little attention, but models are being developed. A recent contribution is Yih and Davidson [126].

10.5 Conclusions

Dynamical modelling and control and real time computation are still new and unknown fields for many sanitary engineers. The term "automation" is often interpreted in a narrow sense by many process engineers. Many design engineers do not appreciate the dynamical character of the processes and steady-state procedures are still almost exclusively used. Therefore there is a clear educational problem how control theory can be suitably applied for different processes in this field.

A better understanding of some basic dynamical phenomena and process dynamical behaviour is certainly needed. There is of course not one all-encompassing dynamical model. Rather there is a whole family of models having different degrees of complexity depending on the nature of the problem for which they are formulated. To choose the mathematical model that suits the nature of the problem at hand is an area, where control engineers could help sanitary engineers to a large extent.

Research in advanced systems analysis and design is being more and more supported. Therefore it is a high probability, that we can report a lot more advanced control systems in the wastewater field within the next few years.

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