PP-78-10

MODELLING AND OPERATIONAL CONTROL OF THE ACTIVATED SLUDGE PROCESS IN WASTEWATER TREATMENT

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November 1978

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PREFACE

Water quality management can be interpreted primarily in two ways: either one understands this term to mean long-term planning of investment in storage and wastewater treatment facilities; or management is understood in a real-time context where one is concerned essentially with short-term operational matters. The traditional view of water quality management is the former interpretation. In general the design of wastewater treatment plants reflects this view and operational aspects of management are ignored. This has important consequences. Frequently the original objectives of a long-term management programme cannot be achieved because of persistently inadequate operational performance of treatment plants. During the past ten years such an inconsistency in the problem formulation of water quality management has become well recognised.

In 1977 a small project funded by the Anglian Water Authority was initiated with the collaboration of the University of Cambridge, U.K. The project was to undertake a study of dynamic modelling and operational control of the activated sludge process in wastewater treatment. This work continues to the present and will continue for some time to come. The three principal investigators include the manager of the Norwich Sewage Works in eastern England, and two persons with various research interests in system identification, water quality management, and fuzzy control. Early in the study it became apparent that the more conventional techniques of control system design would probably not be capable of yielding the practical results that were being sought. For a number of sound reasons we decided to try the novel approach of using fuzzy system theory techniques in synthesizing a controller for the activated sludge biological treatment process. The nature of the problem seemed to suggest this approach and our preliminary results confirm the potential of the technique. The basis of a fuzzy controller is that it exploits the empirical operating experience of the plant manager rather than the analytical properties of a set of mathematical relationships.

This report provides a summary of the project activities up to June 1978. The project will continue, even though two of the investigators no longer reside in the U.K.; the most severe problem which that creates is the increased distance from the treatment plant itself. We are grateful to the Anglian Water Authority, to the University of Cambridge and to IIASA for the support, time and facilities with which to carry out the study.

ABSTRACT

A report is presented on a collaborative study of dynamic modelling and control of the activated sludge process in wastewater treatment. The report divides into four major parts, the first of which presents and discusses the time-series of field data from the Norwich Sewage Works in England. The second part of the paper is concerned with the identification of a model for nitrification in the activated sludge process from the given field data; the technique used for this purpose is an extended Kalman filtering algorithm. A third section deals with the construction of a detailed simulation model which has been used for control system design and evaluation. The final major part of the report introduces some basic ideas of fuzzy control, suggests why conventional control schemes may be of limited value in wastewater treatment systems, and proceeds to define a fuzzy controller developed from the empirical operating experience of the Norwich Treatment Plant manager. The paper also offers some thoughts on future perspectives for the study and for the use of mathematical models as aids to the operational control of wastewater treatment.

Modelling and Operational Control of the Activated Sludge Process in Wastewater Treatment

1. INTRODUCTION

There is a considerable focus of attention on the application of computers and automation in the water and wastewater industries (e.g., Progress in Water Technology, 1977). The terms "automation" and "computerisation" are, in fact, usually understood as synonymous with substituting the activities of man by a machine. Clearly, in the context of straightforward efficiency and ease of operation, when this substitution refers to the actions of turning on and off pumps, blowers, scrapers, etc., automation would seem to be very desirable. In themselves, however, automation and computerisation do not necessarily imply a more efficient, or more systematic, *control* of process behaviour. It is to the question of control, and not automation, that this project is addressed.

The original objectives for the project were divided into two categories: mathematical modelling of the activated sludge process, on the one hand, and the examination of process operating (control) rules by reference to such a computer simulation, on the other hand. It was intended that the model should be a description of *dynamic*, or unsteady-state, behaviour of the process. Although the desirable goal of process control would be to maintain the activated sludge system at a "steady state", the upsets occasioned by shock loadings, bulking sludge, dispersed sludge, or rising sludge conditions are all transient, unsteady-state phenomena. The term "steady state" is, of course, used advisedly: it is merely meant to indicate the situation in which the activated sludge unit performance is oscillating steadily in accordance with the natural diurnal variations of the primary settled sewage. The activated sludge process is never at a true steady state, in the strict sense of the phrase, since from one hour to the next its influent and effluent quality and volumetric discharges have changed. Thus, besides the dynamic character of the model, it was further desired that the model should simulate the primary properties of biochemical oxygen demand (BOD), suspended solids (SS), and ammonia removal in an activated sludge unit. For the control aspects of the study there were two guiding principles: firstly, the intention was to examine an essentially practical approach to activated sludge control; and secondly, there would be some investigation of ways in which routinely monitored information might be used more effectively.

The ideal project for almost any control system design problem has four distinct phases. These are:

- Design and implementation of experimental work and collection of experimental field data.
- Derivation and verification of a mathematical model by reference to the field data.
- Specification of process control objectives, and control system synthesis and evaluation by reference to the mathematical model.
- Installation of the control system on the field unit.

This summary report on studies for 1977/78 is organised along the same lines. Section 2 deals with the experimental data from the activated sludge unit at the Whitlingham (Norwich) Sewage Works; it also contains a brief assessment of some simple statistics of the field data. Section 3 discusses system identification and mathematical modelling; here we have both a success and a failure to report. From the experimental data a model for nitrification can be identified and partially verified but no such identification is possible for a model of BOD and SS removal. The reason for the failure of the latter rests primarily with the poor quality of the field data for system identification purposes. Accordingly, Section 4 describes some important features of a largely theoretical model, particularly those aspects related to the clarification and thickening properties of the clarifier, which has been developed for subsequent testing of process control schemes. The following section, Section 5, focuses upon the specification of a set of operating rules. Since these operating rules are founded upon the empirical experience of the sewage works manager, rather than upon the analytical properties of a set of mathematical equations, they represent something of a departure from standard control system synthesis procedures. Therefore Section 5 is also partly concerned with showing how the kind of control envisaged for an activated sludge process (to be referred to later as fuzzy control) is really quite different from the type of control one might expect to find applied to a distillation column in a petrochemicals plant. After Section 5 in the report we are forced to leave our ideal project outline. The evaluation of process control rules by reference to a computer simulation is still in progress. And, of course, the implementation of the proposed control on an actual activated sludge unit must await decisions consequent upon the findings of the present project. Section 6 deals thus with the possibilities for ongoing and related studies, including (briefly) the subject of preparing a questionnaire for wastewater treatment plant managers. It is hoped that each of Sections 2 to 6 will eventually form the basis of much more detailed reports yet to be prepared.

The major results and interim conclusions from the project are:

- An original verification of a dynamic mathematical model for nitrification in the activated sludge process.
- An original application of fuzzy control techniques in wastewater treatment.
- The development of a practical control scheme which, in principle, requires no further instrumentation or hard-wiring of the plant (vis a vis the specific case of Norwich).
- The development of a useful framework within which procedures for activated sludge process control can be discussed and formulated.

- The identification of the apparent (overriding) importance of effluent total suspended solids concentration measurements as an indication of process operating conditions.
- The identification of the sensitivity of activated sludge unit operation to the movement and settling of the biological floc in the clarifier.
- The conclusion that current models for the dynamic behaviour of the clarifier are somewhat inadequate.

Recommendations for future studies include:

- The undertaking of further specialized experimental work for investigation of BOD and SS removal in the aerator, and of unsteady-state sludge settling in the clarifier.
- Exploration of the potential for real-time simulation and forecasting as a support service in sewage treatment plant management.
- Examination of the effects of activated sludge unit control on variations in the quality of the receiving water body, especially in respect of in-plant and in-stream nitrification.
- The preparation of a questionnaire, for circulation to treatment plant managers, for comparison and assessment of empirical experience of activated sludge unit control.

2. THE EXPERIMENTAL DATA: SOME PRELIMINARY STATISTICS AND COMMENTS

The success of any modelling exercise which sets itself the objective of demonstrating how well, or how badly, the model portrays "reality" is strongly dependent upon the quality of the field data available. As we have said above, the ideal would be the ability to make certain specialized and deliberate experiments. Such experiments are usually designed for the observation of process dynamic behaviour as a response to well defined input disturbances (forcing functions). For instance, in the case of the

the activated sludge unit it might be desirable to measure how the mixed liquor suspended solids (MLSS) concentration and the clarifier effluent BOD and SS concentrations change with time in response to a sudden step increase in the volumetric feed-rate of settled sewage to the aerator. If these responses can be adequately modelled, and if the assumption can be made that the resulting model is also valid for the simulation of plant responses to other forms of influent feed-rate variations, then we should have the basis of a model for control system design and evaluation. Unfortunately, only very rarely is it possible to carry out such experimental work (see for instance Olsson and Hansson, 1976), since two major practical problems have to be overcome:

- While experimenting with the activated sludge unit satisfactory operation of the wastewater treatment plant must still be ensured.
- The manipulation of the input disturbances, i.e., settled sewage flow and quality, may require extraordinary facilities for storage and pumping of sewage flows.

These problems are not insurmountable; but they are, nevertheless, a barrier to rapid progress in the mathematical modelling of activated sludge units, or for that matter any other unit process of wastewater treatment (Beck, 1977).

At the Whitlingham Treatment Plant there is the compensating good fortune of a fairly comprehensive plant instrumentation system and the availability of equally comprehensive laboratory analysis records of activated sludge performance (Cotton and Latten, 1977a, 1977b). Given that it is not possible to experiment with the activated sludge unit, a second best situation - for the modeller - is the use of these records and, in particular, to select from the records periods of operation where the unit has been performing in a less than desirable fashion. It would, for example, be extremely interesting to observe in retrospect the unit's response to a storm-flow input or to a bulking sludge condition. For the purposes of model identification we shall call this type of field data "normal operating conditions"; a term which will distinguish the observation of responses to naturally occurring disturbances from measurements taken under special experimental circumstances.

2.1 The Field Data and Some Simple Statistics

Figure 1 is a schematic diagram of the activated sludge unit. Table 1 gives some simple statistics of those variables which are direct measurements of process operating conditions; the time-series of data for these variables are plotted in Figures 2 to 22. The period covered by the field data is from January 1st to April 30th (1976), which represents a possible total of 121 daily sampled values for each variable.* Table 2 and Figures 23 to 33 likewise give the statistics and plots for a number of variables, such as sludge age, sludge recycle ratio, etc., which can be computed from the directly measured variables. All these latter variables are computed, where necessary, using data that has been interpolated for the missing observations of the directly measured variables of Table 1.

The following additional abbreviations are used in Tables 1 and 2:

COD = chemical oxygen demand
RASS = return (recycle) activated sludge suspended solids.

These and previously defined abbreviations will be used generally throughout the text. Several conditions attach to the measurement and analysis of the variables of Table:

- All BOD measurements are 5-day total BOD measurements in that they include any BOD exerted by suspended particulate material - the difference, therefore, between total BOD and carbonaceous BOD measurements is that the oxidation of organically complexed N is suppressed in the latter.

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*For reference purposes these first and last dates will be denoted by days t_0 and t_{120} respectively.

Table 1. Sample statistics of directly measured variables for the activated sludge process.

Variable	Mean	Standard Deviation	Figure
Influent settled sewage flow (m^3 day^{-1})	2.057×10^4	0.270×10^4	2
Recycle activated sludge flow (m^3 day^{-1})	1.769×10^4	0.326×10^4	3
Surplus sludge wastage rate (m^3 day^{-1})	431	160	4
Air blower volume input (m^3 day^{-1})	3.762×10^5	0.264×10^5	5
Influent SS concentration (gm^{-3})	185	43	6
Influent 5-day, total BOD concentration (gm^{-3})	294	93	7
Influent COD concentration (gm^{-3})	551	107	8
Influent ammonia - N concentration (gm^{-3})	40	5.6	9
Influent pH value	7.45	0.18	10
Influent carbohydrate concentration (gm^{-3})	25	9.5	11
Effluent SS concentration (gm^{-3})	31	18.7	12
Effluent 5-day, total BOD concentration (gm^{-3})	34	16.1	13
Effluent 5-day, carbonaceous BOD (gm^{-3})	14	5.5	14
Effluent COD concentration (gm^{-3})	111	31	15
Effluent ammonia - N concentration (gm^{-3})	14	8.3	16
Effluent nitrite - N concentration (gm^{-3})	2.8	1.8	17
Effluent nitrate - N concentration (gm^{-3})	23	10.8	18
Effluent pH value	7.55	0.16	19
MLSS concentration (gm^{-3})	3145	479	20
RASS concentration (gm^{-3})	5633	922	21
Sludge volume index (mlg^{-1}) [$10^{-6}m^3g^{-1}$]	92	32	22

- The influent and effluent analyses for quality refer to the analysis of 24 bulked once-hourly samples drawn from points A and B respectively in Figure 1; the sample value for any given day denotes those 24 bulked samples collected from 08.00 hr. on that day until 07.00 hr. the following day.
- All flow measurements are measurements integrated for the period 00.00 hr. to 24.00 hr.
- The MLSS, RASS, and sludge volume index (SVI) values are obtained from laboratory analysis of single daily grab samples; the RASS sample is drawn from the clarifier underflow stream.
- All measurements of compound nitrogen forms refer to the concentration of N in the bound form.
- The missing observations for days $t_{105} \rightarrow t_{108}$ (April 15-18, 1976) reflect the timing of the Easter Public holidays.

The computed variables of Table 2 are defined as follows:

- Sludge recycle ratio = (Recycle activated sludge flow-rate)/(Influent settled sewage flow-rate).
- Sludge compaction ratio in clarifier = (RASS)/(MLSS).
- Sludge loading factor (SLF) =
$$\frac{(\text{Influent sewage flow-rate}) \times (\text{Influent total BOD})}{(\text{Aerator volume}) \times (\text{MLSS})}$$
- Influent total BOD loading rate = (Influent sewage flow-rate) × (Influent total BOD)
- Percentage total BOD removal =
$$\frac{(\text{Influent total BOD}) - (\text{Effluent total BOD})}{(\text{Influent total BOD})}$$
- Percentage nitrification =
$$\frac{(\text{Influent ammonia - N}) - (\text{Effluent ammonia - N})}{(\text{Influent ammonia - N})}$$

A solids balance around the clarifier according to,

$$(Q_I + Q_R)(\text{MLSS}) = (Q_I - Q_W)\ (\text{Effluent SS}) + (Q_R + Q_W)(\text{RASS})$$

yields:

Solids influent loading to clarifier = $(Q_I + Q_R)(\text{MLSS})$

Solids removal in clarifier underflow = $(Q_R + Q_W)(\text{RASS})$

Apparent "disappearance" of solids in clarifier =

$$(Q_I + Q_R)(\text{MLSS}) - (Q_I - Q_W)(\text{Effluent SS}) - (Q_R + Q_W)(\text{RASS})$$

where Q_I, Q_R, Q_W are respectively the flow-rates (in $m^3\ day^{-1}$) of the influent settled sewage, recycle activated sludge, and surplus sludge wastage. A final dependent variable, not indicated in Table 2, but shown in Figure 26, is

$$\text{Sludge age} = \frac{(\text{Aerator Volume})(\text{MLSS})}{[(Q_I - Q_W)(\text{Effluent SS}) + Q_W(\text{RASS})]}$$

Inspection of Figure 26 shows that sludge age averages between about 7 and 8 days for the given operating period. Since sludge age is not properly defined when no surplus sludge is wasted, as for instance from day $t_{103} \rightarrow t_{111}$, the statistics of the computed time-series are not given in Table 2.

Figures 34 → 39 show typical diurnal variations in the settled sewage influent flow-rate and its qualitative characteristics. Notice that the timing of these measurements (June 1977) does not correspond with the period covered by the daily sampled data.

2.2 Salient Operating Incidents

Some of the important features of the operational data will be analysed in considerable detail in Section 3, but perhaps we can state now that any attempt at understanding (modelling) a

Table 2. Sample statistics of variables computed from directly measured variables for activated sludge process.

Variable	Mean	Standard Deviation	Figure
Sludge recycle ratio	0.87	0.17	23
Sludge compaction ratio in clarifier	1.81	0.26	24
Sludge loading factor ([kg BOD/kg MLSS]/day)	0.235	0.087	25
Influent 5-day, total BOD loading (kg day^{-1})	6018	1969	27
Percentage 5-day total BOD removal (%)	87.7	6.7	28
Percentage nitrification (%)	63.7	21.0	29
Solids influent loading to clarifier (kg day^{-1})	1.21×10^5	0.26	30
Solids removal in clarifier underflow (kg day^{-1})	1.03×10^5	0.26	31
Apparent "loss" of solids in clarifier (kg day^{-1})	0.18×10^5	0.12	32

process by reference to such data is extremely difficult. More often than not progress in scientific understanding results from experiments carried out under closely controlled situations whereby the variables of interest can be measured rather accurately and in the absence of significant measurement error. These conditions simply do not obtain in the present case. A large portion of the apparently rapid fluctuations in the field data are almost certainly due to a combination of measured input disturbances, random process behaviour, and random measurement error. It is the purpose of this section, therefore, to draw attention to those features of the recorded data which either illustrate the response of the system to more deterministic upsets and fluctuations or which illustrate the clear control response of the plant manager to undesirable process behviour.

Operating Incident 1

This concerns the initial conditions of the activated sludge unit and its subsequent behaviour over the first month (January) of the records. During the Christmas holiday period, i.e., prior to day t_0, an underloaded plant condition allowed a high level of nitrification to become established which led to subsequent problems of denitrification - rising sludge in the clarifier. Thus at the beginning of January we see an increasing and relatively high influent settled sewage flow-rate (Figure 2): this is a deliberate control response* to the nitrification/denitrification situation through which it is hoped that an overloading of the plant will lead to the suppression of nitrification. At the same time the influent BOD (Figure 7) and ammonia - N (Figure 9) are observed to be rising steadily as the raw sewage conditions revert to their normal, i.e., post-holiday, strength. From day $t_4 \rightarrow t_8$ a faulty recycle activated sludge pump (see Figure 3) gives rise to a severe reduction in MLSS concentration (Figure 20),

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*A peculiarity of the Whitlingham Treatment Works - the settled sewage may be divided between trickling filter and activated sludge secondary treatment.

and a drop in the level of nitrification (Figures 16,18,29). The reduced rate of solids removal in the clarifier underflow also leads to an apprent increase in the sludge compaction ratio in the clarifier (Figure 24). Throughout the whole of January a desired dissolved oxygen (DO) concentration set-point of 3 gm^{-3} was specified, although in practice diurnal variations of DO in the aerator effluent were roughly between 1 gm^{-3} and 3.5 gm^{-3}. Nevertheless, it is possible to observe that the air demand of the plant demonstrates a clear weekly pattern of behaviour during January - Figure 5. Towards the end of the month the relatively high influent flows, which resulted from a combination of additional rainfall and the receipt of a larger portion (50%) of the settled sewage flow, were cut back to a 45%/55% split of the sewage between activated sludge/trickling filter units.

Operating Incident 2

By day t_{39} (February 9th) a DO level of 1 gm^{-3} could not be maintained in the aerator and the effluent was noted to contain a high degree of fine solids (see Figure 12). In fact the effluent total BOD, carbonaceous BOD, and COD (Figures 13,14,15) had been rising since about day t_{34}. On the other hand, the process of nitrification, which had slowly re-established itself from mid-January onwards (Figure 29), had faltered by the beginning of February. (The unrealistically low level of nitrification on day t_{40} is probably a consequence of spurious random fluctuations in the ammonia - N measurements, with a particularly low influent ammonia - N concentration being in evidence.) It is interesting, but pure speculation, to suggest that this loss of nitrification impairs the settleability properties of the biological floc which in turn gives rise to the eventual loss of solids over the clarifier weir. It is further somewhat inconsistent that the oxygen demand in the aerator cannot be satisfied at a time when nitrification rates are unusually low. No less confusing are the following, in chronological order: the extremely high sludge loading factor for t_{39} (Figure 25) - a possible reason for a high oxygen demand; the apparent *gain* of solids in the clarifier at t_{41} (Figure 32); the significant dip in the effluent pH on days t_{43} and t_{44} (Figure 19); and perhaps even the low influent carbohydrate concentrations for $t_{42} \rightarrow t_{47}$ (Figure 11) which follow a period of generally higher carbohydrate strengths. It has been stated (Olsson, 1975) that carbohydrate concentrations and sludge settleability properties are related in the sense that an excess of carbohydrates is required for the formation of sticky polysaccharides which promote good flocculation properties of the sludge. On the point concerning an apparent gain or disappearance of solids in the clarifier more will be said later. It may well be that the only event which can thus be associated with some determinism to this operating incident is that the reduced sludge wastage rates of $t_{46} \rightarrow t_{49}$ (Figure 4) assist in the general recovery of the plant. This includes the achievement of a higher MLSS level, which had previously been particularly low at day t_{39} (Figure 20).

Operating Incident 3

The third period of significant operational changes starts with the sudden loss of virtually complete nitrification between days t_{58} and t_{59} (February 28/29), Figures 16,17,29. Yet even here it is not at all easy to describe the mechanisms governing the reversal of a high nitrification level (about 97% on t_{58}) to a low level of some 30% for t_{67}. For instance, the relatively large residual effluent nitrite - N concentration on day t_{59} (Figure 17) might suggest that a high rate of conversion from ammonia - N was still active while a lower rate of conversion to nitrate - N had occurred. In contradiction, the effluent nitrate - N concentration (Figure 18) shows no substantial change from t_{58} to t_{59} but drops significantly between t_{59} and t_{60}. The progressive reduction in nitrification is at any rate completed by day t_{67}. This downward trend is matched by a similar downward trend in the difference between total and carbonaceous BOD's during $t_{53} \rightarrow t_{63}$ (Figure 33) and by successive drops in the SVI values over the period $t_{53} \rightarrow t_{68}$ (Figure 22). While none of the SVI measurements for the whole operational period indicate a poorly settling sludge, such a temporary improvement in sludge settleability properties (for $t_{53} \rightarrow t_{68}$) tends to discount the earlier remark that a fully nitrifying plant gives a well settling floc. One can say with slightly greater confidence, however, that since the process of nitrification is sensitive to changes in the operating environment, the loss of nitrification could well have been accelerated by the odd combination of observed conditions for for day t_{63}. We have on this day, firstly, an inexplicable drop in the air blower input to the plant (Figure 5), second, a peak value for the percentage BOD removal (Figure 28), and last, a sudden reversal of apparent solids "disappearance" in the clarifier i.e., a net "gain", occasioned by a high withdrawal rate of solids in the clarifier underflow (Figures 31,32).

It is now appropriate to discuss precisely what is meant by "an apparent loss of solids in the clarifier" - definition of this term is given above in section 2.1. A net loss of solids means that on a day-by-day basis more solids appear to be entering the clarifier than are leaving it. Conversely, as observed here, if more solids appear to leave the clarifier than enter it, we have a net gain of solids. What then is the reason for the persistent loss of solids in the clarifier, see Figure 32? Two answers are proposed: one which favours an explanation based on the nature of the MLSS and RASS measurements; and one which favours a certain hypothesis about the biochemical mechanisms of substrate removal in the activated sludge process.

- *The measurement process* - Suppose that as a result of normal and natural diurnal oscillations the maximum and minimum values of suspended solids (as MLSS or RASS) occur at different times for different spatial locations in the aerator/clarifier/recycle sludge circuit. Hence, if the grab samples for MLSS and RASS are taken simultaneously, but clearly at different locations in the circuit, they will reflect different phases of their respective diurnal oscillations. It may occur thus that our measurements here show MLSS at or near its maximum daily value, whereas the RASS observations relate to a median point in their diurnal cycle. Such a situation would "explain" the apparently persistent loss of solids in the clarifier; but it forces the less plausible suppostion that on day t_{63}, and likewise on days $t_{97} \rightarrow t_{100}$ and $t_{113} \rightarrow t_{115}$, grab samples were taken at a quite different time of day.

- *The biochemical process* - Busby and Andrews (1975) propose a model of substrate/micro-organism interaction in the activated sludge process which includes a mechanism for *rapid* initial capture and entrainment of soluble and suspended substrate by the activated sludge floc upon contact with the incoming settled sewage. Subsequent stabilisation of the floc occurs during a second and later reaction of substrate breakdown by micro-organism metabolism. Suppose now that substrate capture is dominant in the aerator while substrate metabolism is dominant in the clarifier. This would satisfy the persistent loss of solids from the clarifier provided a significant fraction of metabolised floc-substrate is converted to soluble metabolic end-products. For day t_{63} one must then argue that the lack of aeration leaves the floc in a state unfavourable for the process of substrate metabolism, or that the floc passes relatively quickly through the clarifier with relatively little time for these reactions to take place. This is not necessarily inconsistent with a high percentage of BOD removal, which should reflect the ability for substrate capture as opposed to substrate metabolism, yet nor is it a hypothesis that can be substantiated in any way.

It may be concluded that each argument leaves much to be desired, although for all its other random manifestations we might favour the reasoning of the measurement process. In spite of this it is still a modeller's profession to search for coincidences; and the coincidence of circumstances on day t_{63} seems more than just a combination of random events.

Operating Incident 4

This last incident involves a complex sequence of observations which divides roughly into two phases of development. The first phase concerns events up to the Easter holiday, days $t_{105} \rightarrow t_{108}$; the second phase follows events from the end of the holiday period until the end of the complete observation period.

On day t_{95} (April 5) the DO content of the effluent is observed to be persistently less than 1.0 gm^{-3}, despite the fact that for some considerable length of prior operation the air blowers had been working at their maximum capacity. In addition the MLSS conditions had been steadily falling from a peak value at day t_{85} (Figure 20). A first (control) response to the situation on day t_{95} is the reduction of surplus sludge wastage rate (Figure 4). From t_{95} onwards both the effluent SS and COD (Figures 12 and 15) - though significantly not the effluent total BOD - begin to increase; two peak values are reached at t_{99} and t_{101} thus indicating a considerable loss of solids over the clarifier weir on these days. No doubt this state of affairs is not improved by the abnormally high influent suspended solids concentrations (Figure 6) for t_{101} and then t_{103}. The increasing sludge compaction ratio between t_{96} and t_{99} (Figure 24) is probably partly a consequence of a reduced hydraulic loading of the clarifier which results from the second (control) response to the continuing deterioration in process behaviour: on day t_{98} the settled sewage influent flow-rate was restricted (Figure 2). This action itself precipitates a poor quality finely dispersed sludge since the floc is being physically broken apart by the excessive agitation of the diffused-air aeration system - compare with the earlier remarks on effluent SS values for t_{99} and t_{101}. By t_{101} the settled sewage influent flow-rate has fallen to a minimum level (Figure 2); and by t_{103} the continuing loss of solids over the clarifier weir has led to the sludge wastage rate being reduced to zero (Figure 4). Further points to notice, where these observations may have some bearing on the subsequent events of phase two of this operating incident (below), concern the following:

another occurrence of apparent solids gain in the clarifier (Figure 32)* over the period $t_{97} \rightarrow t_{100}$; the particularly low RASS and SVI levels for $t_{102} \rightarrow t_{105}$ (Figures 21 and 22) - this latter (SVI) seems to contradict what one would expect from the prevailing dispersed floc condition; and the transient drop in the influent ammonia - N concentration as the Easter holiday is approached, t_{103} and t_{104} (Figure 9).

During the days immediately after the Easter holiday, $t_{109} \rightarrow t_{111}$ (April 19-21), plant operation appears satisfactory with low effluent SS, total BOD, and ammonia - N conditions (Figures 12,13,16). The relaxation of the constraints imposed by phase one of the operating incident (above), including a step change from 0.75 to 1.0 in the recycle ratio on days t_{105} and t_{106} (Figure 23), is such that by t_{109}/t_{110} the unit is again receiving normal influent sewage loadings (Figure 2). At this point, t_{111}/t_{112}, perhaps because it is sensitive to *changes* in the levels of the process operating environment, nitrification is suddenly lost once again and not recovered before the end of the recorded period (Figures 16,18,29). Within a day or so of the loss of nitrification, t_{113}, a suspected spillage of toxic material into the receiving sewer network was reported. There is, however, very little evidence in these records which would substantiate the occurrence of the spillage. Towards the end of April (t_{120}) MLSS has returned to a high level (Figure 20); yet throughout this final period DO conditions were noted to be unsatisfactory and during $t_{95} \rightarrow t_{112}$ the biological floc was also observed to be in a poor state with no ciliates present.

General

For the general status of the activated sludge plant and its influent disturbances we might comment upon the following. Unlike most other properties the ammonia - N strength of the influent

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*For once here the solids removal rate in the clarifier overflow is significant - usually it is about two orders of magnitude smaller than the inflow and underflow loading rates.

settled sewage shows a fairly constant, time-invariant behaviour (Figure 9). On the other hand, the influent flow-rate exhibits discernible weekly fluctuations (Figure 2), and when the recycle ratio is held constant (Figure 23), the recycle activated sludge flow-rate also accordingly has weekly patterns of variation (Figure 3). In fact, these winter months of 1976 represent something of an experimental period of commissioning the plant in which the plant manager was assessing alternative strategies for recycle control. As a hint of the hierarchy of control manoeuvres (see also Section 5) notice that almost daily decisions on surplus sludge wastage rate are made (Figure 4), whereas manipulation of the recycle rate is far less frequent (Figures 3 and 23). Since this was a time of commissioning, it is unfair to remark that the plant never attained a stable, satisfactory operating state: the gradual increase in aeration rate and the long period of maximum aeration with yet low DO levels are indicative of the problems (Figure 5). Some of these problems undoubtedly relate to the gain and loss of nitrification and its side-effects. For a plant such as Norwich, where no discharge constraint attaches to the effluent ammonia - N concentration, nitrification is not always a bonus. Nevertheless, the process of nitrification provides us with the more conclusive - probably one should say less inconclusive - aspects of the modelling results to be discussed in the next section.

3. SYSTEM IDENTIFICATION: MODELLING THE NITRIFICATION PROCESS

One reason why models for the nitrification of waste materials are somewhat easier to verify than models for corresponding carbonaceous BOD removal and SS removal is that for this substrate/ micro-organism interaction process a fairly specific substrate and fairly specific group of organisms can be identified. In other words the biochemical model of Monod (1949) for the growth kinetics of a micro-organism species is a closer approximation to reality for nitrification than it is, say, as a description of BOD/(viable cell fraction) MLSS interaction. At any rate, in practice this would appear to be true for since the work of Downing et al. (1963), the verification of nitrification models has provided more clear-cut successes than any equivalent studies of BOD and SS removal in an activated sludge unit. Our present study is no exception to the rule. It can be concluded that the identification and verification of a *dynamic* model for nitrification is a qualified success; any similar attempts at modelling other processes of waste removal are unqualified failures. The nitrification modelling results will be the subject of a considerably more detailed future report. Thus the presentation here is intentionally brief, although it is pertinent to discuss first some of the principal elements of modelling, modelling techniques, and the current problems of describing biochemical process behaviour.

3.1 Observation of Biochemical Process Kinetics

It has already been mentioned at the beginning of Section 2 that the quality of field data bears a direct relationship to the expected quality of the modelling results. This is a general statement which applies to any system or process that one chooses to model. However, in the case of modelling biochemical process behaviour the problem of poor quality field data is exacerbated by the additional problem of relating that which can be measured to the essential nature of the process biochemistry. Both problems can be discussed with the aid of Figure 40.

To give a more immediate appreciation of this schematic diagram let us suppose the following, that:

(i) The group of variables denoted by $\underline{d}$, *measured input disturbances*, comprise the recorded variations in influent total BOD, SS, ammonia - N concentrations and so forth.

(ii) The group of variables denoted by $\underline{\xi}$, *unmeasured (unknown) input disturbances*, might include such items as random variations in the concentration of dispersed bacteria, or sudden impulsive loads of toxic materials entering the aerator via the settled sewage flow. Other undetected disturbances, which in concept can be equated with input disturbances, may arise from the process environment, for instance, random fluctuations in the mixing regime of the aerator liquors.

(iii) *The process state variables*, both $\underline{x}_m$ and $\underline{x}_u$, are quantities that characterise the essential properties and behaviour of a process. There are two types of state variable: those that can be measured (easily), $\underline{x}_m$, such as aerator MLSS, BOD, and sludge blanket level in the clarifier, etc.; and those that are extremely awkward, if not impossible, to measure, $\underline{x}_u$, as for example, aerator *nitrosomonas* concentration, or the concentration of inert, non-degradable matter attached to the biological floc.

(iv) The group of variables denoted by $\underline{z}$ are termed *measured output variables*. In fact, usually these variables simply represent measurements of the (measurable) state variables, $\underline{x}_m$, and thus the labels state and output are more or less interchangeable. However, in order to emphasise the notion of an output response of the process to an input disturbance, we can visualise the clarified effluent nitrate - N concentration and pH value as typical output variables.

(v) This last group of variables, $\underline{\eta}$, represent the respective (random and systematic) *measurement errors*, originating from the process instrumentation and laboratory analysis, which are inherent in all measurements $\underline{z}$ and which thereby preclude the possibility of $\underline{z}$ being an absolutely exact measure of $\underline{x}_m$.

All the above five groups of variables, then, are assumed to vary with time for a dynamic model of the activated sludge unit.

Now let us describe the reason for the three block representation of the system behaviour in Figure 40. Starting with *Block 1*, we have the fundamental microbiology and biochemistry of waste substrate removal by micro-organism metabolism. At this level a high degree of literally *microscopic* detail would be required to characterise (model) the complete microbiology and ecology of an activated sludge floc. And in many ways - to be noted later in Sections 4 and 5 - the structure of relationships and the dominant species of this microbiological system, though microscopic in detail, can have macroscopic consequences in terms of choosing aeration rates, of avoiding sludge settling problems, and so on. It must be admitted that an "accurate" model of the process biochemistry, with all the intricate interdependences between, say, sludge bacteria, anaerobic/aerobic filamentous bacteria, free swimming and attached ciliated protozoa, would be both large and unwieldy as well as probably unjustified in many applications. The arguments supporting this lack of justification follow shortly.

For *Block 2* the more *macroscopic* features of the process state dynamics, such as variations in the mixed liquor pH and temperature, will influence what happens at the microscopic biochemical level. Reciprocally, the synthesis, respiration, decay, and grazing activities of the biological community (in Block 1) can be translated into changes of the aerator effluent total BOD, and into variations in the quantity and quality of the MLSS (in Block 2). In general, however, most of the microscopic detail of Block 1 falls under the category of variables which are not easily measured, $\underline{x}_u$, and hence this fine detail is "lost", as it were, to the process environment (Block 3). The relatively small number of variables which may be measured, $\underline{x}_m$, amount to the more macroscopic, crude measurements of quantities such as BOD, RASS, and ammonia - N concentrations.

Block 3 represents in part the system environment, from which all manner of unobserved disturbances and unpredictable mechanisms of behaviour ($\underline{\xi}$) will interact with the more deterministic features of the phenomena accounted for in Blocks 1 and 2. Block 3 also represents the instrumentation and analytical procedures, from which arise unavoidable components of measurement error ($\underline{\eta}$). Thus Block 3 is intended to introduce elements of uncertainty into the picture of a system's behaviour, and these in turn further obscure the view of the central basis of the system, namely its biochemistry and microbiology.

So finally, what does the systems analyst, or modeller, really see of the process dynamics? He sees very little indeed: only the observed variations in *some* of the inputs, $\underline{d}$, and *some* of the outputs $\underline{z}$, which means that in effect a quite inadequate foundation is available for verifying a highly complex model of a process such as activated sludge.

3.2 Some Preliminaries on Modelling Methods

A widely used procedure for testing mathematical models is the method of "trial and error" deterministic simulation depicted in Figure 41(a). That is to say, starting with some initial choice of model, this model, or a subsequent modification thereof, is run repeatedly through the time-series of field data. The measurements of $\underline{d}$ are substituted into the model, the model predictions are compared with the observations $\underline{z}$ and, if there are large errors between predicted and observed behaviour, the model may be adjusted (between each run) either in the manner of alterations to parameter (coefficient) values or of alterations to the form of the model equations. The essence of this method is that it is informal, although that is not to suggest that it is therefore not a valid approach, and the method tends to rely on nature being deterministic to all intents and purposes.

Clearly such an approach does not deal explicitly with the inevitable uncertainty in a system's behaviour - an uncertainty which has already been noted with respect to Figure 40. A more formal method of model assessment, in particular the method used to obtain the results of section 3.3, is illustrated in Figure 41(b). The similarities between Figures 40 and 41(b), and at the same time the principal differences between Figure 41(b) and Figure 41(a), are as follows. For Figure 41(b) the block labelled "reality", for want of a better word, is acknowledged to be subject to random disturbances, $\underline{\xi}$, while the output measurements, $\underline{z}$, are seen to be corrupted with measurement error, $\underline{\eta}$. These additions have their counterparts in the modelling procedure by the incorporation of a formal estimation algorithm, whose operation is partly determined by some quantification of the uncertainty related to $\underline{\xi}$, and $\underline{\eta}$, *and* of the uncertainty in the model as a true representation of reality. From this specific set of algorithms, called an Extended Kalman Filter (EKF), it is possible to obtain estimates of the measured group of state variables, $\underline{x}_m$, the inaccessible (i.e. not measurable) state variables, $\underline{x}_u$, and the set of parameters, such as growth-rate constants, $\underline{\alpha}$, which appear in the model. All of these estimates can be used in some fashion to modify or update an inadequate model and to check that the final form of the model is reasonably adequate in the judgement of the analyst.

The details of the EKF need concern us no further. But the information provided by the filter, however, is important both for an appreciation of the modelling results of Section 3.3 and for an appreciation of how the filter might be usefully applied in other contexts, see Section 6. The name of the algorithm, moreover, serves to give an intuitive feeling for what it is trying to achieve in a mathematical sense. The filter behaves so as to eliminate, or filter out, the random "noise" effects of the $\underline{\xi}$, and $\underline{\eta}$ variables, and hence to determine a statistically "best" estimate, $\hat{\underline{x}}_m$ and $\hat{\underline{x}}_u$, of the true state of the process, $\underline{x}_m$ and $\underline{x}_u$. (And since $\underline{z}$ is never an exact measure of $\underline{x}_m$, we can never be certain of the correct values for the $\underline{x}_m$ variables.) From the available information, i.e., the measurements $\underline{d}$ and $\underline{z}$, the filter attempts, therefore, to reconstruct the information about $\underline{x}_u$ and $\underline{x}_m$.

3.3 Verification of a Model for Nitrification

The model to be verified is a straightforward application of a dynamic model for nitrification presented earlier by Poduska and

Andrews (1975). For the purposes of a very brief description, the model can be decomposed into two basic conceptual sections: its assumptions about the process biochemical reactions in the aerator; and its idealisation of the hydraulic regimes of the aerator and clarifier. These two components are presented respectively in Figures 42(a) and 42(b). The major assumptions of the model are that:

- o All biochemical reactions take place in the aerator.
- o The species *nitrosomonas* and *nitrobacter* grow according to a Monod growth function; these species mediate respectively the rate of conversion of ammonia - N to nitrite - N and the rate of conversion of nitrite N into nitrate - N.
- o There is no internal generation of ammonia - N from organically bound nitrogen by heterotrophic bacteria.
- o The rate of nitrification is essentially independent of ambient dissolved oxygen and temperature conditions.*

The model consists, therefore, of five ordinary differential equations derived from the five component mass balances for ammonia - N, nitrite - N, nitrate - N, *nitrosomonas*, and *nitrobacter*:

$$\begin{bmatrix} \text{Rate of change of} \\ \text{component concen-} \\ \text{tration in aerator} \end{bmatrix} = \begin{bmatrix} \text{Rate of inflow} \\ \text{of component} \\ \text{to aerator} \end{bmatrix} - \begin{bmatrix} \text{Rate of outflow} \\ \text{of component} \\ \text{from aerator} \end{bmatrix} + \begin{bmatrix} \text{(Production -} \\ \text{Consumption of} \\ \text{components in} \\ \text{aerator)} \end{bmatrix}$$

Although not marked in Figure 42(a), all components pass to the clarifier in the aerator effluent stream, and all components are returned to the aerator with the recycle activated sludge stream. Only the component of ammonia - N is assumed to enter the aerator with the settled sewage influent. It is necessary to make certain quite severe assumptions about the settling and hydraulic properties

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*Unfortunately, no data could be obtained for either average daily temperature or DO levels for the given observed period.

of the clarifier in order to be able to calculate the concentrations of nitrosomonas and nitrobacter in the recycle sludge stream.

Thus let us turn to Figure 42(b). Here the completely mixed CSTR (Continuously Stirred Tank Reactor) idealisation implies that all component concentrations in the aerator are identical with the same component concentrations in the aerator effluent. We know, however, that in practice the true mixing behaviour of the aerator lies somewhere between a CSTR and a plug-flow reactor. The clarifier (hydraulic) model makes the assumption that for ammonia - N, nitrite - N, and nitrate - N, the respective substance concentrations in the aerator effluent, clarified overflow effluent, and clarifier underflow are all equal. For the nitrifying organisms a fraction p of the aerator effluent concentration is withdrawn in the clarifier underflow and the remaining fraction (1 - p) leaves the clarifier through the overflow effluent stream; p is defined as a coefficient of solids/liquid separation efficiency. If we denote the recycle sludge concentration of *nitrosomonas* by x_{RNS} and its concentration in the aerator effluent by x_{ANS}, it is possible to illustrate how this model of the clarifier relates to the notion of a sludge compaction ratio. Hence, a mass balance across the clarifier yields:

$$\underbrace{(Q_I + Q_R)x_{ANS}}_{\text{Inflow}} = \underbrace{(Q_I - Q_W)(1 - p)x_{ANS}}_{\text{Overflow}} + \underbrace{(Q_R + Q_W)x_{RNS}}_{\text{Underflow}}$$

which after rearrangement gives:

$$x_{RNS} = \left\{ \frac{[Q_R + pQ_I + (1 - p)Q_W]}{(Q_R + Q_W)} \right\} x_{ANS}$$

where the expression {....} is equivalent to a compaction ratio. Note that because all flow-rates are varying from one day to the next, the simulated compaction ratio of this expression is not constant just as neither is the (observed) computed compaction ratio of Figure 24. In fact, from the modelling results it turns out that with p estimated to be 0.88, i.e., an estimated efficiency of 88% separation for the clarifier, the above expression would give an average *estimated* compaction ratio of 1.98. This figure of 1.98 compares with an average *observed* value for the compaction ratio of 1.81 (Table 2). There is a possible explanation of this discrepancy which refers back to the previous discussion of Section 2.2. The model of the clarifier, as given above, assumes a perfect balance of solids across the clarifier. In contrast, however, it is observed that this rarely happens according to our recorded data (Figure 32): on average (see Table 2) about 10% fewer solids leave the clarifier each day than enter it. The difference in the two compaction ratio figures also suggests a discrepancy of 10% fewer solids leaving the clarifier in practice than in the model. Doubtless this is an oversimplified argument, since the model of the clarifier is, as are most other such models, a considerable simplification of extremely complex process behaviour (compare with our recommendations and conclusions in Section 1).

Figure 43 shows the observed and estimated variations for the five components (state variables) of the model, where the observations ($\underline{z}$) are taken to be the conditions of the clarifier effluent analysis. Inspection of the *reconstructed* dynamic behaviour of the unmeasured state variables ($\underline{x}_u$) representing the aerator concentrations of *nitrosomonas* and *nitrobacter* indicates that there are approximately three distinct phases of interest, namely periods $t_4 \rightarrow t_{33}$, $t_{36} \rightarrow t_{58}$, and $t_{65} \rightarrow t_{111}$. But before discussing these variations it is important to realise that the fact that the model estimates for $\hat{\underline{x}}_m$ generally follow the course of the observations $\underline{z}$ in Figures 43(a),(b),(c) is deceptive. The apparently good fit of the model to the data is indeed only an appearance. The deception is bound up with the way in which the Extended Kalman Filter estimation algorithms have been applied to the model and field data. Recalling Figure 41(b) notice that the model estimates in Figure 43, i.e., $\hat{\underline{x}}_m$, are based upon a knowledge of the measurements $\underline{d}$ *and* the measurements $\underline{z}$. The net effect of combining the model and field data in such a manner is, on the whole, one of repeatedly correcting the raw model prediction* closer to the actual observation. We shall return to this point again in Section 6; more detailed attention will also be given to the subject in the complete account of these results - to be prepared. For the present, suffice it to say that the results of Figures 43(a), (b),(c) are but a meagre reward to the considerable amount of effort invested in the modelling exercise. The nature of the field data, the requirement of the model for reconstructed estimates of the nitrifying bacteria ($\underline{x}_u$), and other adverse mathematical properties of the model, all contribute to the difficulty of the exercise. Note, however, that over the period of missing observations for $\underline{z}$, $t_{69} \rightarrow t_{80}$, where the model estimates are equivalent to the raw model predictions obtained in the manner of Figure 40, the model gives a respectable performance of prediction forward to the next observations at t_{81}.

With respect to Figure 43 recall that in Section 2.2 (Operating incident 1) we have already commented upon the loss of nitrification on day t_4 due to a faulty recycle sludge pump. In Figures 43(d) and 43(e) it can be seen that between t_4 and t_{33} both groups of nitrifying organisms are able to recover from this upset; their population concentrations increase at almost exactly identical rates. For the same period Figure 43(b) shows the model to be estimating a consistently higher level of aerator effluent nitrite - N concentration than was actually observed. If anything, this suggests that the model's estimated rate of production of nitrite - N is here relatively too high in comparison with the corresponding estimated rate of consumption of nitrite - N.

At about t_{34} the process of re-establishing nitrification is temporarily halted with an accompanying drop in the levels of *nitrosomonas* and *nitrobacter* (Figures 43(d) and 43(e)). It is possible to associate this event with the increasing loss of solids in the clarifier overflow from t_{34} onwards - see Section 2.2 (Operating Incident 2); a situation which, though only a minor change in the

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*i.e., the prediction from the model fed to the estimation algorithm in Figure 41.

operating environment, is sufficient to reduce significantly the ability to maintain nitrification. Both the observed and computed rise in nitrite - N concentration at this time indicates that the rate of nitrite - N conversion to nitrate - N has dropped more rapidly than the ammonia - N to nitrite - N conversion rate. In fact, for the following twenty days or so, $t_{36} \rightarrow t_{58}$, the unsteady recovery of the *nitrosomonas* population is rather faster than that of the *nitrobacter* population - compare the "slopes" of Figures 43(d) and 43(e) between t_{36} and t_{58}. The residual nitrite - N also remains at a substantially higher value during this period, Figure 43(b).

Whereas the rise of the *nitrosomonas* concentration is faster, its subsequent fall over $t_{59} \rightarrow t_{65}$ is equally more precipitate than the reduction in the level of the *nitrobacter* population. No satisfactory argument for a mechanism governing this sudden decline in nitrification can be deduced, see also Section 2.2 (Operating Incident 3). Nevertheless, once again the nitrifying organisms slowly re-establish themselves from t_{65} onwards to t_{111}. The *nitrobacter* generally appear less sensitive to oscillatory behaviour than do the *nitrosomonas* bacteria: the growth of *nitrobacter* is more steadily maintained and possibly even slightly faster than the growth-rate of nitrosomonas. By t_{112}, however, conditions are changing such that at the end of the experimental period both species of organism have been reduced to very low concentrations and nitrification has more or less ceased. Here too we are again left with no clear insight into why there should be such a quick reversal of the activated sludge unit's capacity for nitrification.

Thus, in general one may conclude that the model, while it is partially substantiated by the observed behaviour, does not contain a realistic description of the sudden losses of nitrification that can occur in practice. The process of nitrification seems overall to be highly sensitive to the way in which the unit is being operated.

4. AN ACTIVATED SLUDGE PROCESS SIMULATION MODEL

The "ideal project" specification of Section 1 for process modelling and control system synthesis would now require an approximately *verified* simulation model to be available for the evaluation of design control schemes. As we have seen with the preceding section, however, model verification proves to be a largely unattainable goal since the field data do not permit any reasonable comparison of models for carbonaceous BOD and SS substrate removal. The dynamic model for nitrification from Section 3.3 must, therefore, be combined in this instance with a theoretical, i.e., essentially not verified, model for carbonaceous substrate removal, where the details of this latter are mostly drawn from the literature (Curds, 1973; Busby and Andrews, 1975; Olsson, 1975). The main purpose of this intermediate section is a brief discussion of the qualitative features of the activated sludge simulation model - a more complete treatment is to be given in an additional report. An appreciation of the model is relevant only in so much as it conveys an understanding of how various "cause/effect" relationships are simulated and hence how the control rules of Section 5 are designed to manipulate "causes" in order to avoid, or recover from, undesirable "effects".

4.1 Process Biochemistry for the Aerator

All biochemical and microbiological activity is assumed to take place in the aerator portion of the activated sludge unit according to the schematic diagram of Figure 44. The overall microbiological model brings together, as it were, three submodels:

- part (i) - removal of soluble and suspended carbonaceous substrate by heterotrophic sludge bacteria;
- part (ii) - nitrification and the nitrifying bacteria (see also Section 3.3);
- part (iii) - a prey-predator system of dispersed bacteria and attached/free-swimming protozoa.

Part (i) of the model forms the basic characterisation of BOD/MLSS interaction and it is this submodel which often suffices as a complete description of the process in other investigations. A principal modification included in part (i) is the conceptual decomposition of the sludge mass into "stored", "active", and "inert" fractions; this is due to Busby and Andrews (1975). The hypothesis of a rapid initial uptake of substrate by the biological floc originates from this conceptual decomposition - compare with Section 2.2 (Operating Incident 3). The quickly captured substrate is maintained in the stored mass phase; the active mass metabolises the stored mass (not the substrate)- and finally the active mass decays naturally to an inert phase, where this inert phase also includes inorganic and non-biodegradable organic suspended matter. There is provision in the model for the return of some inert mass to a substrate form.

Part (ii) of the model is virtually independent of part (i) at this microbiological level, although as recognised in Figure 44 it is quite possible that some ammonia - N is taken up and released in the metabolism of the heterotrophic sludge bacteria. Furthermore, there may be production of nitrate - N in this same carbonaceous oxidation process. However, all these minor links between parts (i) and (ii) are assumed to be neglibible in the current application of the model. Hence the major interaction between nitrification and BOD/SS removal derives indirectly from the effects of nitrification/denitrification on the loss of solids from the system - see below in Section 4.2.

The relationship between the sludge bacteria subsystem, part (i), and the dispersed sewage bacteria subsystem, part (ii), are in contrast most important. The structure of part (iii)'s prey-predator model is based upon the work of Curds (1973); the purpose of its inclusion is for the simulation of a bulking sludge condition. Unlike the other organisms accounted for in Figure 44 the dispersed sewage bacteria and the free-swimming form of protozoa predator are assumed not to flocculate (settle) and therefore are not compacted in the secondary clarifier. The dispersed bacteria, when present in too high a number, are assumed to be responsible for the inability of the sludge to settle. They are thus interpreted as fulfilling the role of filamentous bacteria as discussed in Section 5. Notice that the possible connection between parts (ii) and (iii) of the model, namely predation of the nitrifying bacteria by the protozoa (Lijklema, 1973), is assumed to be insignificant.

A further property of the simulation model, which is implicit in Figure 44, is that of the aerator dissolved oxygen (DO) balance, here defined as a function of the following source and sink terms:

- rate of addition of DO from the air blowers,
- rate of removal of DO in aerator effluent stream,
- rate of DO consumption in stored substrate to active mass metabolism,
- rate of DO consumption by respiration of the active mass,
- respective rates of DO uptake by ammonia - N to nitrite - N conversion and by nitrite - N to nitrate - N conversion.

The effects of variations in aerator DO levels are primarily those of the *preferential enhancement* of dispersed bacteria and nitrifier growth-rates over the growth-rate of sludge bacteria at higher concentrations of DO. The model thereby simulates the observed tendency (at Norwich) for aerobic filamentous bacteria to prosper under conditions of over-aeration. It is assumed for the simulation that the available automatic closed-loop control of DO maintains the desired DO set-point. Alternatively when the aerator oxygen demand rises to the maximum air blower capacity, or drops to the minimum air blower rate required for adequate mixing, the dissolved oxygen balance computes accordingly the resultant (non set-point) DO value. In the event that a conservative toxic substance enters the plant (see also Figure 44) the model will respond by registering a rapid drop in air blower input with a subsequent increase in aerator DO content above its desired level. The effects of a toxic substance are simulated as increased death-rates (as opposed to decreased growth-rates) for the active mass, dispersed sewage bacteria, attached protozoa, and nitrifying organisms.

The overall organisation of Figure 44 reflects the earlier characterisation of process behaviour given in Figure 40. For example, we have classified the model into the groups of input disturbance (cause) variables, $\underline{d}$, the state variables, $\underline{x}_m$ and $\underline{x}_u$, and the output response (effect) variables, $\underline{z}$. Notice then, that the air blower input is placed in a quite separate category, $\underline{u}$, as a *control variable*. The relationships between the output variables $\underline{z}$ and manipulation of the control variables $\underline{u}$ will, of course, be the subject of Section 5.

4.2 Compaction Ratio and Solids Settling in the Clarifier

Despite several attempts at greater sophistication, dynamic models of the clarifier settling behaviour remain in a largely primitive state (see Olsson, 1975). Yet it is in the clarifier that the quite undesirable situations of bulking or rising sludge, among other factors, determine the important residual suspended solids (SS) concentration of the clarified effluent. Our simulation model of the activated sludge unit probably differs from the majority of its predecessors in its description of the clarifer compaction and clarification functions. The model's inadequacy as a representation of "reality" is also strongly tied to this section of the simulation; this is regrettable but, for the time-being, unavoidable.

In the same manner as before in Section 3.3, the behaviour of the clarifier is assumed to be purely a matter of fluid mechanics. Since the aerator is idealised as a CSTR (compare with Figure 42(b)), each component of the microbiological model, i.e., the state variables in Figure 44, passes into the clarifier at the same concentration as that existing in the aerator. According to Figure 45 those components which do not settle with the biological floc, such as the dispersed bacteria, unmetabolised substrate, and so on (see Figure 44), pass through the clarifier into the overflow and underflow recycle with no change of concentration.

Those components which settle and are compacted with the biological floc are assumed to be withdrawn in the recycle sludge at a concentration C times as great as their respective concentrations in the clarifier mixed liquor influent stream. The ratio C is denoted by the *compaction ratio*; it is the determination of this factor which is fundamental to the clarifier model's settling and clarification properties. Although the idea of a compaction ratio is the same as that introduced earlier, the computation involved here is quite different from the expression given in Section 3.3.

The qualitative features of the computation for the solids compaction ratio, C, are shown in Figure 46. We see that C is a function of sludge recycle and surplus sludge wastage rates and of the clarified effluent suspended solids (ESS) concentration. These two relationships express respectively the dependence of sludge thickening on sludge underflow withdrawal rate and the intuitive idea that if a greater (lesser) portion of solids is lost over the clarifier weir then fewer (more) solids are available for recycling purposes. In turn ESS, which is assumed to determine in part the effluent total BOD (ETBOD), is described as a function of three factors: the influent solids loading to the clarifier; a bulking sludge condition; and a rising sludge condition. The bulking sludge condition is simulated as an occurrence which is precipitated by the increase of the dispersed (or filamentous) bacteria concentration above an arbitrarily specified threshold level. The rising sludge situation is likewise simulated as an event which depends upon *both* a high level of nitrate - N concentration in the aerator effluent *and* a long retention time of the compacted solids in the clarifier. Thus the clarifier model is dependent upon the behaviour of the aerator biochemistry through the nitrate - N and dispersed bacteria concentrations. And vice-versa the aerator model is dependent upon the clarifier fluid mechanics through the compaction ratio C and the flow-rate of recycled sludge.

The model described thus embodies most of the qualitative features required for a simulation against which the control rules of the next section can be tested.

5. PROCESS CONTROL RULES

In a controlled process the function of the controller can be defined as follows: the controller collects all available information, i.e., measurements $\underline{d}$ and $\underline{z}$ in Figures 40 and 44, from the system being controlled and uses this information to manipulate some of the system variables, $\underline{u}$ in Figure 44, in order to bring about *some desired process performance.* Usually this desired process performance is gauged by the behaviour of the response variables $\underline{z}$ and their closeness to a set of desired values, $\underline{r}$ say. The aim of this section is to discuss the broad objectives for desirable activated sludge process performance and to discuss the formulation of control rules for the manipulation of the controlling variables $\underline{u}$.

First, however, it is necessary to outline some principal features of standard control engineering in order to see why our present approach is somewhat different from conventional control system design procedures.

5.1 Conventional Process Control: Some Principal Themes

Figure 47 shows a rearrangement of Figure 40 with the addition of two basic elements of controller design, the *feedforward* and the *feedback* controller principles. The activated sludge process depicted in Figure 1 in fact contains one example each of the application of the feedforward and feedback controllers; these examples will serve to illustrate our argument.

The *feedforward principle* is concerned with cancelling out the effects on the output variables ($\underline{z}$) of the *measured disturbances* of process behaviour ($\underline{d}$). In other words, information about the disturbance is relayed to the controller which then initiates control actions designed to nullify the effects of these disturbances before they "reach" the outputs. Now consider the recycle sludge flow-rate control of Figure 1 in the context of Figure 47, where for the sake of the example the absence of the feedback control loop can be assumed. In this case the measured disturbance variable, d, is the settled sewage influent flow-rate and the controlling variable, u, is the recycle sludge flow-rate. The notion of recycle control as a fixed proportion (ratio) of the influent flow is one of attempting to attenuate fluctuations in the substrate/micro-organism ratio conditions of the aerator and thus to dampen, but not altogether cancel, the variations in the clarified effluent quality. The important point for understanding the feedforward control principle is that the controller utilises measured information about the incoming input disturbances.

The feedforward controller principle has, among other drawbacks, the disadvantage that it does not utilise a measurement of the output behaviour ($\underline{z}$) and therefore cannot take account of any inevitable misalignment between desired and actual performance of the process. Such errors between desired and actual output responses, as detected by ($\underline{z}$ - $\underline{r}$), might arise from those input disturbances ($\underline{\xi}$) which are not measured and about which we have no information. The *principle of the feedback controller* is thus one of using information on the process output behaviour ($\underline{z}$) in order to attenuate, or suppress, the undesirable effects of disturbance variables which are not measured, i.e., $\underline{\xi}$. Recalling Figure 1 once more we see that the closed-loop automatic control of aerator DO levels fulfils the role of a feedback controller - supposing that the feedforward controller component is absent in Figure 47. For example, a number of unforseen and undetected variations in the influent substrate strength or the respiration rate of the biological floc may affect the aerator DO level (z). The air blower input (u) is then manipulated through the feedback controller to correct for any tendency of the actual DO level to be disturbed away from its set-point value (r).

It is, of course, quite feasible that one would wish to combine the advantages of both types of controller. Suppose that it is possible to feed back on-line measurements of the aerator MLSS concentration to the controller. In this situation a feedforward/ feedback controller might manipulate the recycle sludge flow-rate (u) according to some balance between the controller's knowledge of both the incoming disturbances ($\underline{d}$), e.g., influent flow-rate, and the output response ($\underline{z}$), e.g., MLSS concentration. Similarly, if a rapid measure of the influent settled sewage oxygen demand were available, a feedforward/feedback controller-based on the existing feedback controller of Figure 1 - can be visualised for manipulation of the air blower input.

Having introduced these two basic principles of control, our purpose is to examine those attributes of a given system which make it amenable to control engineering design procedures. This will lead to the important question of:

- How relevant are most "conventional" control engineering design procedures to a comprehensive control of the activated process?

The large majority of successful control engineering design applications depend upon the following:

- A valid and accurate model of process dynamic behaviour.
- The availability of a reliable, robust instrumentation for the rapid collection of information about actual process performance.
- For the case of mass transfer processes, the capacity to store flows and substance masses.
- The ability to specify clear, precise, unambiguous process performance objectives.

Let us answer the question posed above by dealing with each of these points in turn.

Firstly, from the preceding analysis of Sections 3.3 and 4 it is doubtful whether we can conclude that we have a valid and accurate model of the activated sludge unit. Thus to take the mathematical analytical properties of the model that we do have - a considerable simplification of a complex process - and to base the control system design on these properties may lead to a very inadequate controller.

In the second place, while it is true that on-line sensors for the water and wastewater industries are improving in scope and accuracy, many of the variables that can now be measured, e.g., MLSS, COD, relate only to the macroscopic characteristics of activated sludge behaviour - see Section 3.1 and Figure 40. And perhaps more important still, such macroscopic instrumentation, since it cannot communicate the microscopic detail of the biological community, is not altogether capable of identifying, say, a bulking or a rising sludge situation; nor does it eliminate the importance of *qualitative* observations of sludge odour and colour.

The third item - capacity for storage - refers to the implementation of the control action once this has been determined by the controller. The problem can be best illustrated by an oft-quoted example: in order to suppress many of the variations induced by large incoming substrate fluctuations, equalisation tanks have been proposed; equivalently, the *flexibility* of operation afforded by a large buffer capacity of sludge, as for example in the clarifier, would also seem desirable. In any event, when the plant has been built, i.e., after the design stage, operational control will always be limited in its effectiveness by any such shortcomings of process design.

Lastly, the ability to state precise objectives has two aspects of interest. On the one hand, in contrast to the petrochemical industries, it is not natural to specify precise effluent BOD and ammonia - N concentrations which the activated sludge controller must maintain at all times (we shall return to this point in Section 5.2.2). On the other hand, again in contrast to the petrochemical industries, if clear objectives for the nature of process operation are not given, and if tangible economic penalty functions for bad performance cannot be imposed, then there may be little incentive to innovate control.

After taking stock of all four points, we can summarise by saying that conventional control engineering procedures have, at least for the present, a qualified relevance in wastewater treatment problems. As evidenced by the installation of two control loops on the activated sludge plant at Norwich, these methods can be usefully applied when some, if not all, of the desirable attributes of the system obtain in practice. But this does not necessarily constitute a *comprehensive* control of the activated sludge process. The applications we have cited certainly assist in the day-to-day running of the plant; yet they do not resolve all the issues and decisions that are required to determine, say, the manipulation of sludge wastage rate, or the setting of the desired recycle ratio and dissolved oxygen values to be maintained by individual control loops.

Thus a conventional control analysis of the activated sludge process would not necessarily encompass some of the most important qualitative observations and quantitative decisions and actions of plant operation and management. Above all a conventional analysis ignores that particular blend of expertise that a plant manager can bring to bear upon controlling what is, in fact, a very difficult process to control. For the next section, Section 5.2, we shall attempt to address the following question as the key theme of our approach to the control of the activated sludge process:

- Should automation and control always seek to eliminate the human element from the control loop?

One point about this question deserves special mention for it brings us to the crux of the difference between "automation" and "control". *Automation* is here understood as the automation of information retrieval and communication and the automation of implementing control actions. *Control* is interpreted as the use of the information retrieved for the determination of the control actions to be implemented. In this latter context it is proposed that the human element should not be removed. Rather, such valuable empirical experience, as opposed to the analytical properties of a set of mathematical equations, should be exploited in the design of a controller for the activated sludge process.

5.2 An Alternative Approach to Activated Sludge Control

Since it is not intended to employ the model of Section 4 (and Section 3.3) as a tool in the analytical design of a controller, it may be useful to point out that the model is to be applied as a simulation for trial and error evaluation of various potential control rule configurations. These control rule configurations are referred to subsequently either as the controller or as the control algorithm; the particular set of rules presented here are, in effect, a *first version* of the controller.

If it is accepted that a plant manager has considerable previous experience in controlling an activated sludge unit, the question must be answered as to how such largely qualitative, sometimes almost intuitive, understanding can be utilised in a formal quantitative control algorithm. For instance, if asked to formulate a set of operating rules for activated sludge control it seems natural to start thinking in terms of statements like:

(i) "If MLSS concentration low and decreasing then decrease sludge wastage rate".

(ii) "If effluent SS concentration much greater than 30 gm^{-3} then increase recycle ratio by a lot temporarily".

(iii) "If effluent total BOD concentration is high and if air blower input demand is abnormally low then check for toxic spillage".

The difficulties of quantifying a "low MLSS concentration" or of implementing the control action "increase recycle ratio by a lot" are immediately recognisable. Nevertheless, if it were possible to obtain a complete list of such rules, then it might also be possible to use them as a support service in the day-to-day decisions which have to be made for activated sludge process control. What is really required is both a framework for evolving a consensus of opinion on appropriate operating rules, and a calculus for manipulation of these rules. The following, then, is a first attempt at deriving a controller based on the kinds of qualitative, linguistic statements quoted above. All of the control statements and definitions reported below are derived from a series of discussions between the first two authors of this article.

5.2.1 The Concept of Fuzzy Control

The idea of using *fuzzy* variables as a means of describing *qualitative* relationships is due to Zadeh (1965), and from this original idea the notion of fuzzy control has evolved (see, for example, Tong (1977)). The term fuzzy, arises rather naturally because of the inherent imprecision of a variable with a quantity "low" or "a lot".

Figure 48 shows that the fuzzy control system synthesis problem can be separated into three categories (as labelled in the diagram):

(1) The translation of (quantitative) operational measurements and forecasts into a (qualitative) framework suitable for manipulation by the fuzzy controller.

(2) The derivation of the list of control rules and logic statements, i.e., the specification of the controller.

(3) The re-interpretation of (qualitative) decisions into (quantitative) control actions.

Part (2) of the overall problem implies in practice a knowledge of the calculus of fuzzy set operations; however, this is not of primary concern here. Each subproblem will thus be dealt with in turn, but before doing so it is necessary to return to a discussion of some basic characteristics of fuzzy variables.

Fuzzy Variables: Suppose that we call MLSS concentration a *fuzzy variable*. And now, in accordance with the statement made earlier, let us consider what is meant by the *fuzzy set* (B) of values for MLSS concentration which are low, i.e.,

$$B = \{\text{MLSS concentration low}\} \quad .$$

It is possible to define, see Figure 49, a *membership function* $\mu(B)$ which expresses the degree of membership of any given MLSS concentration in the fuzzy set {MLSS concentration low}. Hence for $\mu(B) = 1.0$ the corresponding MLSS concentration is clearly considered to be low, while for $\mu(B) = 0.0$ we might say that MLSS concentration is quite definitely not low. Where there are values of $\mu(B)$ between 0 and 1, the associated range of MLSS concentrations might be thought of as not exactly low but something approximating this condition. Similarly the fuzzy sets A, C, D can be defined (see also Figure 49) as alternative characterisations of MLSS concentrations, where A, C, and D are,

A = {MLSS concentration very low}

C = {MLSS concentration medium}

D = {MLSS concentration high} .

Notice that certain values of MLSS concentration, e.g., about 2600 gm^{-3}, are somewhat indeterminately placed with a partial membership of more than one fuzzy set; in this case 2600 gm^{-3} MLSS concentration would belong to the set low (B) with a degree of membership 0.9, and it would also belong to the set medium (C) with a degree of membership 0.4, say.

Problem 1 - Input Information Translation: A number of such fuzzy sets can be defined for each input fuzzy variable, where input refers here specifically to information input to the controller - see Figure 48. From the preceding discussion of Section 5.1, with reference to Figure 47, the input information to the controller can be in the form of process input disturbance measurements ($\underline{d}$) and output response measurements ($\underline{z}$). Alternatively, with reference to Figure 41 and Section 3.2, the input information can be of a type which represents reconstructed estimates of the process state variables ($\hat{\underline{x}}_m$, $\hat{\underline{x}}_u$) or even forecasts and predictions from a mathematical model - see also Section 6.2. But from whatever source the information is retrieved, it will still usually be in the manner of a precise real number and it will require *translation into the framework of fuzzy set membership functions.* This could be achieved directly by reading off values from the membership function plots of Figure 49. However, it is more convenient, especially for reasons of computer storage, to assign certain levels of degree of membership to discrete ranges of the fuzzy variable as given in Table 3. If a measurement of MLSS concentration of 3460 gm^{-3} is obtained, for example, then it is translated as having 0.6 degree of membership of the set C and 0.2 degree of membership of the set D. And from this point onwards the controller uses not the number 3460 gm^{-3} but the numbers $\mu(C) = 0.6$ and $\mu(D) = 0.2$ for the characterisation of the current status of MLSS concentration in the activated sludge aerator.

Table 3. Fuzzy set definitions for MLSS concentrations.

MLSS concentration (gm^{-3})	< 1500	1500-2000	2000-2400	2400-2700	2700-3000
Very small, $\mu(A)$	1.0	0.9	0.3	0	0
Small, $\mu(B)$	0	0.1	1.0	0.9	0
Medium, $\mu(C)$	0	0	0	0.6	1.0
Large, $\mu(D)$	0	0	0	0	0

MLSS concentration (gm^{-3})	3000-3300	3300-3600	3600-4000	> 4000
Very small, $\mu(A)$	0	0	0	0
Small, $\mu(B)$	0	0	0	0
Medium, $\mu(C)$	1.0	0.6	0	0
Large, $\mu(D)$	0	0.2	0.9	1.0

Problem 2 - the Controller Specification: The principal feature of the fuzzy controller is, in our present context, the list of logical statements about desirable control actions as responses to, say, undesirable upsets in process performance. Merely for the sake of illustration, and in order not to preempt the more detailed discussion of the rules evolved for the Norwich plant (Section 5.2.2), we might imagine the controller specification to be the following set of statements:

(1) "IF" {MLSS concentration low} "AND" "IF" {MLSS concentration decreasing slowly} "THEN" {Decrease SWR by a small amount}.

(2) "IF" {Effluent ammonia - N concentration high} "AND" "IF" {Effluent SS concentration normal} "THEN" {Decrease SWR by a large amount} "AND" {Increase DOSP by a large amount}.

(3) "IF" {Effluent SS concentration high} "THEN" {Increase RRSP by a lot temporarily}.

where the additional abbreviations used are:

SWR = (surplus) sludge wastage rate

DOSP = dissolved oxygen concentration set-point (desired value)

RRSP = recycle ratio set-point (desired value)

These three rules, together with an available calculus for fuzzy set operations, permit the computation of a fuzzy control decision, or action, given the input information on the system's (fuzzy) operational state as above. It is helpful to normalise the controller and its computational processes as a kind of look-up table: the particular combination of operational conditions determines the entry in the look-up table, and for each entry there will be an associated combination of control actions.

Problem 3 - Interpretation of the Output Control Action: We are now in a position to consider Problem 3 of Figure 48. As with the controller input variables so too can the output variables be defined in fuzzy terms. Figure 50 gives example definitions of four fuzzy sets for the control variable *change* of sludge wastage rate (denoted ΔSWR). The computations of the controller algorithms lead to an output membership function, say Figure 51, which then has to be interpreted as a unique choice of ΔSWR. The point is that even though the control command "decrease SWR by a small amount" might be intuitively comprehensible, it is in fact necessary to specify a precise increase of, say 1.5 or 2.0 or 2.5 m^3hr^{-1} which is related to some pump or valve setting. For the computed fuzzy control action of Figure 51 it would be reasonable to implement an increase of $1.5m^3hr^{-1}$ in SWR. The first reason for this choice is that the output control variable at 1.5 m^3hr^{-1} has a 1.0 degree of membership of the computed fuzzy set. And secondly those fuzzy input variable conditions which suggest a larger increase in SWR - indicated by the right-hand tail of the membership function of Figure 51 - are only a weak influence on the choice of output control action.

Unfortunately, the final control decision is not always so easy to interpret. In Figure 52 there is obviously a conflict between decreasing the SWR by a small amount or increasing it by a large amount; in addition neither peak in the computed output set has a 1.0 degree of membership. This raises several problems and not all of these problems have been fully resolved yet in the theoretical aspects of fuzzy control. There are two questions of particular relevance: why is it that such an ambiguous and inconclusive output command function can arise; and how should one implement control under such ambiguity? To answer the first question we may observe that when two or more rules determine a value for the same control variable there always exists a possibility for in-built conflict in the set of control rules. When an inconclusive control command is given, it is probable that the operating conditions of the plant are at a point in the control look-up table - recall this analogy from above - where no control rule has been specified from the previous experience of the plant manager. In answer to the second question we may note that one method of interpretation is to take that value of the control variable which represents the centre of area point of the output fuzzy set. For Figure 52 such an approach suggests implementing no change of SWR, or something not deviating significantly from that, which in a sense is consistent with the conflicting advice provided by the controller.

5.2.2 Rules and Fuzzy Set Definitions for the Norwich Plant

Three control variables are available for manipulation at the Whitlingham (Norwich) Treatment Works:

- The rate at which diffused air is supplied to the aerator.
- The rate of recycle sludge flow.
- The rate of surplus sludge wastage.

In our specification of a fuzzy controller the first two control variables will be treated in an implicit fashion because of the following. It is assumed that the fuzzy controller is concerned only with determining values for the *aerator DO level* and *recycle ratio set-points*. Thereafter it is further assumed that the already existing automatic control loops (Figure 1) will maintain actual DO concentrations and recycle ratios at their respective desired set-points. Thus instead of the above three variables, the three control variables will be referred to as:

- The aerator dissolved oxygen set-point (DOSP).
- The recycle ratio set-point (RRSP).
- The rate of surplus sludge wastage (SWR).

A fourth control variable can be manipulated at Norwich, namely the influent settled sewage flow (see Section 2.2). However, since the objective is to derive a rather more general controller, although the controller will inevitably be substantially specific to Norwich, the possibility of this fourth control variable is discounted.

A summary of some of the most important desirable (and undesirable) operating performance conditions related to each of the three control variables is given in Table 4.

Our discussions yielded next the "portfolio" of control rule groups delineated in Tables 5 → 11 which correspond to the following "set-piece" events, incidents, and observations

(1) Control of MLSS concentration (Table 5).

(2) Bulking sludge due to aerobic filamentous bacteria (Table 6).

(3) Rising sludge due to denitrification in clarifier (Table 7).

(4) High effluent total BOD concentration (Table 8).

(5) Loss of nitrification (Table 9).

(6) Normal operating conditions (Table 10).

(7) Qualitative observations (Table 11).

In Tables 5 → 11 those observations/rules categorised as (a), (b), etc., denote essentially separate events and control reactions. For completeness the portfolio of rules also includes diagnostic information on the plant operating status.

No doubt the reader will from hereon perceive a series of compromises made for the purposes of the study but which successively remove the problem formulation and solution away from reality. Hopefully these compromises are not too great; later it should be possible to lift their restrictions. A first very significant compromise is the assumption that an effluent total BOD (or some other measurement of unconverted soluble/suspended substrate) is immediately available for control purposes - more will be said of this subsequently. Secondly, it is assumed that loss of nitrification is detected by the ammonia - N measurement alone and in preference to any measurement of a nitrogenous BOD such as might be deduced from the difference between total and carbonaceous BOD measurements.

Table 4. General objectives for individual control variables.

Control Variable	Desirable Objectives
Aerator dissolved oxygen set-point (DOSP)	o Governs the general rate of waste substrate removal. o Ideally just sufficient air input is required as maintains a small residual DO concentration. o For nitrification slightly higher residual DO concentrations are required. o Note - Higher residual DO concentrations demand excessive air input (increased operational costs); they can promote the growth of undesirable filamentous bacteria; they may cause physical dispersion and breakdown of biological floc through excessive agitation.
Recycle ratio set-point (RRSP)	o Governs the general rate of waste substrate removal. o Governs the balance of total solids storage between aerator and clarifier. o Note (i) - A low recycle sludge may imply the return of a poor quality sludge which has been subjected to a longer anaerobic phase in the clarifier; this may also promote denitrification and problems of rising sludge. o Note (ii) - A high recycle sludge rate may be unnecessary and therefore incurs excessive plant operational costs.
Sludge wastage rate (SWR)	o Used to maintain desirable MLSS levels. o Used to achieve desirable sludge loading factor, i.e., ratio of influent total BOD/MLSS concentration. o Influences both nitrification and general carbonaceous substrate removal. o Note - A daily decision is taken regarding the current rate of sludge wastage.

Table 5. Operating rule group (1) - control of MLSS concentration.

	Observation/Event/Objective		Diagnostic/Control Action
(a)	MLSS high and increasing	→	Increase sludge wastage rate
(b)	MLSS low and decreasing	→	Decrease sludge wastage rate
(c)	MLSS low and decreasing rapidly	→	Set sludge wastage rate to zero
(d)	RASS high (thick sludge)	→	Modify SWR chosen from (a) by small decrease in SWR
	RASS low (thin sludge)	→	Modify SWR chosen from (a) by small increase in SWR
(e)	MLSS decreasing rapidly and RASS increasing rapidly	→	Check for faulty operation of pumps withdrawing sludge from clarifier

<u>Abbreviations</u>: MLSS = Mixed liquor suspended solids
RASS = Return activated sludge suspended solids
SWR = Surplus sludge wastage rate.

Table 6. Operating rule group (2) - bulking sludge due to aerobic filamentous (dispersed) bacteria.

Observation/Event/Objective		Diagnostic/Control Action
SBL rising; ESS $< 30\ \text{gm}^{-3}$		
↓		
SBL rising; ESS $> 30\ \text{gm}^{-3}$		
↓		
Attempt to lower SBL and check condition later	→	Increase recycle sludge rate for a short period*
↓		
SVI measurement high: examine presence/absence of (aerobic) filamentous bacteria		
↓		
Prevent growth of (aerobic) filamentous bacteria	→	Reduce DO set-point in aerator**

Abbreviations:

ESS = (Clarified) effluent suspended solids
SBL = Sludge blanket level in clarifier
SVI = Sludge volume index

*A similar rule is programmed on the process computer at Norwich; it is activated by a signal from the sludge blanket level indicator.

**For anaerobic filamentous bacteria this rule would be reversed.

Table 7. Operating rule group (3) - rising sludge due to denitrification in the clarifier.

Observation/Event/Objective		Diagnostic/Control Action
SBL rising; ESS < 30 gm^{-3}		
↓		
SBL rising; ESS > 30 gm^{-3}		
↓		
Attempt to lower SBL and check condition later	→	Increase recycle sludge rate for a short period
↓		
Sludge observed to be "gassing"		
↓		
Prevent nitrification in aerator	→	Increase sludge wastage rate

Table 8. Operating rule group (4) - high effluent total BOD.

Observation/Event/Objective	Diagnostic/Control Action
ETBOD is high; ESS < 30 gm^{-3}	
↓	
High ETBOD is not caused by a high nitrogenous BOD	
↓	
(a) Hydraulic/organic overloading of plant	→ Decrease sludge wastage rate; possibly increase recycle sludge rate.
↓	
(b) Air blower input demand is abnormally low; aerator DO concentration rising	→ Check for toxic spillage in plant

<u>Abbreviations</u>: ETBOD = Effluent total BOD.

Table 9. Operating rule group (5) - loss of nitrification.

Observation/Event/Objective	Diagnostic/Control Action
Effluent ammonia - N concentration is high; ESS < 30 gm^{-3}	
↓	
Alter plant environment to achieve full nitrification	→ Decrease sludge wastage rate; possibly increase aerator DO set-point

Table 10. Operating rule group (6) – normal operating conditions.

Observation/Event/Objective		Diagnostic/Control Action
ESS, ETBOD, MLSS, Ammonia – N, and RASS are within normal desired ranges ↓		
Return all three control variables to within normal settings if previous control actions caused these variables to be set at extreme values	→	Reduce high SWR (vice-versa) Reduce high RRSP (vice-versa) Reduce high DOSP*

*The lowest operating DO set-point value is assumed to be 0.5 gm^{-3}; this is also assumed to be the most desirable DO set-point

Table 11. Operating rule group (7) – qualitative observations.

Observation/Event/Objective		Diagnostic/Control Action
(a) Sludge odour (recycle stream)	→	Sludge requires additional aeration; increase DOSP
(b) Sludge colour (recycle stream)	→	Sludge loading factor is too high; increase RRSP
(c) Sludge condition: settleability; "gassing"; and foaming	→	Inherent ability of sludge to form a floc; release of nitrogen gas suggesting denitrification in the settler.

General Operating Philosphy: The rules of Tables 5 → 11 are summarised in an abbreviated form of controller logic statements in Table 12. For a list of abbreviations used in Table 12 see Table 13. Table 12 represents the starting point for the evaluation of fuzzy controller performance by reference to the simulation model of Section 4. Notable compromises in the translation of Tables 5 → 11 into Table 12 are therefore the omission of diagnostic statements and qualitative observations which simply cannot be tested with the simulation. Using the shorthand notation of Table 12 the control statements translate back thus, e.g., for Rule 10,

> "IF" {ESS is large} "AND" "IF" {Aerobic filamentous bacteria are causing a bulking sludge} "THEN" {Decrease DO set-point by a large amount}.

from which it is possible to point out the following. The variables FIL and DENIT in Table 12 and 13 are *not* fuzzy variables, since it seems unrealistic to "fudge" the issues of whether there is a rising or a bulking sludge condition. Hence these variables can have values 0 or 1 depending respectively upon the absence or presence of the condition (see also Section 4).

Table 12 perhaps best illustrates some fundamental principles underlying the operating control philosophy for the activated sludge unit. Inspection of the list of fuzzy input information to the controller indicates that seven variables - ETBOD, ESS, MLSS, RASS, NH_3-N, FIL, DENIT - fall under the category of output response observations, $\underline{z}$, in Figure 47. A further variable, ΔMLSS, though representing a rate of change of the state of the process, may also be considered to be a response observation ($\underline{z}$). The remaining three input variables, DOSP, RRSP, SWR, provide information about the current status of the desired control variable set-points ($\underline{r}$), or in other words information about the current values of the control variables themselves ($\underline{u}$). The significant feature of the three controller output fuzzy variables, ΔDOSP, ΔRRSP, ΔSWR, is that they are concerned with control actions that implement *changes* to the existing values (levels) of

Table 12. Fuzzy controller statements.

Portfolio Group	Rule	ETBOD	ESS	MLSS	RASS	NH_3-N	ΔMLSS	DOSP	RRSP	SWR	FIL	DENIT	ΔDOSP	ΔRRSP	ΔSWR
1	1			L			MP								SP
	2			L			LP								LP
	3			VS			SN								SN
	4			VS			MN								LN
	5			L	L										SN
	6			L	S										SP
2	7		M											SP	
	8		L											LP	
	9		M								1		SN		
	10		L								1		LN		
3	11		M									1			SP
	12		L									1			LP
4	13	M	S			S									SN
	14	L	S			S									LN
5	15		S			M							SP		
	16		S			M									SN
	17		S			L							LP		
	18		S			L									LN
6	19	S	S	M	M	S		L					LN		
	20	S	S	M	M	S			S					SP	
	21	S	S	M	M	S			L					SN	
	22	S	S	M	M	S				S					SP
	23	S	S	M	M	S				L					SN

Table 13. List of abbreviations used in Table 12 - for fuzzy set definitions see Tables 14 → 29.

Abbreviation	Definition
ETBOD	Effluent total BOD
ESS	Effluent suspended solids
MLSS	Mixed liquor suspended solids
RASS	Recycle activated sludge suspended solids
NH_3-N	Ammonia - N
ΔMLSS	(Daily) rate of change in MLSS
DOSP	Aerator dissolved oxygen set point
RRSP	Recycle ratio set-point
SWR	Sludge wastage rate
FIL	Presence of filamentous bacteria (bulking sludge)
DENIT	Presence of denitrification (rising sludge)
ΔDOSP	Change of dissolved oxygen set-point value
ΔRRSP	Change of recycle ratio set-point value
ΔSWR	Change of sludge wastage rate
VS	Very small
S	Small
M	Medium
L	Large
SN	Small negative (decrease)
MN	Medium negative (decrease)
LN	Large negative (decrease)
SP	Small positive (increase)
MP	Medium positive (increase)
LP	Large positive (increase)

the input control variables. We might denote such variables by $\Delta \underline{u}$ in order to distinguish them from the group of variables $\underline{u}$. Two important characteristics of the general operating philosophy can now be defined:

- The fuzzy controller, for this particular specification, is essentially a feedback controller in the sense of Figure 47, since it does not receive any information on influent or measured disturbances; however, it deals with transformations of $\{(\underline{z} - \underline{r}), \underline{u}\}$ information into control actions of the type $\Delta \underline{u}$, rather than with transformations of error observations, $(\underline{z} - \underline{r})$, into actions $\underline{u}$.
- The basic nature of the controller reflects broadly the following sequence of events: a part(s) of the process is observed to move outside the bounds of desirable performance; a number of *changes* are made to the current *levels* of the controlling variables in response to the undesirable situation; sufficient changes are implemented until the offending condition is returned to within desirable limits; lastly, the levels to which the controlling variables have been altered are assessed, and if any of the three (DOSP, RRSP, SWR) lie outside a normally acceptable range they are cautiously changed back to within the acceptable range.

This latter property of the fuzzy controller in Table 12 signifies a substantial departure from the more usual function of a controller which is to determine current levels (settings) for the control variable, $\underline{u}$. Table 12 divides accordingly into Rules 1 → 18, which are response actions conditioned upon various process upsets, and into Rules 19 → 23, which undertake the procedure of re-adjusting the control variable levels once all other operational objectives are satisfied.

A second observation on Table 12 is related to the importance of effluent suspended solids (ESS) measurements. For each of the Rules 7 → 18 the prevailing ESS conditions either dictate the nature of the control action or are required to be satisfactory before control action can be implemented to deal with disturbances not affecting the objective of a properly clarified effluent. A similar observation can be made in respect of the importance of sludge wastage rate, or rather changes thereof, (ΔSWR), as a control action. Twelve of the Rules 1 → 18 specify an alteration in the setting of sludge wastage rate, whereas relatively few changes of dissolved oxygen levels and recycle sludge flow-rates are required by the controller.

The overall operational objectives for the activated sludge unit are implicit in Rules 19 → 23 of Table 12. The interpretation of these operational objectives is linked to the appropriate set definitions (marked by an asterisk) for the fuzzy variables given in Tables 14 → 29. Again, as with the process control rules, the fuzzy set definitions have been derived on the basis of discussions between the first two authors of this report. Referring to Tables 14 and 15, for ETBOD and ESS, the following may be noted: although Royal Commission standards call for an effluent not exceeding concentration levels of 20 gm^{-3}BOD and 30 gm^{-3}SS, it is possible in practice that some control action might be initiated given a satisfactory but deteriorating quality of the effluent. That is to say, the controller provides for operation about some rather *imprecise* (fuzzy) desired maximum values for ETBOD and ESS. By the same token it may also be possible that, although some of the effluent quality constraints are exceeded by a marginal amount, this may not warrant the implementation of a control response.

Two points should be noted with respect to the fuzzy set definitions for the control variables, Tables 27,28,29. Nominally, any of the changes specified by the controller would be carried out once per day in accordance with current management practice. If this practice were altered such that control actions might be taken two or three times each day, then in principle changes of the same magnitude would be implemented. Tables 27 and 29 show that in fact only precise discrete changes to DOSP and SWR can be made in view of the nature of physical constraints imposed by

Table 14. Fuzzy set definitions for effluent total BOD (ETBOD) concentrations. (Note: in this and Tables 15 → 29 the set marked with an asterisk denotes the desirable operating range.)

ETBOD (gm^{-3})	< 10	10-15	15-17.5	17.5-20	20-22.5	22.5-25	25-27.5	27.5-30	30-35	> 35
Small*	1.0	1.0	1.0	0.8	0.3	0.1	0	0	0	0
Medium	0	0	0.1	0.3	0.8	1.0	1.0	0.6	0.2	0
Large	0	0	0	0	0	0	0.2	0.4	0.9	1.0

Table 15. Fuzzy set definitions for effluent suspended solids (ESS) concentrations.

ESS (gm^{-3})	< 20	20-25	25-27.5	27.5-30	30-32.5	32.5-35	35-40	40-42.5	42.5-45	45-47.5	47.5-52.5	>52.5
Small*	1.0	1.0	0.9	0.8	0.3	0.1	0	0	0	0	0	0
Medium	0	0	0.1	0.3	0.9	1.0	1.0	0.9	0.5	0.2	0	0
Large	0	0	0	0	0	0	0	0.2	0.4	0.9	1.0	1.0

Table 16. Fuzzy set definitions for MLSS concentrations.

MLSS (gm^{-3})	< 1500	1500-2000	2000-2400	2400-2700	2700-3000	3000-3300	3300-3600	3600-4000	> 4000
Very small	1.0	0.9	0.3	0	0	0	0	0	0
Small	0	0.1	1.0	0.9	0	0	0	0	0
Medium*	0	0	0	0.6	1.0	1.0	0.6	0	0
Large	0	0	0	0	0	0	0.2	0.9	1.0

Table 17. Fuzzy set definitions for return activated sludge SS (RASS) concentrations.

RASS (gm^{-3})	< 3000	3000-3500	3500-4000	4000-4500	4500-5000	5000-5500	5500-6000	6000-7000	> 7000
Very small	1.0	0.2	0	0	0	0	0	0	0
Small	0.1	0.9	1.0	0.2	0	0	0	0	0
Medium*	0	0	0.1	0.7	1.0	1.0	0.8	0.4	0
Large	0	0	0	0	0	0	0.1	0.6	1.0

Table 18. Fuzzy set definitions for ammonia - N (NH_3-N) concentrations.

NH_3-N (gm^{-3})	< 15	15-17.5	17.5-20	20-22.5	22.5-27.5	27.5-30	30-32.5	> 32.5
Small*	1.0	0.9	0.7	0.2	0	0	0	0
Medium	0	0	0.2	0.9	1.0	0.9	0.2	0
Large	0	0	0	0	0	0.3	0.8	1.0

Table 19. Fuzzy set definitions for nitrogenous BOD (NBOD) concentrations.

NBOD (gm^{-3})	< 7.5	7.5-10	10-12.5	12.5-17.5	17.5-20	20-22.5	> 22.5
Small*	1.0	0.8	0.2	0	0	0	0
Medium	0	0.3	0.9	1.0	0.9	0.3	0
Large	0	0	0	0	0.2	0.9	1.0

Table 20. Fuzzy set definition for rate of change of ESS (ΔESS) concentration.

ΔESS ($gm^{-3}day^{-1}$)	< 10	10-12.5	12.5-15.0	> 15
POSITIVE	0	0.4	0.8	1.0

Table 21. Fuzzy set definitions for rate of change of MLSS (ΔMLSS) concentration.

ΔMLSS $(gm^{-3}day^{-1})$	<-1500	(-1500) (-1000)	(-1000) (-600)	(-600) (-300)	(-300) (-80)	(-80) (+80)	80 300	300 600	600 1000	1000 1500	> 1500
Large Negative	1.0	0.9	0.2	0	0	0	0	0	0	0	0
Medium Negative	0	0	0.6	1.0	0.2	0	0	0	0	0	0
Small Negative	0	0	0	0.2	1.0	0	0	0	0	0	0
Small Positive	0	0	0	0	0	0	1.0	0.2	0	0	0
Medium Positive	0	0	0	0	0	0	0.2	1.0	0.6	0	0
Large Positive	0	0	0	0	0	0	0	0	0.2	0.9	1.0

Table 22. Fuzzy set definitions for rate of change of RASS (ΔRASS) concentration.

ΔRASS $(gm^{-3}day^{-1})$	<-1250	(-1250) (-1000)	(-1000) (-750)	(-750) (-500)	(-500) (+500)	500 750	750 1000	1000 1250	> 1250
Negative	1.0	0.9	0.7	0.1	0	0	0	0	0
Positive	0	0	0	0	0	0.1	0.7	0.9	1.0

Table 23. Fuzzy set definitions for rate of change of nitrogenous BOD (ΔNBOD) concentration.

ΔNBOD $(gm^{-3}day^{-1})$	<-10	(-10) - (-5)	(-5) - (+5)	5 - 10	> 10
Negative	1.0	0.7	0	0	0
Positive	0	0	0	0.7	1.0

Table 24. Fuzzy set definitions for dissolved oxygen set-point (DOSP) value.

DOSP (gm^{-3})	0.5	1.0	1.5	2.0	2.5
Normal*	1.0	0.9	0.8	0.7	0
Large	0	0	0.1	0.4	1.0

Table 25. Fuzzy set definitions for recycle ratio set-point (RRSP) value.

RRSP	0.5	0.6	0.7	0.75	0.8	0.85	0.9	0.95	1.0	1.05
Small	1.0	1.0	0.8	0.2	0	0	0	0	0	0
Normal*	0	0	0.1	0.5	0.9	1.0	1.0	1.0	1.0	1.0
Large	0	0	0	0	0	0	0	0	0	0

RRSP	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.5	1.6	1.7
Small	0	0	0	0	0	0	0	0	0	0
Normal*	1.0	1.0	1.0	1.0	1.0	0.9	0.6	0.2	0	0
Large	0	0	0	0	0.1	0.3	0.7	0.9	1.0	1.0

RRSP	1.8	1.9	2.0
Small	0	0	0
Normal*	0	0	0
Large	1.0	1.0	1.0

Table 26. Fuzzy set definitions for surplus sludge wastage rate (SWR)

SWR (m^3hr^{-1})	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
Small	1.0	1.0	0.9	0.6	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Normal*	0	0	0	0	0	0.2	0.5	0.8	1.0	1.0	1.0	1.0	1.0	0.9	0.7	0.5	0.1	0	0
Large	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.6	0.9	1.0

Table 27. Fuzzy set definitions for change of DOSP (ΔDOSP)

ΔDOSP (gm^{-3})	-1.0	-0.5	0.5	1.0
Large Negative	1.0	0	0	0
Small Negative	0	1.0	0	0
Small Positive	0	0	1.0	0
Large Positive	0	0	0	1.0

Table 28. Fuzzy set definitions for change of RRSP (ΔRRSP)

ΔRRSP	-0.25	-0.2	-0.15	-0.1	0.1	0.15	0.2	0.25
Large Negative	1.0	0.9	0.2	0	0	0	0	0
Small Negative	0	0	0.5	1.0	0	0	0	0
Small Postive	0	0	0	0	1.0	0.5	0	0
Large Positive	0	0	0	0	0	0.2	0.9	1.0

Table 29. Fuzzy set definitions for change of SWR (ΔSWR)

ΔSWR (m^3hr^{-1})	-4	-2	2	4
Large Negative	1.0	0	0	0
Small Negative	0	1.0	0	0
Small Positive	0	0	1.0	0
Large Positive	0	0	0	1.0

the pumps, valves, and blowers involved in the controlling mechanisms. The operating ranges for all three control variables, DOSP, RRSP, SWR (Tables 24,25,26), are also subject to maximum and minimum physical bounds.

To summarise, then, Table 12 can be viewed as the first version of a fuzzy controller for the activated sludge process; for the present, it has not been appropriate to include all the rules and all the variables, e.g., NBOD, ΔESS, ΔRASS, ΔNBOD (Tables 19,20,22,23, respectively), for which we have derived fuzzy set definitions.

6. CONTINUING AND RELATED STUDIES

The *continuing* part of our studies focuses upon the examination of the structure and performance of the fuzzy controller by reference to the activated sludge simulation model of Section 4. Already, certain features are emerging which require special attention; some of these are noted here. *Related studies*, on the other hand, are mainly concerned with the future potential for mathematical model applications in this field; some comment, however, is also offered on parallel studies of operational management of activated sludge units.

6.1 The Controller

The results expected from the analysis of the controller will inevitably be strongly qualified by the fact that the simulation of the activated sludge unit, and in particular the clarifier model, does not accurately reflect "reality". If a part of the controller is found to be unsatisfactory it may imply that part of the model is unsatisfactory and not necessarily that the control statements are incorrect. Nevertheless, even without the simulation studies the preparatory work on the derivation of the controller in Section 5 has revealed insights into the character of activated sludge control and possible directions for further analysis. Several questions are of particular interest:

- How sensitive is the successful performance of the controller to the absence of effluent BOD measurements - Section 5.2.2 and Table 12 would suggest that a majority of the control statements rely upon SS measurements and not BOD measurements?
- Can the performance of the controller be improved by the inclusion of rules and measurements related to *influent disturbances* of the plant, i.e., a feedforward control component? (see also Section 6.2).
- Do the rules of Table 12 contain any inherent conflict situations; can new control statements be devised which give definitive action for those parts of the controller look-up table which account for the many combinations of operating conditions not covered by the current controller?
- Has the discussion of activated sludge control led to the specification of "artificial" rules, that is rules suggested by the analyst rather than by the plant manager?
- And lastly, is the general operating philosophy embodied in the controller essentially a sound basis for control? We have already noted how the nature of the controller differs from what one might have expected. Inspection of Table 12 indicates that the use of recycle ratio set-point (RRSP) control is not clearly defined; for example, in other than normal operating conditions, i.e., for Rules 1 → 18 of Table 12, there is provision only for an increase, with no subsequent decrease, of RRSP. Or alternatively, an overall impression is that most control actions relate to sludge wastage rate (SWR). Thus alterations of RRSP (and of dissolved oxygen set-point) should perhaps be made only when SWR is at a value close to its minimum (zero) or maximum permissible levels; in other words, ΔRRSP is conditional upon the status of SWR. Further, it is necessary to examine potential improvements to be derived from changes in the frequency and timing at which observations and control actions should be taken.

In the present study no attention has been given to the matter of implementing the fuzzy controller on a process computer. This is because we do not yet see the likelihood that such implementation is appropriate or possible - the computer at Norwich, for instance, is currently fully occupied. Ultimately, however, the availability of an on-site, operational fuzzy controller is envisaged primarily as a kind of support service for day-to-day management: the plant manager would be encouraged to interact with the controller in a "conversational mode". But having implemented the controller does not imply that its structure is defined for all time thereafter. Part of the conversational mode of interaction would ideally be allocated to updating the performance of the controller. It is of special interest in this respect to mention the work of Gillblad and Olsson (1977) on the computer control of a medium-sized wastewater treatment plant at Gävle in Sweden. Their approach has several similarities with the proposals of Section 5, in that it connects a certain sequence of control actions with a given fuzzy combination of operational conditions (states). Indeed, Gillblad and Olsson recommend that the controller should be adapted as new empirical experience becomes available for inclusion. Such empirical experience amounts to, for example, the logging of sequences of events that lead to a well identified undesirable operational state, which in turn can be remedied, or better forestalled, by a suitable combination of control actions.

One final aspect of the controller studies is that of the preparation of a questionnaire for circulation among treatment plant managers. Section 5 of this report has been written partly with the intention that it should form the basis of such a questionnaire. An additional feature which might be included would be a more detailed description of the average (qualitative) characteristics of the raw sewage entering the Whitlingham Plant. It is well known that different treatment plants receive sewage of quite different characteristics and that this has a bearing on the way in which the unit processes of treatment are operated. The objectives of the questionnaire would thus not necessarily be to obtain a consensus of opinion on how to manage an activated sludge unit. Instead the questionnaire is regarded as a framework for cataloguing, comparing, and extending the wealth of practical experience that exists on the day-to-day regulation of the activated sludge process.

6.2 Model Applications

So far in this study mathematical models have been employed largely as a means (simulation) for evaluating process control schemes. Other contexts for the application of models are discussed elsewhere, Beck (1977); among these applications, one which is of particular importance concerns the benefits of having operational models installed in an on-site process computer. The main purposes of such models would be to provide, like the fuzzy controller, a support service for decision making and a means of supplementing and restructuring the routine monitored information presented to the plant manager. In the former respect a process model might be used for rapid on-line evaluation of the short-term future consequences (over a period of a few hours, say) of alternative current control actions. In the latter respect, there are broadly two classes of problem to be considered:

- the prediction of future events, typically the expected variations in quality and flow-rate of the settled sewage influent to the aerator,
- the estimation of process state variables (x) from noise-corrupted observations (z); the reconstruction of information about variables ($\underline{x}_u$) which are important for the control function, but which are not directly measured by instruments, e.g., concentrations of nitrifying bacteria (see Figure 41(b) and Sections 3.2 and 3.3).

A good example of the idea of state reconstruction is the use of dissolved oxygen profile measurements along the aerator for estimation of the biological activity of the mixed liquor, see for example Olsson and Andrews (1977).

The mention of noise-corrupted observations raises an issue of special relevance to the application process control: it deals with some possible limits on the accuracy of control. Recalling Figure 47 we notice that the feedback controller operates upon a perceived error between output response observations and the desired set-point values, i.e., $(\underline{z} - \underline{r})$. Yet in fact the real objective of control is not to match the observations $(\underline{z})$ to $\underline{r}$ but to match the actual state of the process $(\underline{x}_m)$ to $\underline{r}$. From the historical point of view the original reason for the development of process state estimation techniques (e.g., the Kalman filter) was just such that the effects of noise ($\underline{\eta}$ in Figure 47), or uncertainty, could be filtered out before applying the control function to the error between state estimate $(\hat{\underline{x}}_m)$ and desired performance $(\underline{r})$. In practice, therefore, one might use the estimates of the effluent ammonia - N concentration in Figure 43(a) for control purposes instead of the measurements.

All this, of course, may not be immediately practicable; but it is worth bearing in mind that it may well become so, and such model applications would then deserve serious consideration.

7. CONCLUSIONS

This report summarises a study in the dynamic modelling and operational control of the activated sludge process; further studies concerned with the evaluation of various controller schemes are still in progress. The major results discussed in the report include the verification against field data of a model for nitrification in an activated sludge unit and the development of a fuzzy controller based on empirical operating experience. Other more detailed conclusions from the study, together with recommendations for future work, are given in the introduction, Section 1, to the report.

The considerable problems and difficulties of the exercise in model identification and verification confirm our previous experience (Beck, 1976) and the experience of others, e.g., Olsson (1976). The quality of field data available for analysis leaves much to be desired. But that is not to conclude that modelling applications should be dismissed, since models may be of significant value in a control context. Indeed, there is good reason to be rather more optimistic about the future of control applications in wastewater treatment. Control engineering embraces a wide variety of control system synthesis techniques: one relatively recent development, namely fuzzy control, seems to be well-suited to the type of conditions, e.g., complex behaviour and limited accuracy of mathematical models, which prevail in a sewage treatment plant. This is an approach to controller design which relies upon an ability to codify empirical experience and not upon the analytical properties of a set of equations.

Hitherto there has been a widespread tendency to concentrate efforts on broadening the scope of measured information available for control. Consequently less thought has been given to the possibilities for improving the ways in which already available measurements can be presented to the plant manager. The potential for the use of models in this context of forecasting, state estimation, state reconstruction, and on-line evaluation of control decisions, is very much unexplored.

ACKNOWLEDGEMENTS

The authors are indebted to a number of people for permission to undertake this study. We should like to thank, therefore, Mr. P. Cotton and Mr. J. Hemsley of the Norwich Sewage Division, Anglian Water Authority, and Professor A.G.J. MacFarlane and Mr. M.D.C. Dyne of the Control and Management Systems Division, University Engineering Department, Cambridge.

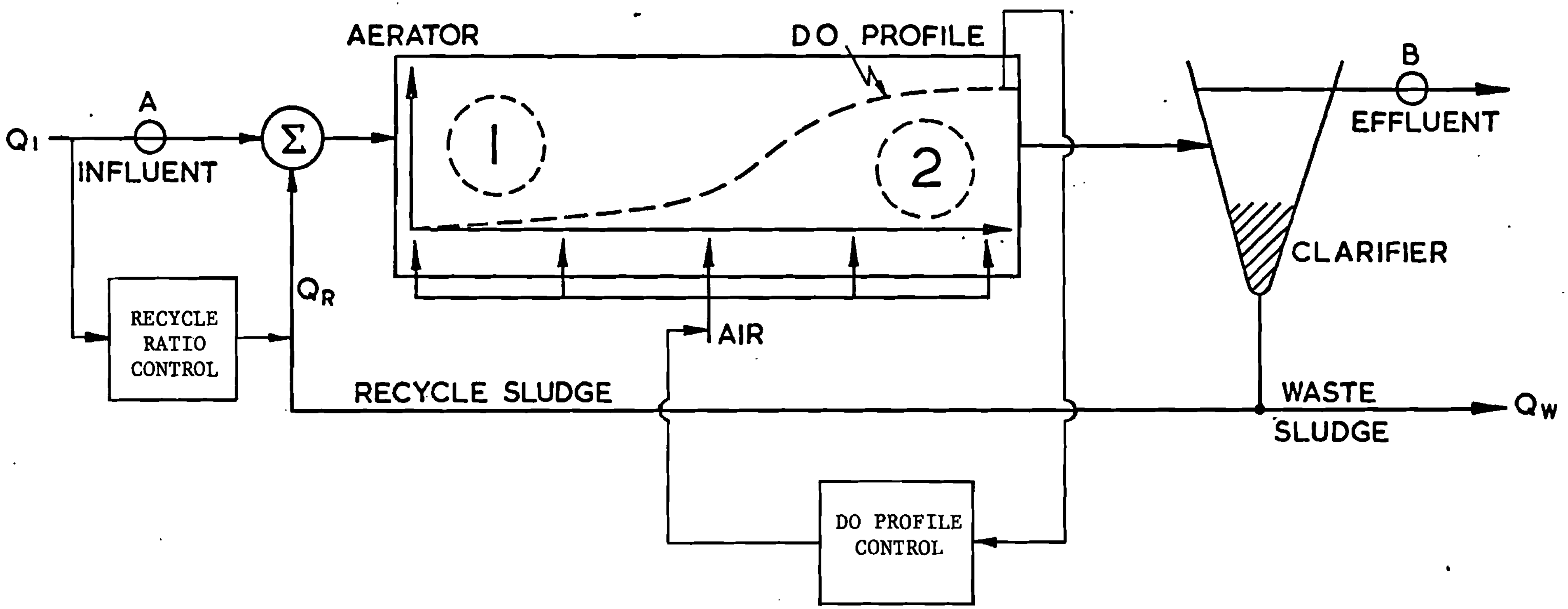


Figure 1. Schematic diagram of the activated sludge unit; control loops are indicated for the Whitlingham (Norwich) Plant.

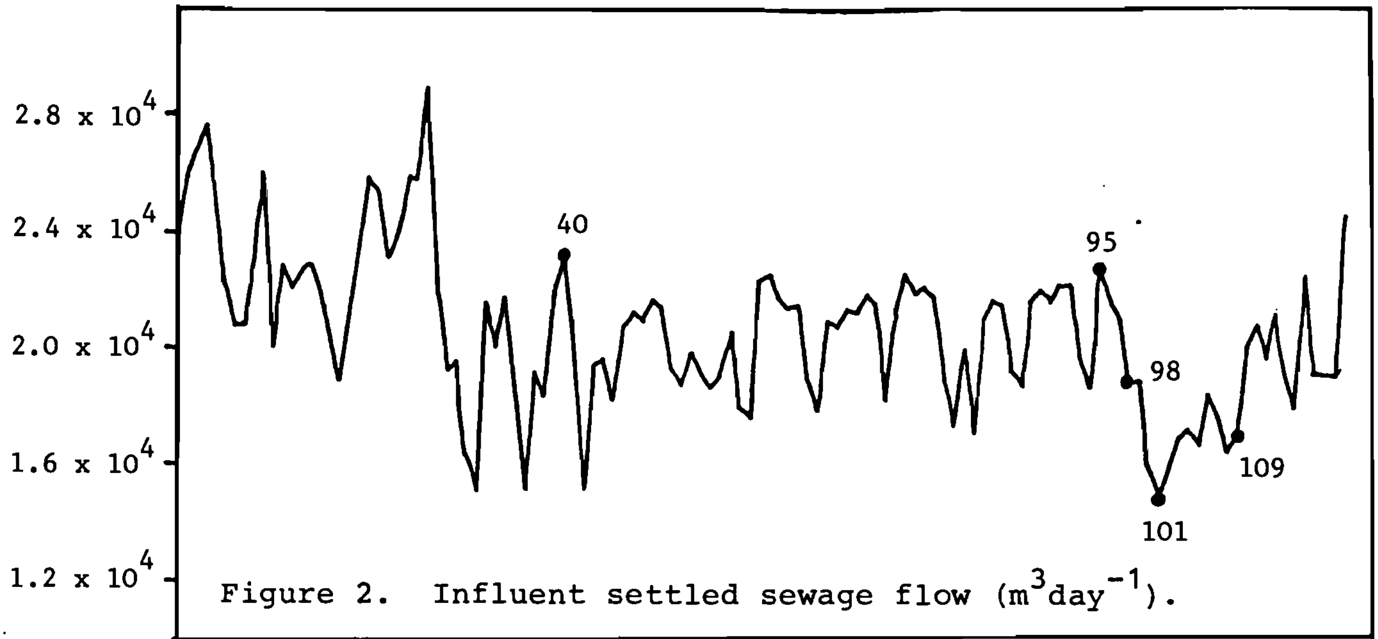


Figure 2. Influent settled sewage flow ($m^3 day^{-1}$).

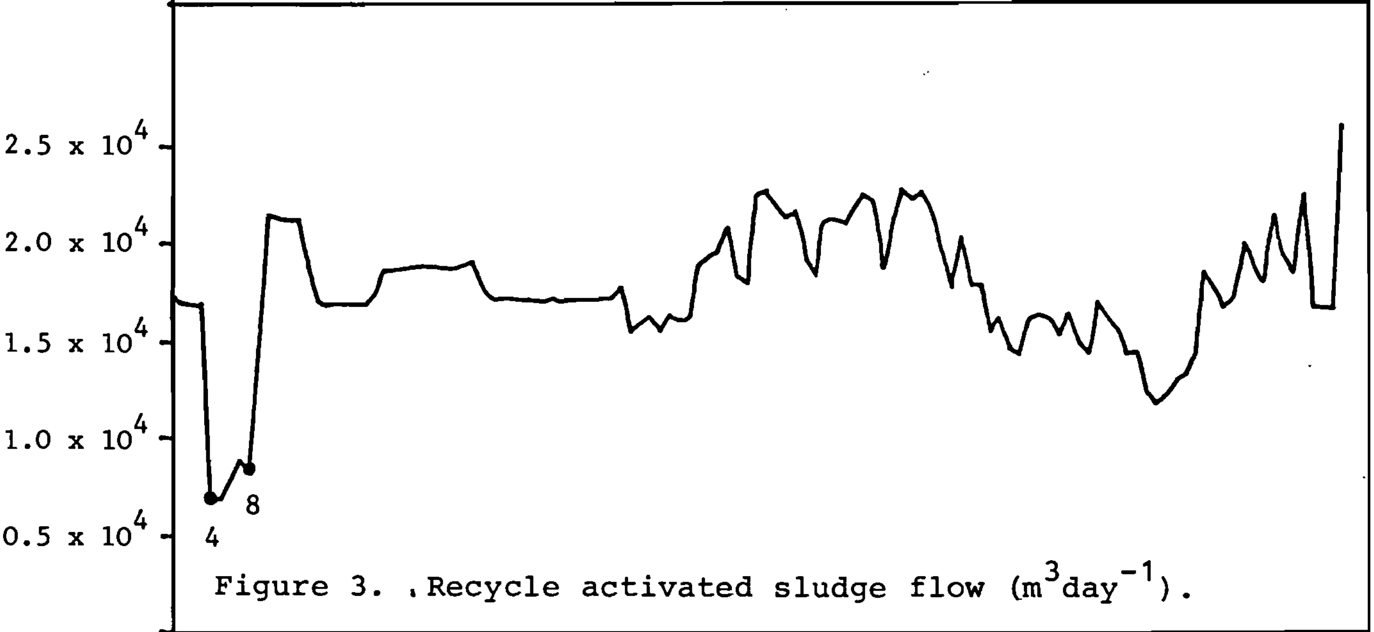


Figure 3. Recycle activated sludge flow ($m^3 day^{-1}$).

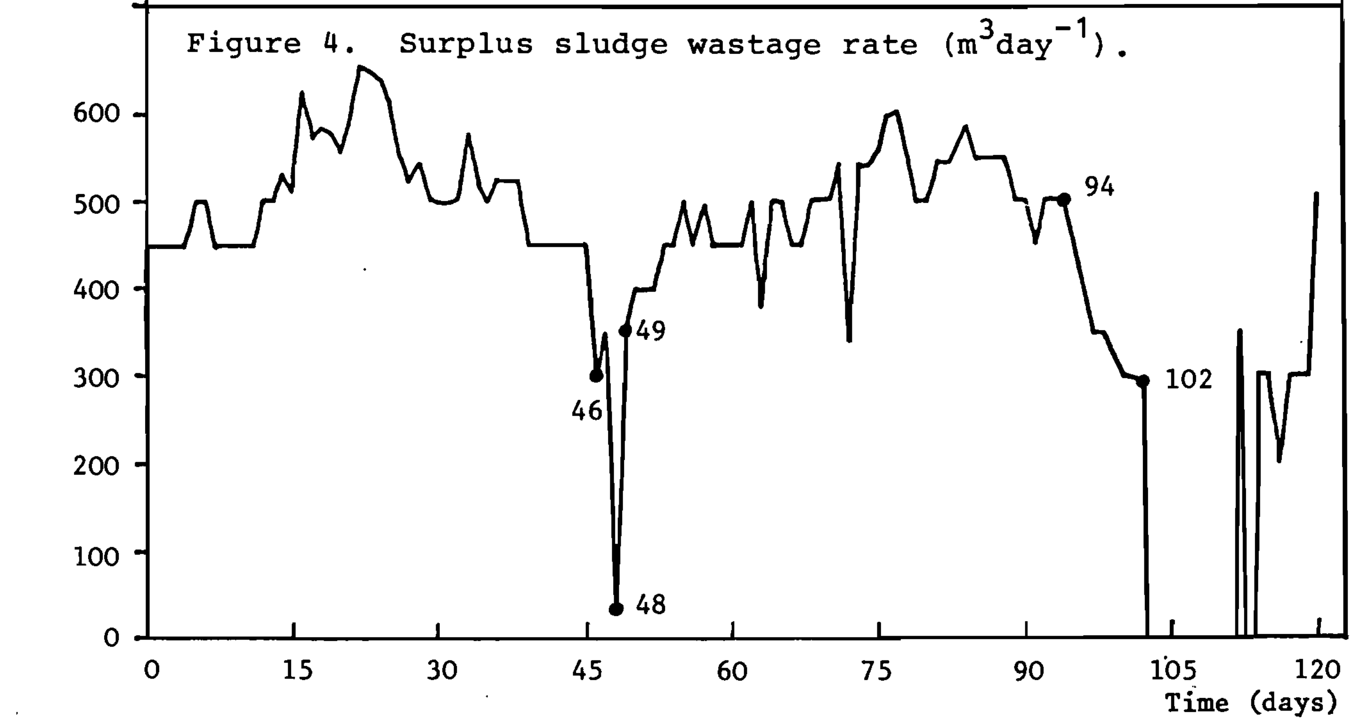


Figure 4. Surplus sludge wastage rate ($m^3 day^{-1}$).

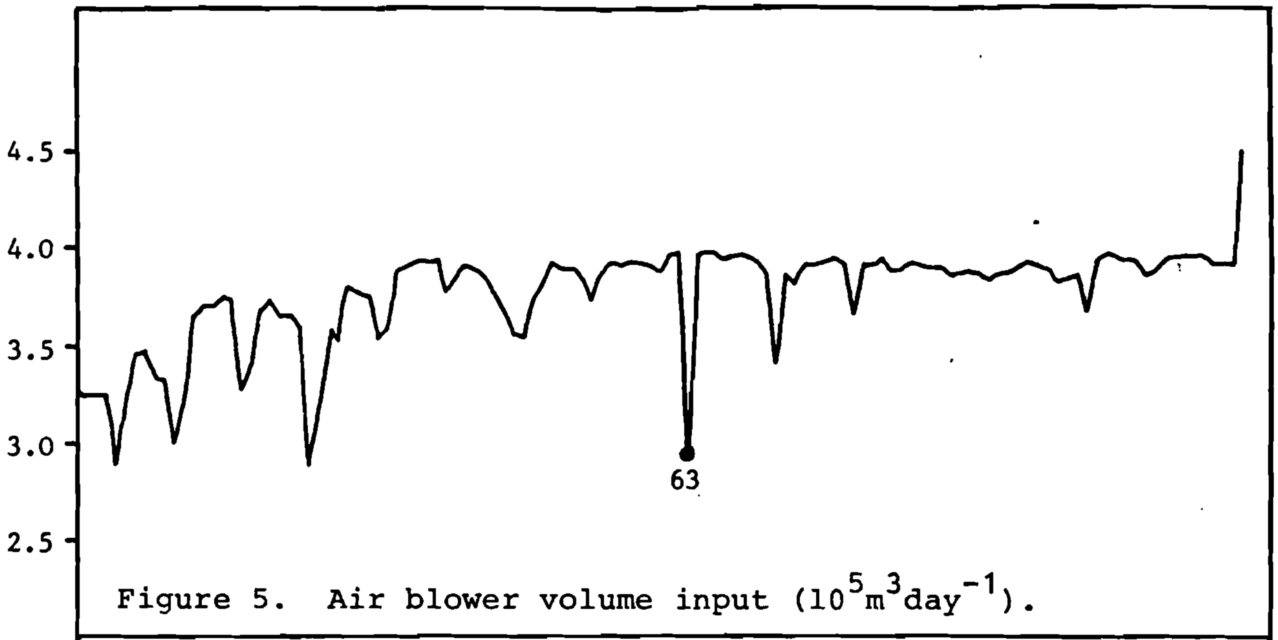


Figure 5. Air blower volume input ($10^5 m^3 day^{-1}$).

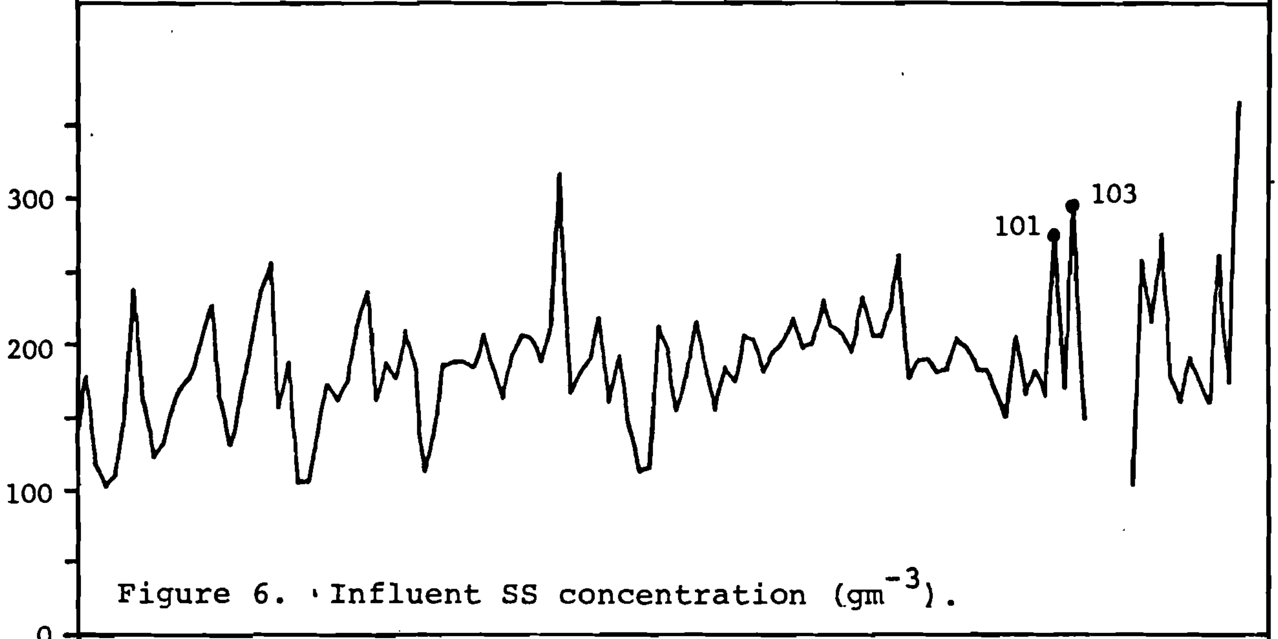


Figure 6. Influent SS concentration (gm^{-3}).

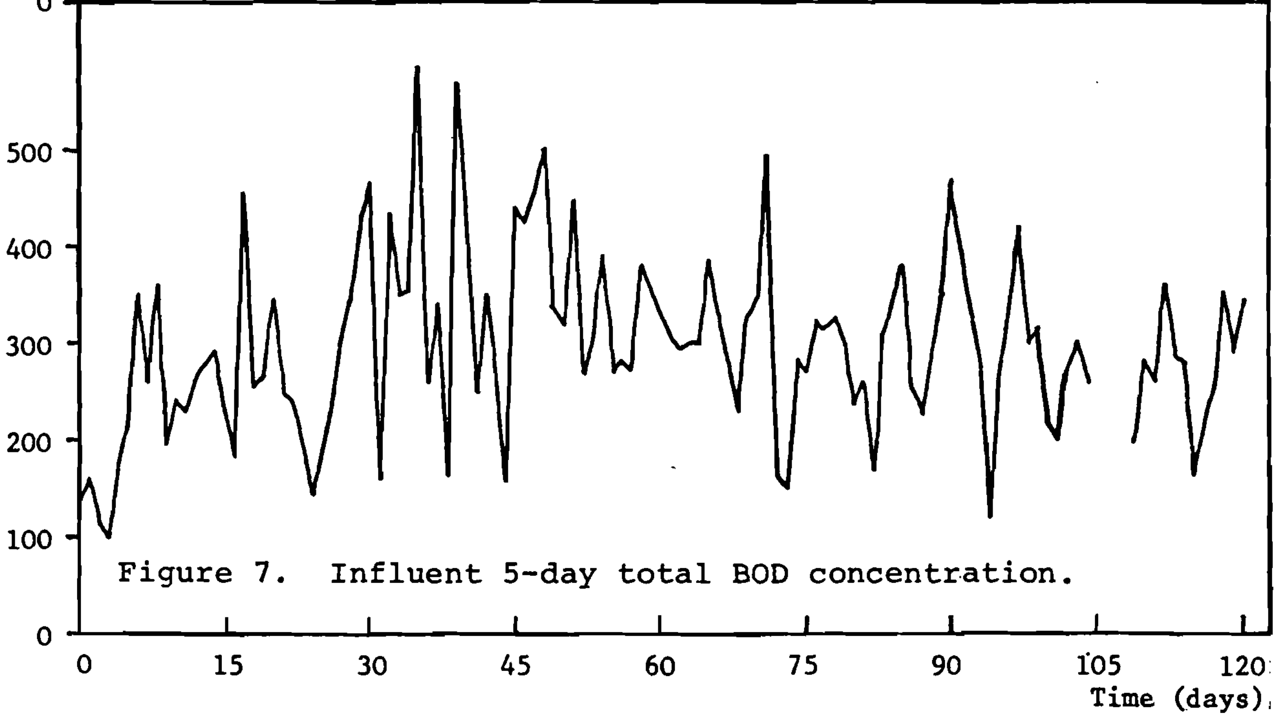


Figure 7. Influent 5-day total BOD concentration.

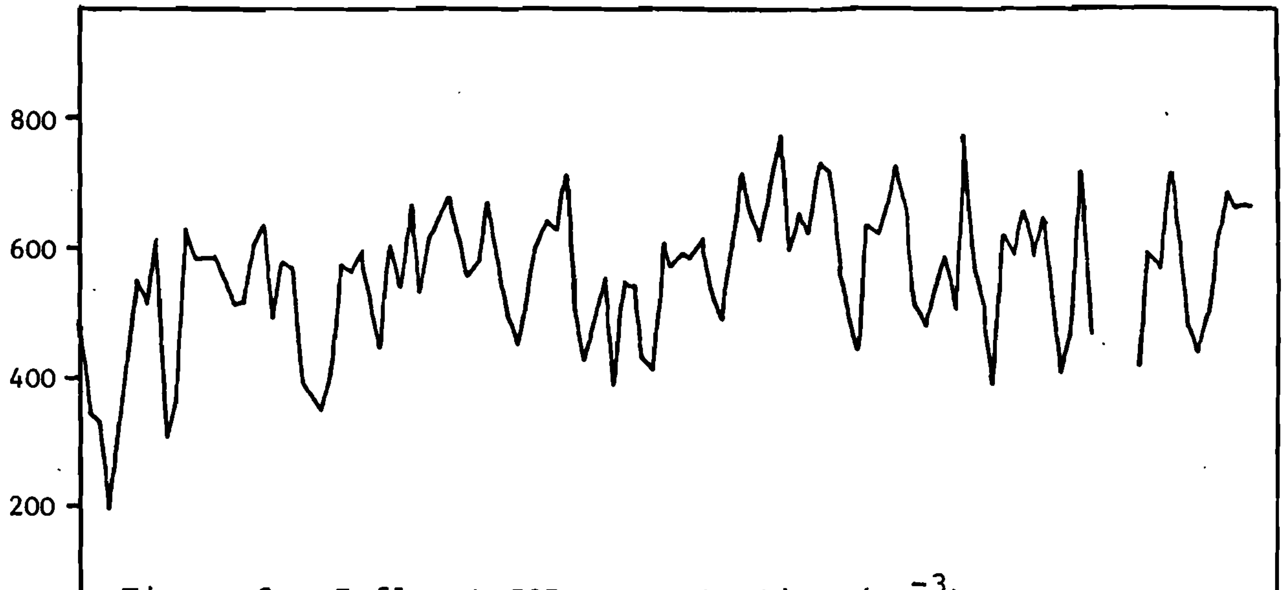


Figure 8. Influent COD concentration (gm^{-3}).

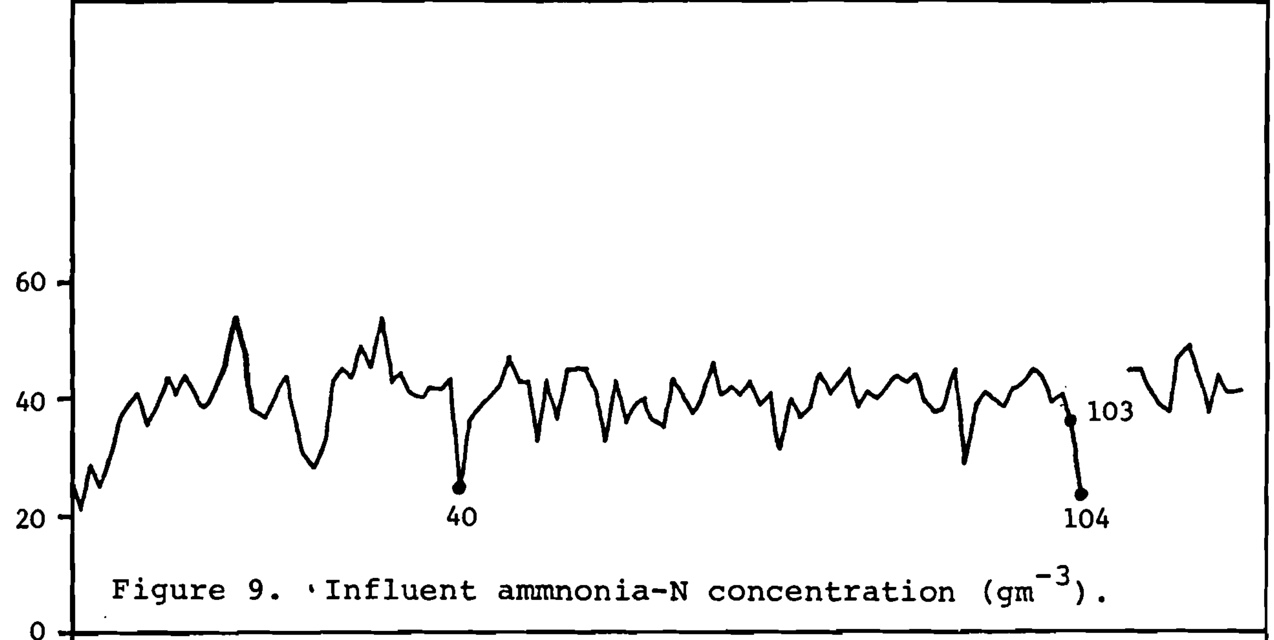


Figure 9. Influent ammnonia-N concentration (gm^{-3}).

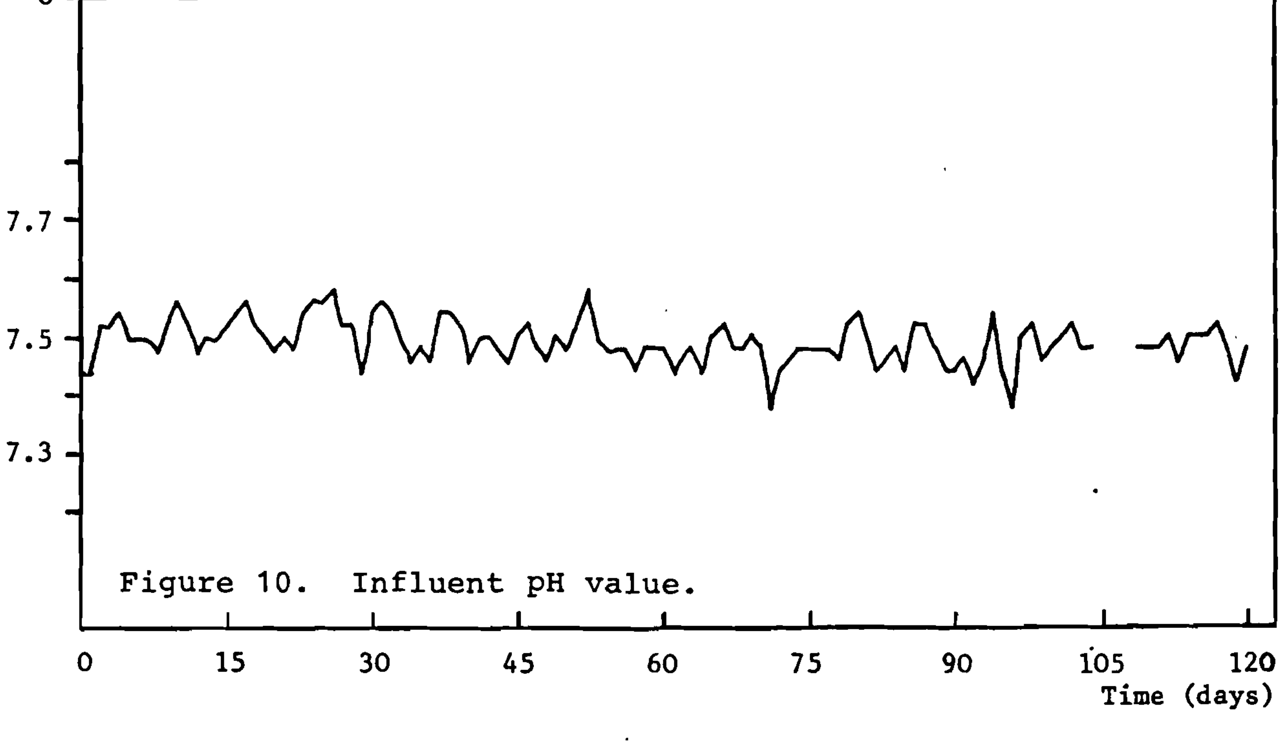


Figure 10. Influent pH value.

Figure 11. Influent carbohydrate concentration (gm^{-3}).

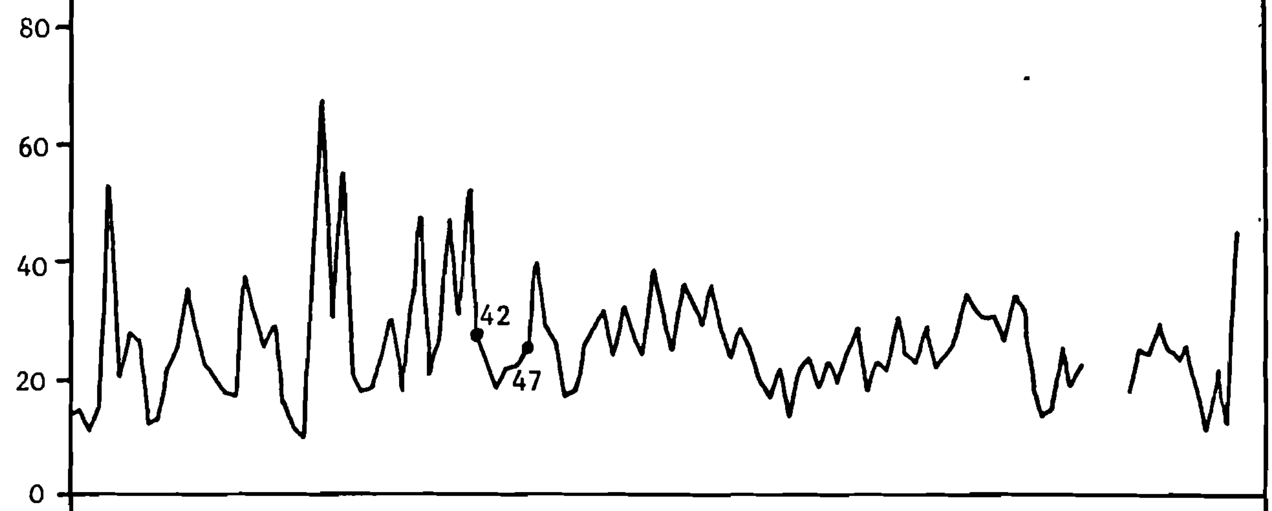


Figure 12. Effluent SS concentration (gm^{-3}).

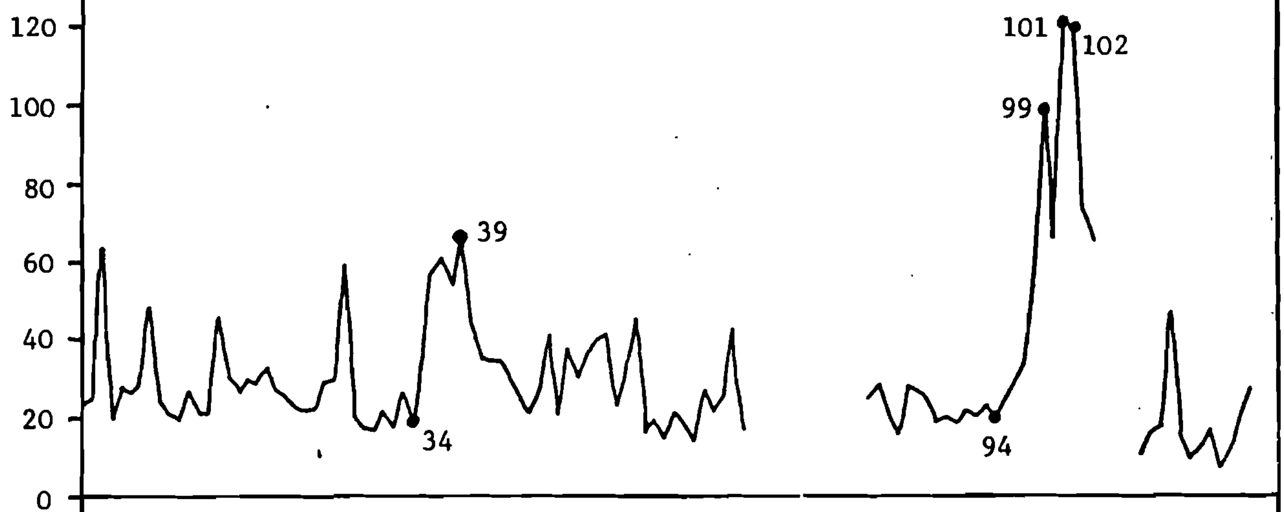


Figure 13. Effluent 5-day total BOD concentration (gm^{-3}).

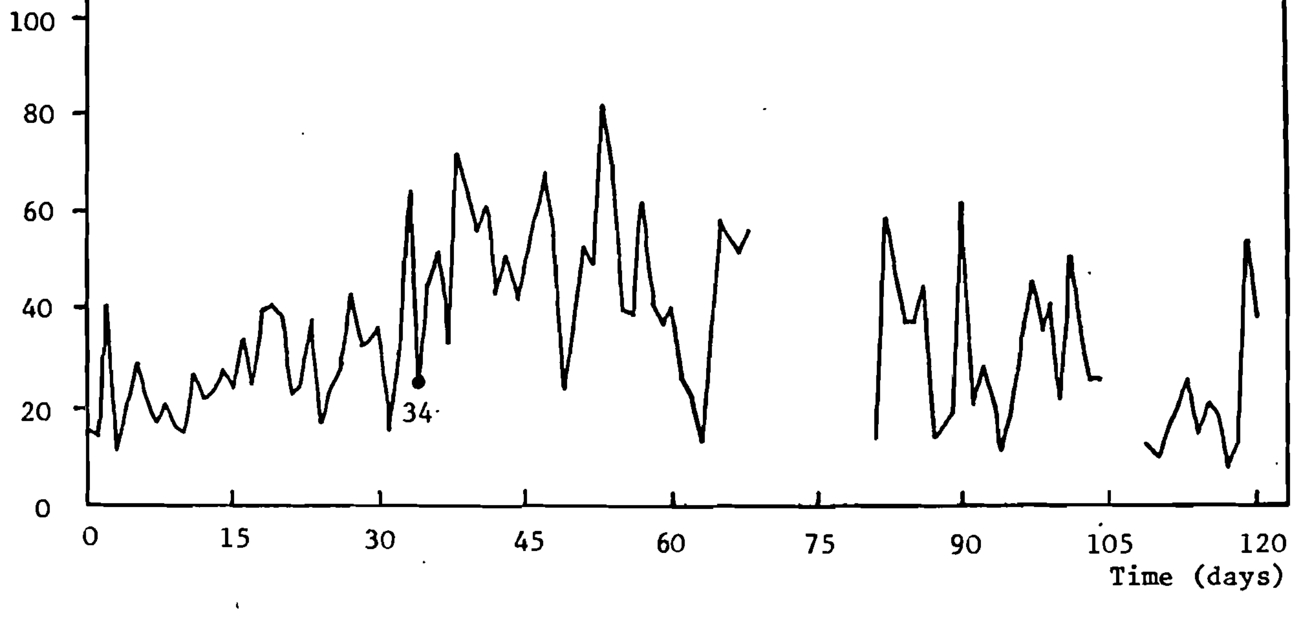


Figure 14. Effluent 5-day carbonaceous BOD (gm^{-3}).

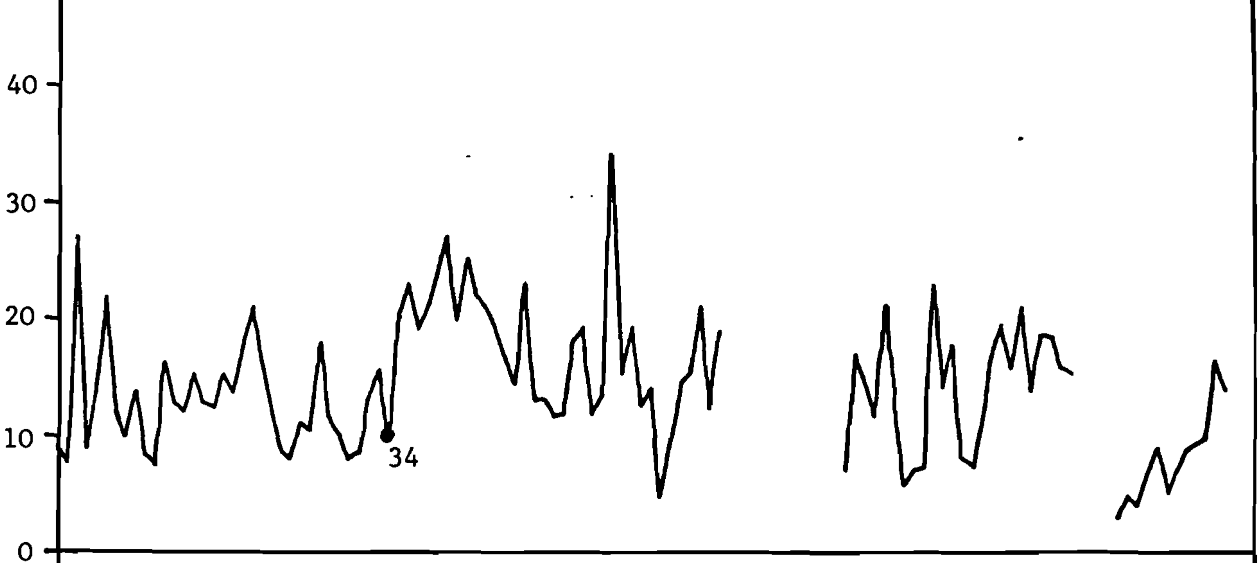


Figure 15. Effluent COD concentration (gm^{-3}).

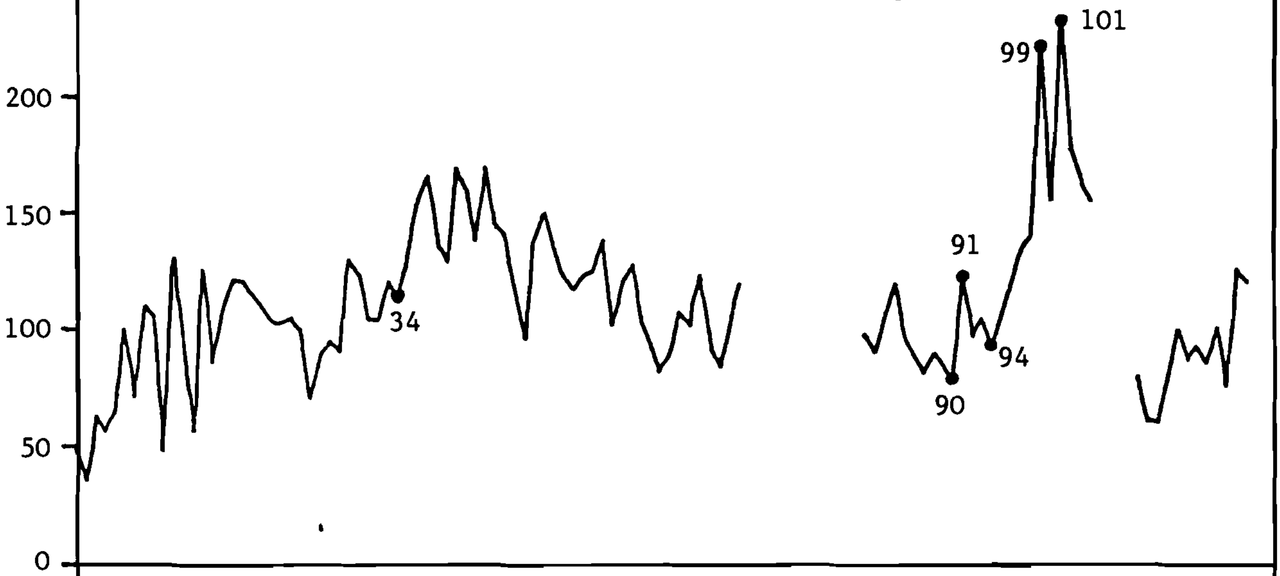


Figure 16. Effluent ammonia-N concentration (gm^{-3}).

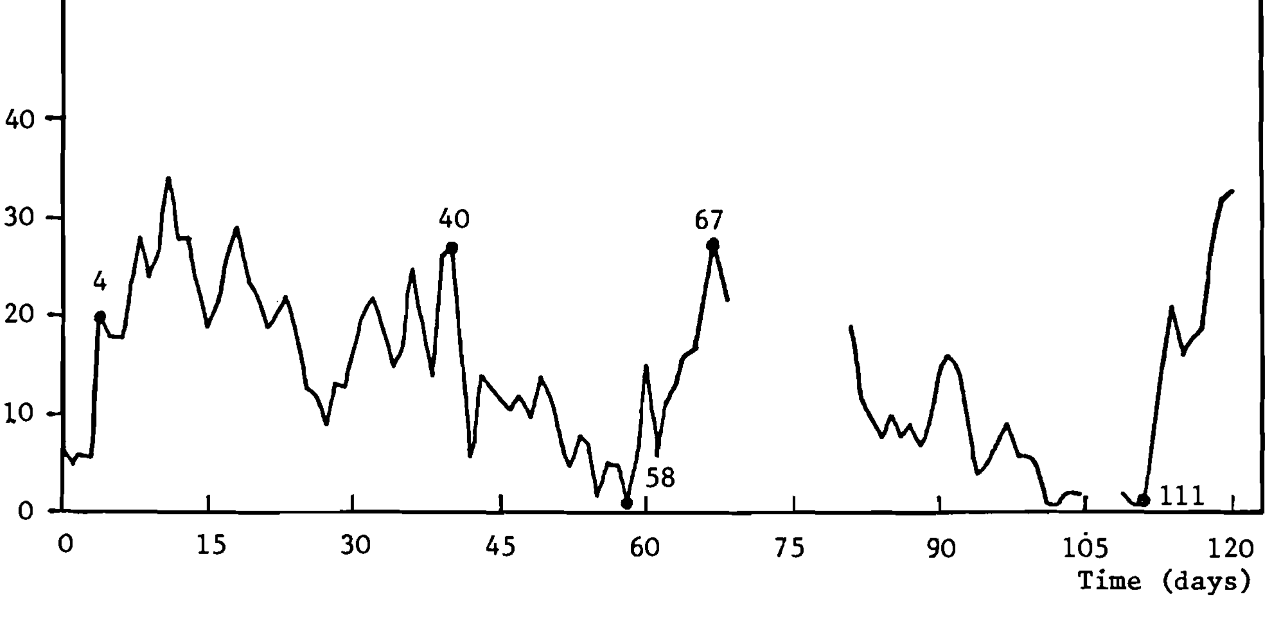


Figure 17. Effluent nitrite-N concentration (gm^{-3}).

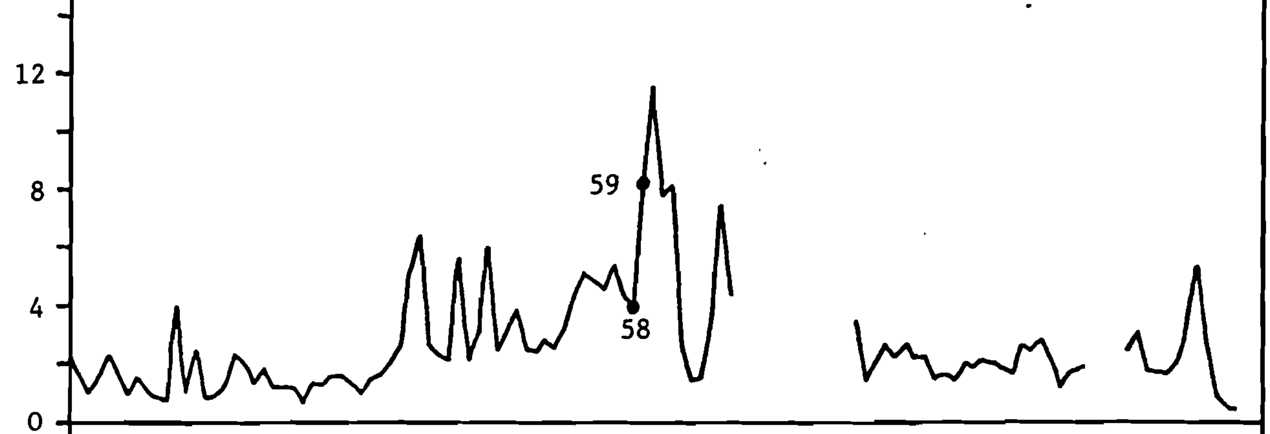


Figure 18. Effluent nitrate-N concentration (gm^{-3}).

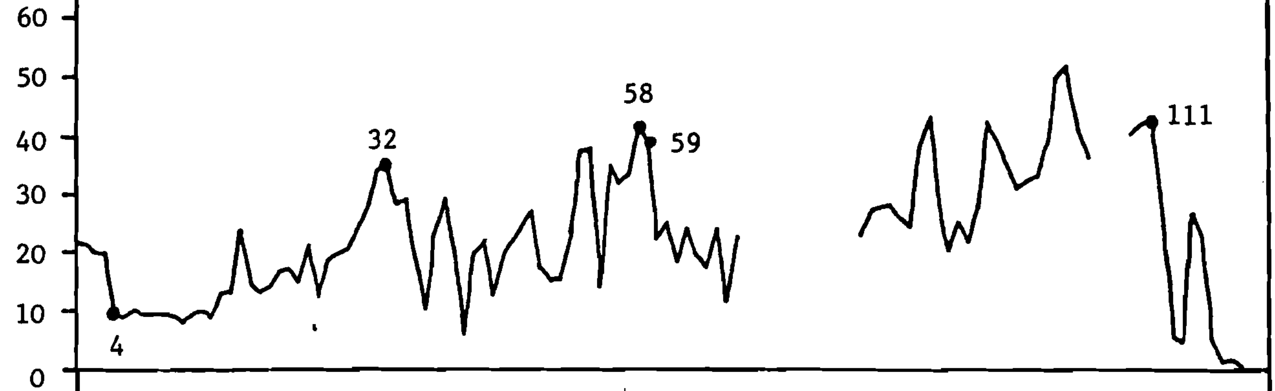


Figure 19. Effluent pH value.

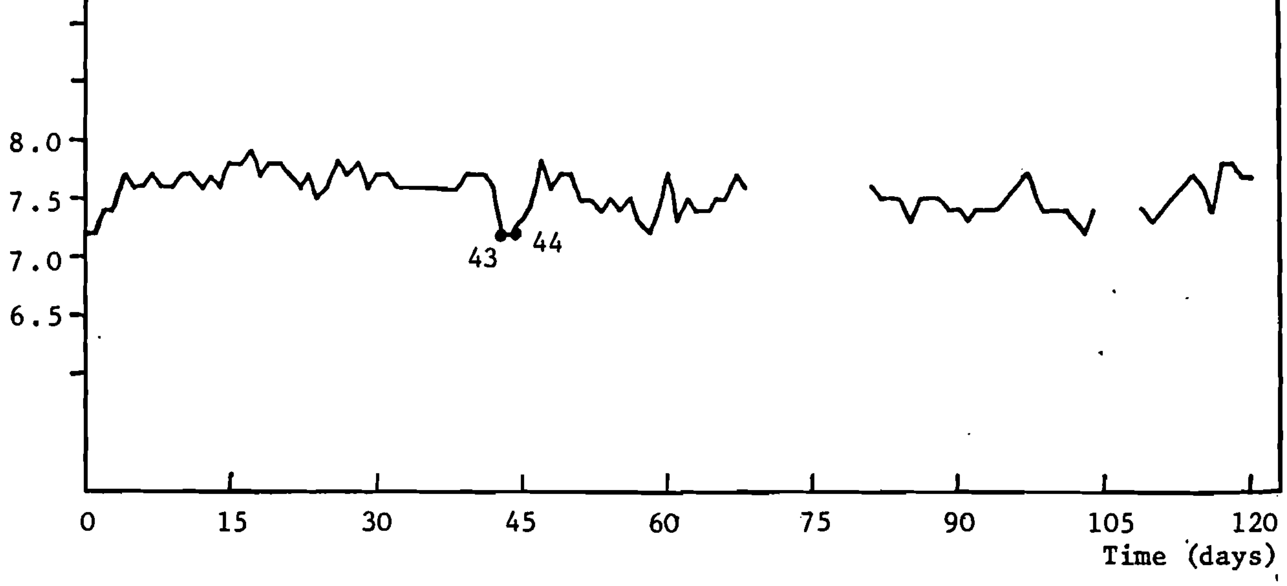


Figure 20. MLSS concentration (gm^{-3}).

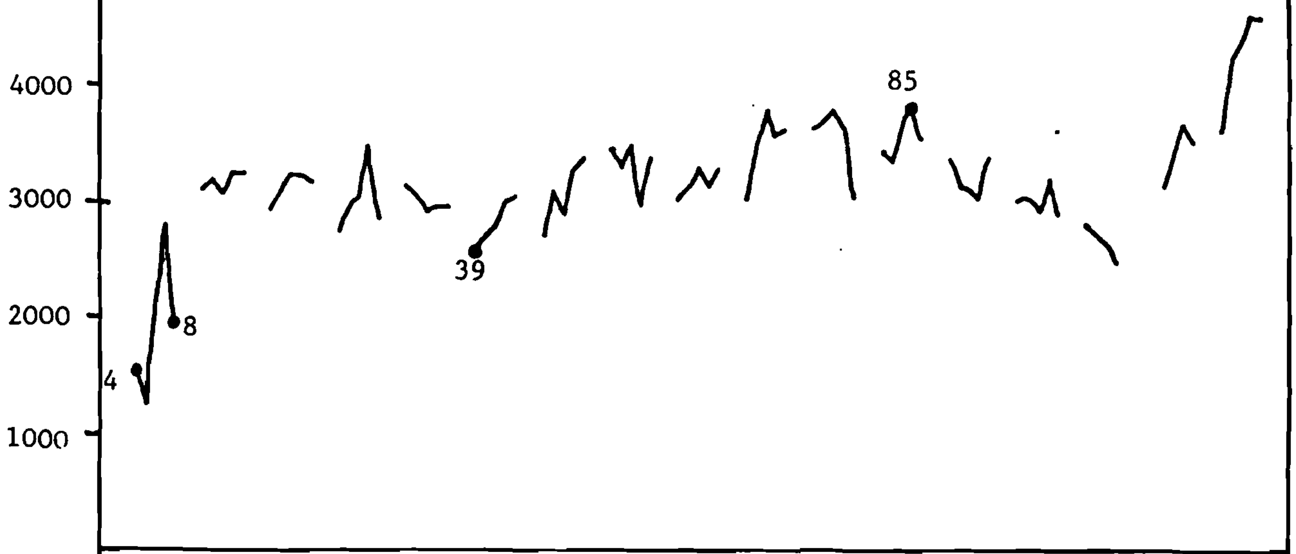


Figure 21. RASS concentration (gm^{-3}).

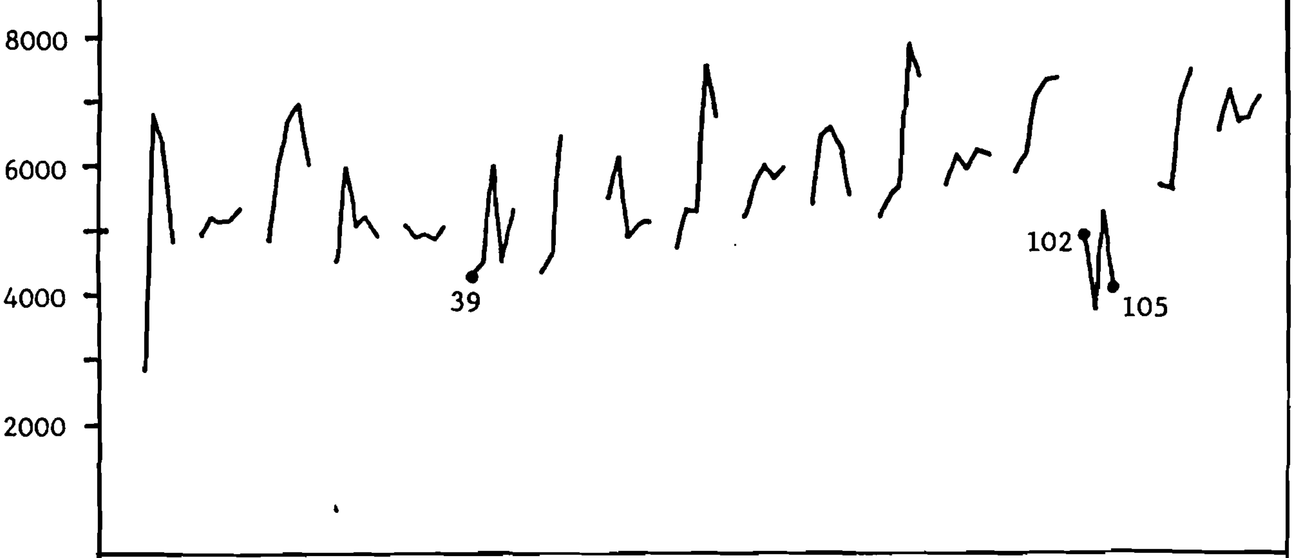


Figure 22. Sludge volume index (mlg^{-1}).

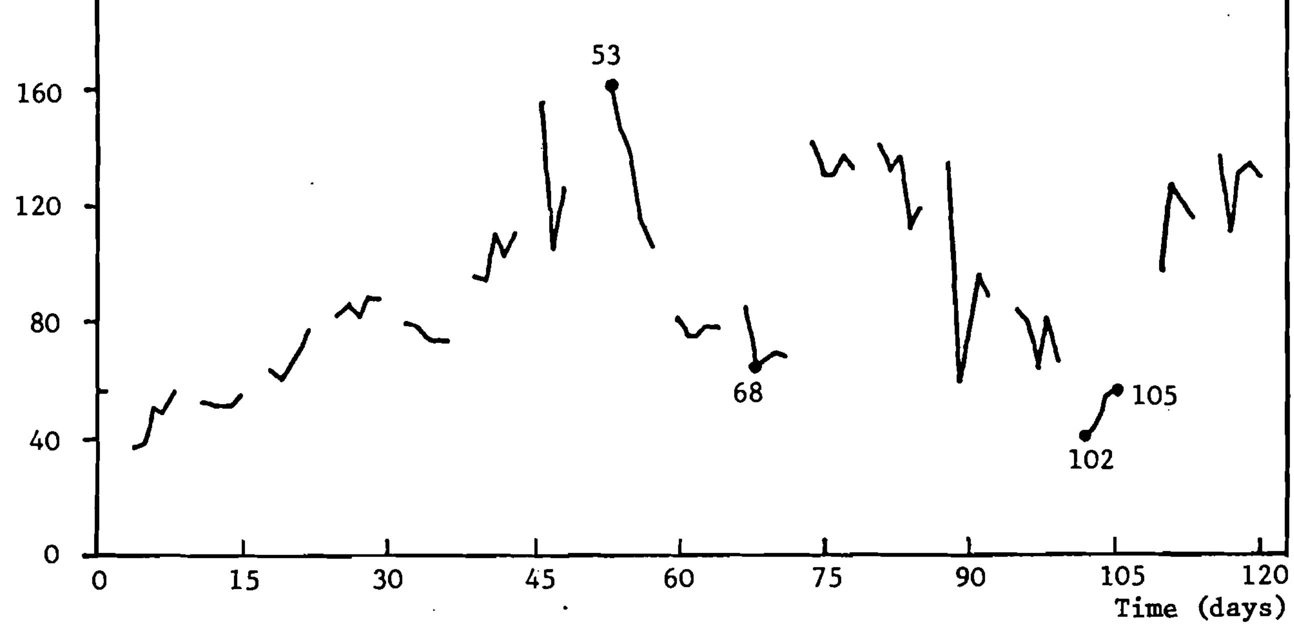


Figure 23. Sludge recycle ratio.

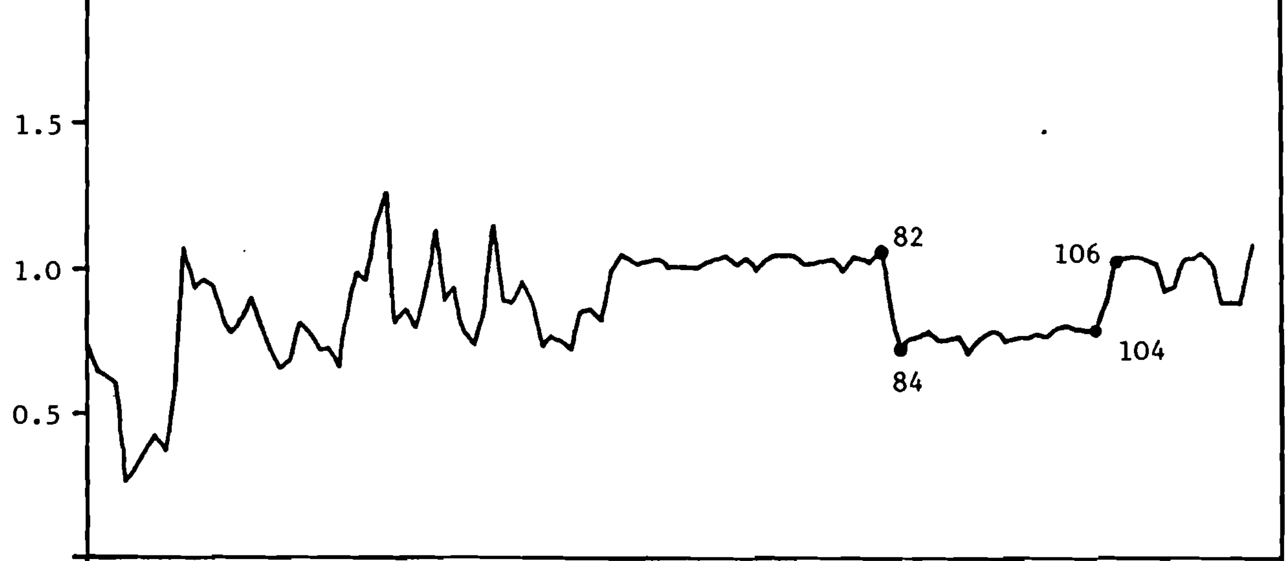


Figure 24. Sludge compaction ratio in clarifier.

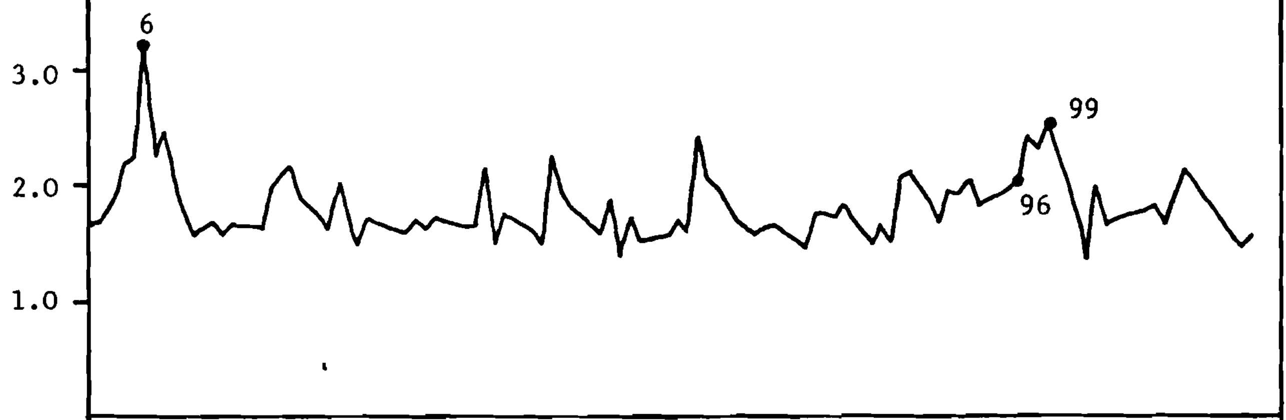
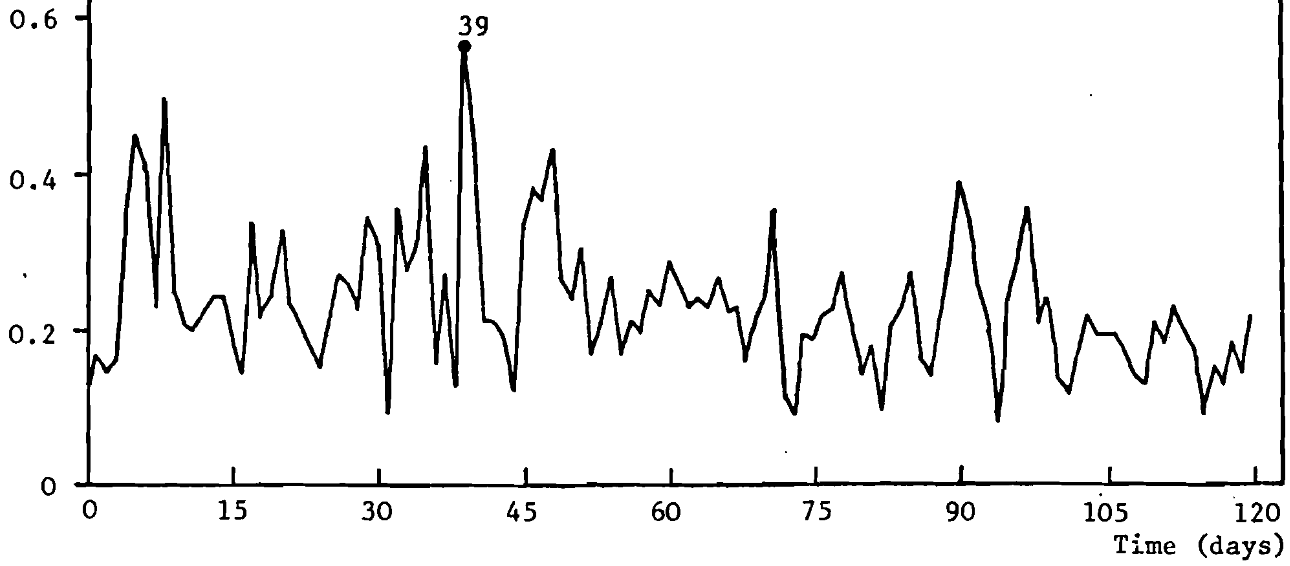


Figure 25. Sludge loading factor ([kgBOD/kgMLSS]/day).



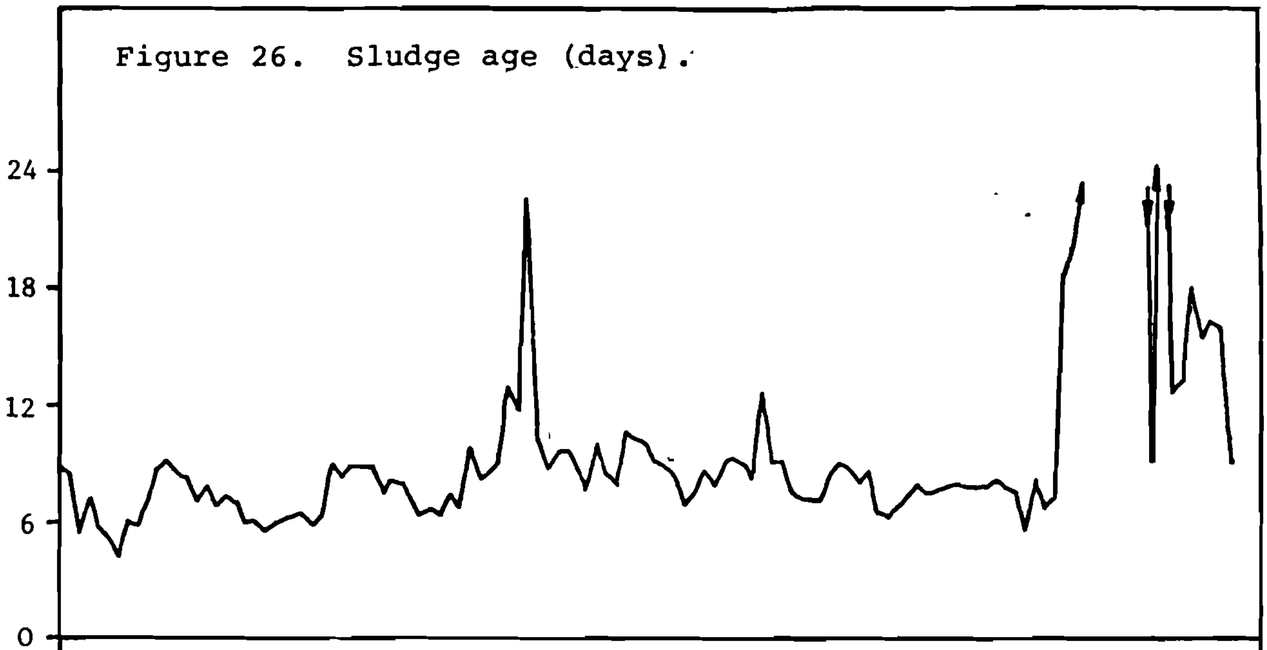


Figure 26. Sludge age (days).

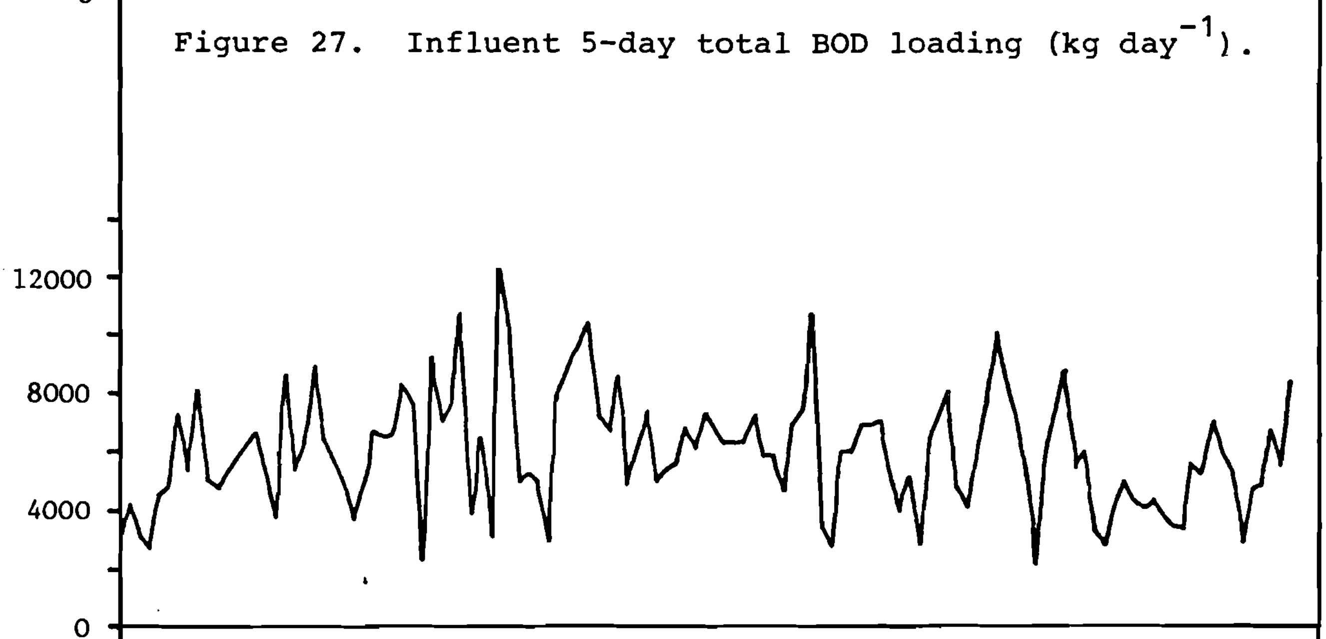


Figure 27. Influent 5-day total BOD loading (kg day^{-1}).

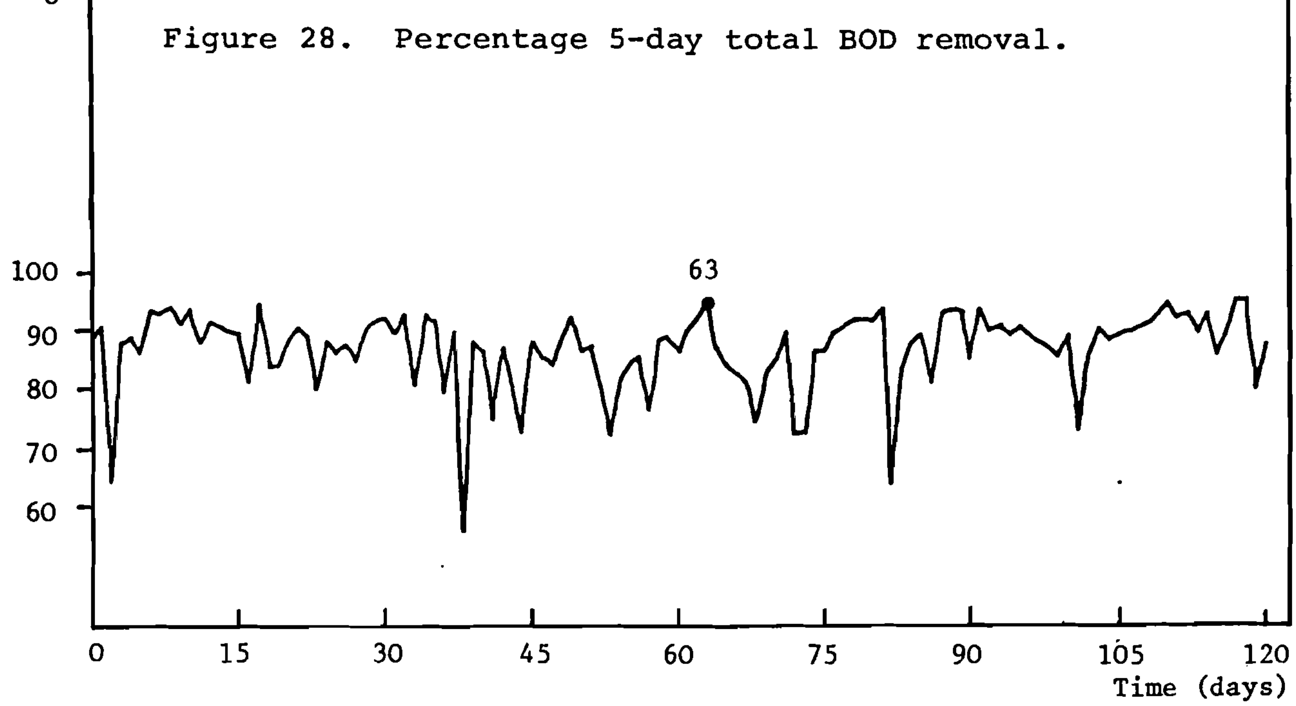


Figure 28. Percentage 5-day total BOD removal.

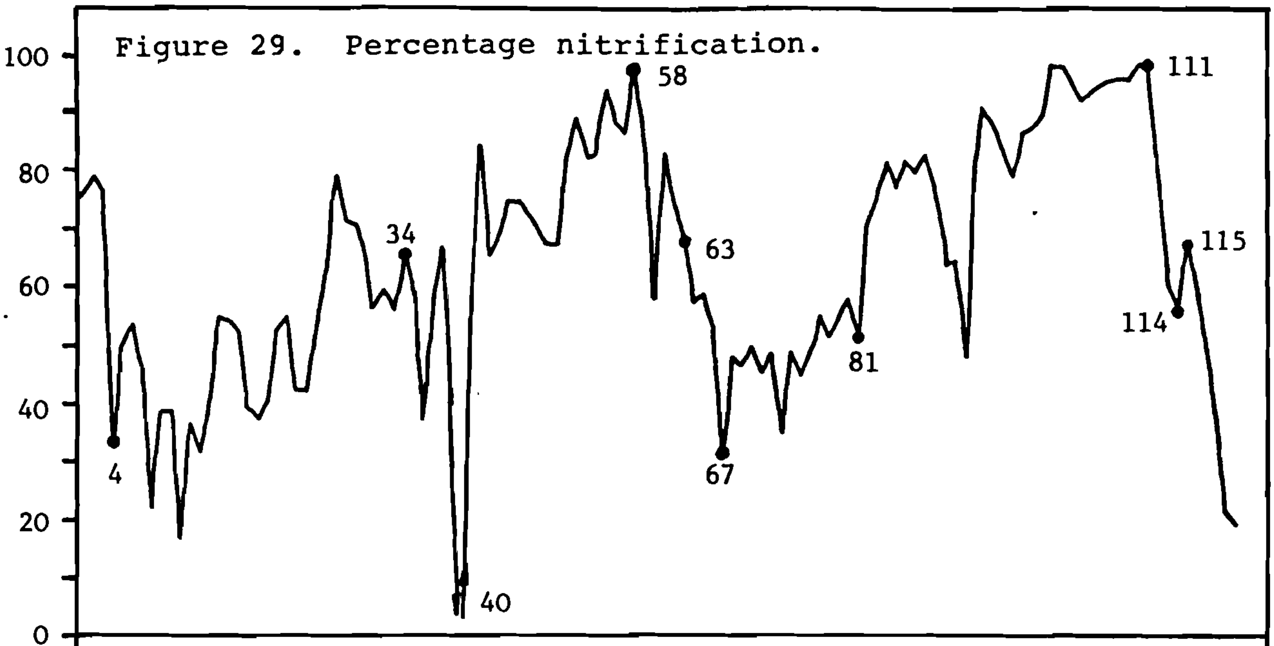


Figure 29. Percentage nitrification.

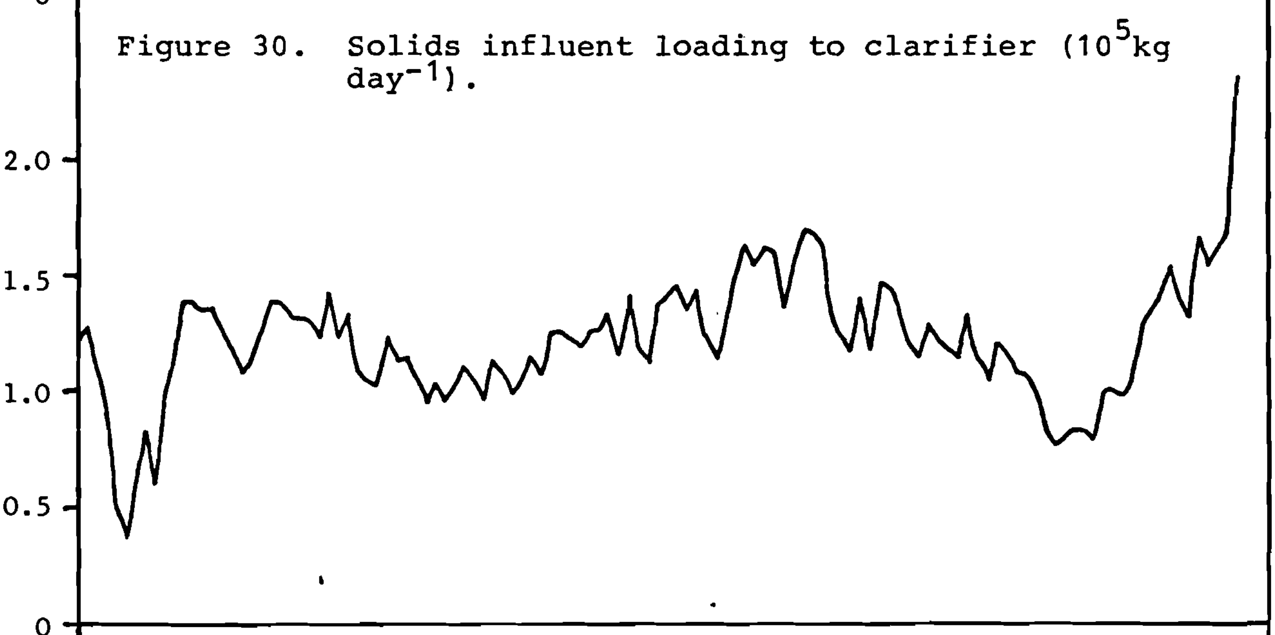


Figure 30. Solids influent loading to clarifier (10^5kg day^{-1}).

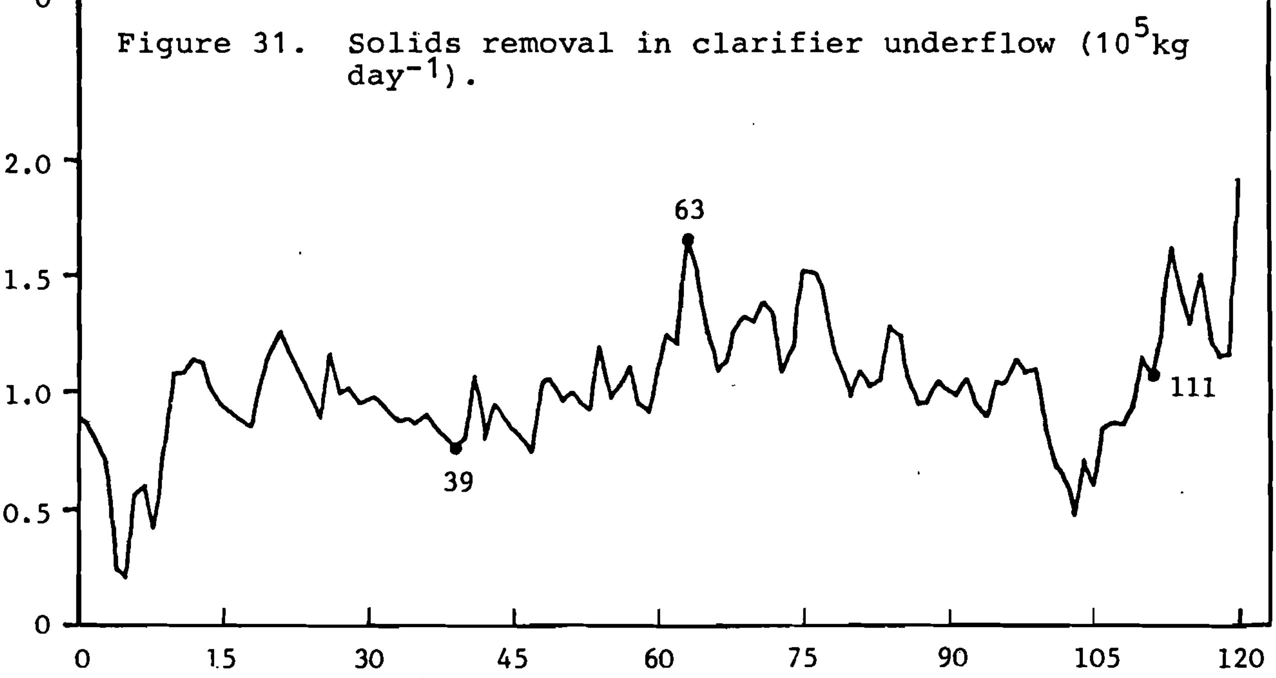


Figure 31. Solids removal in clarifier underflow (10^5kg day^{-1}).

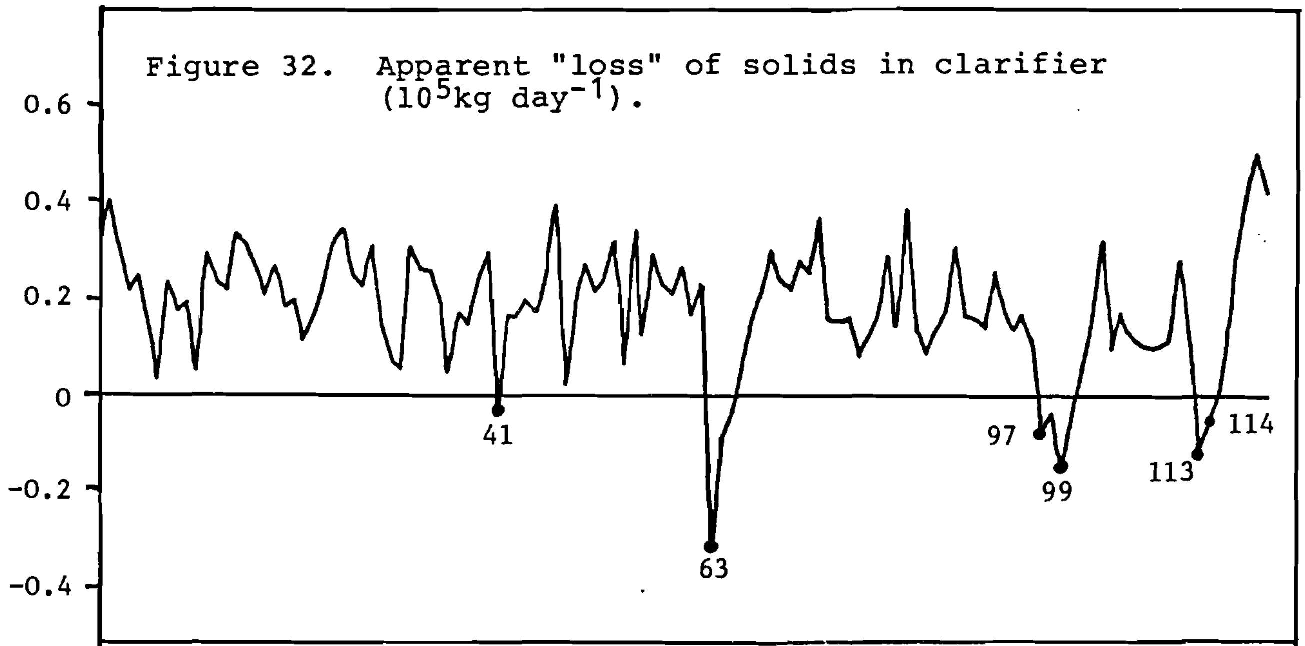


Figure 32. Apparent "loss" of solids in clarifier (10^5kg day^{-1}).

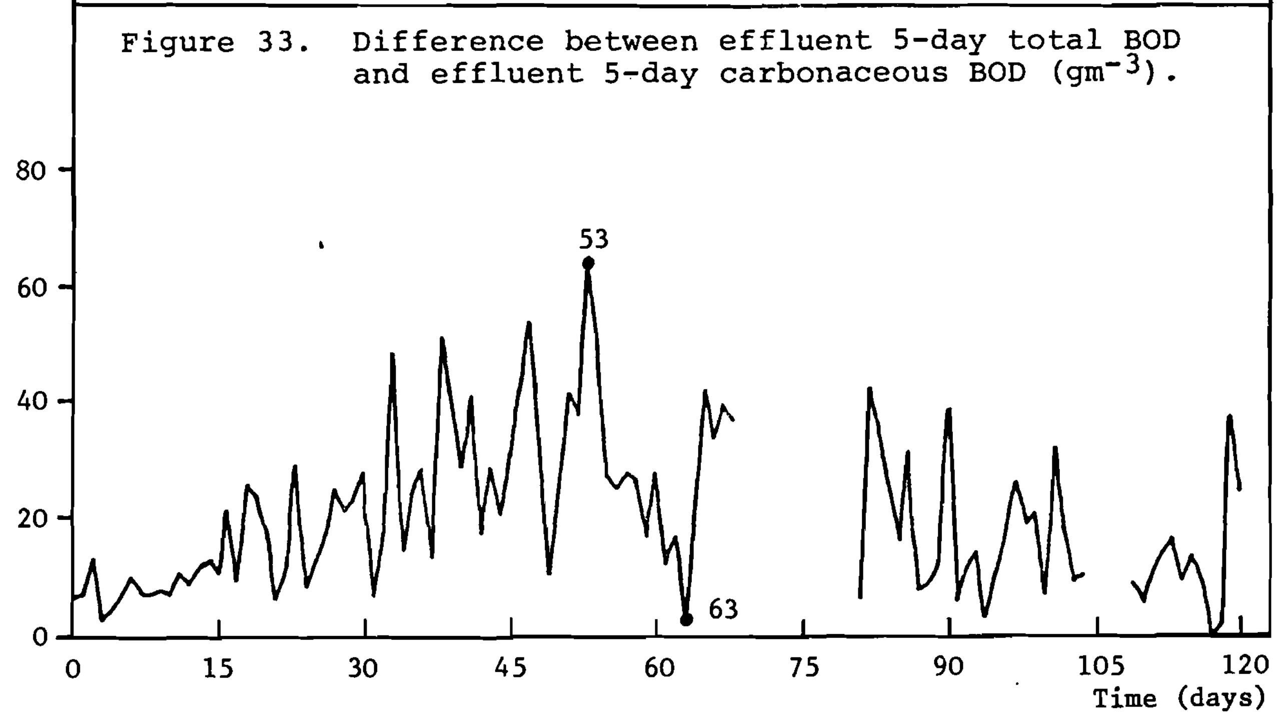


Figure 33. Difference between effluent 5-day total BOD and effluent 5-day carbonaceous BOD (gm^{-3}).

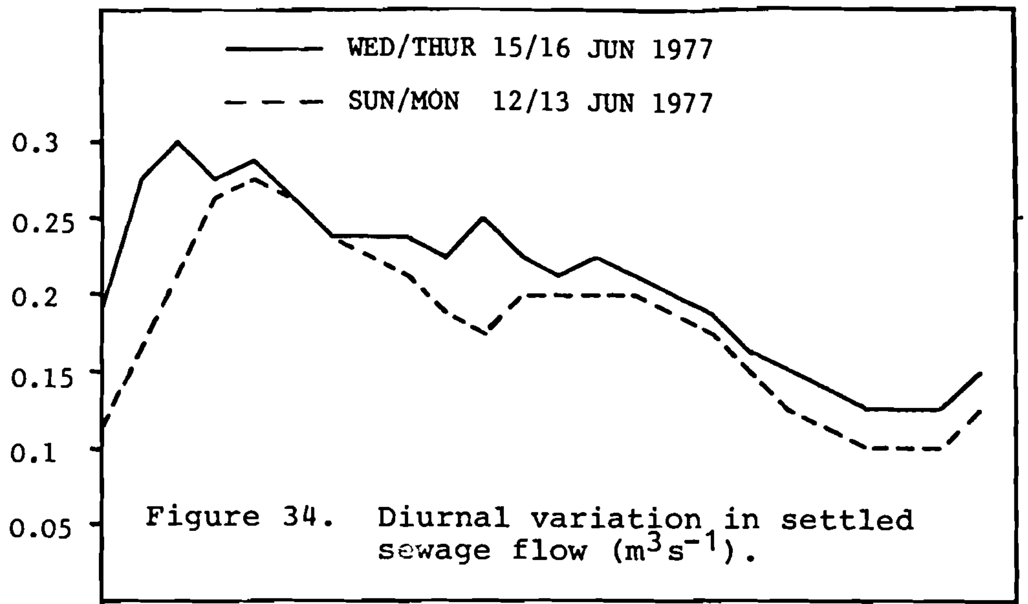


Figure 34. Diurnal variation in settled sewage flow (m^3s^{-1}).

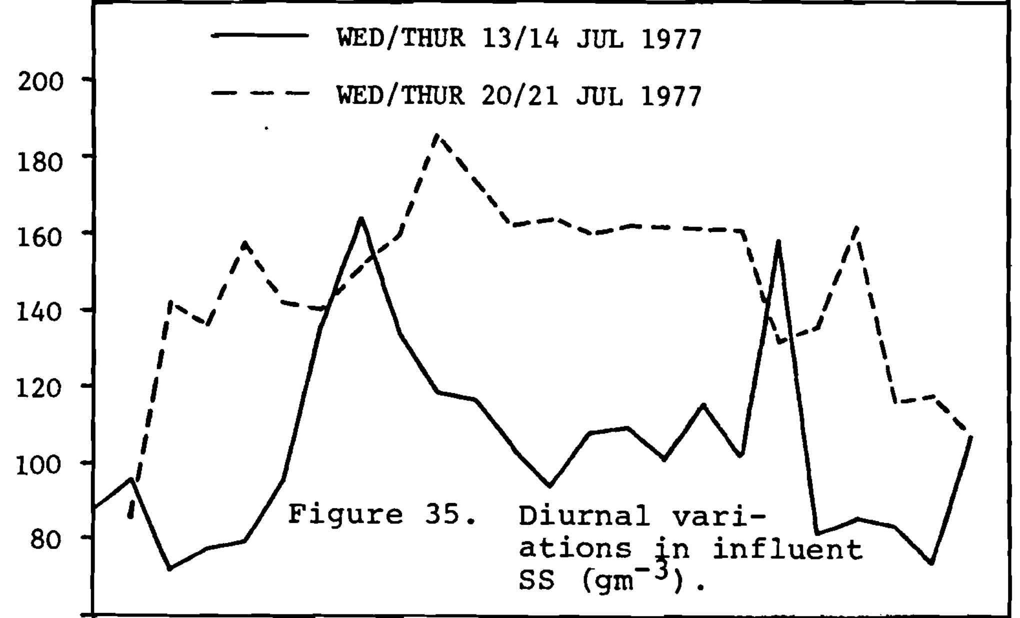


Figure 35. Diurnal variations in influent SS (gm^{-3}).

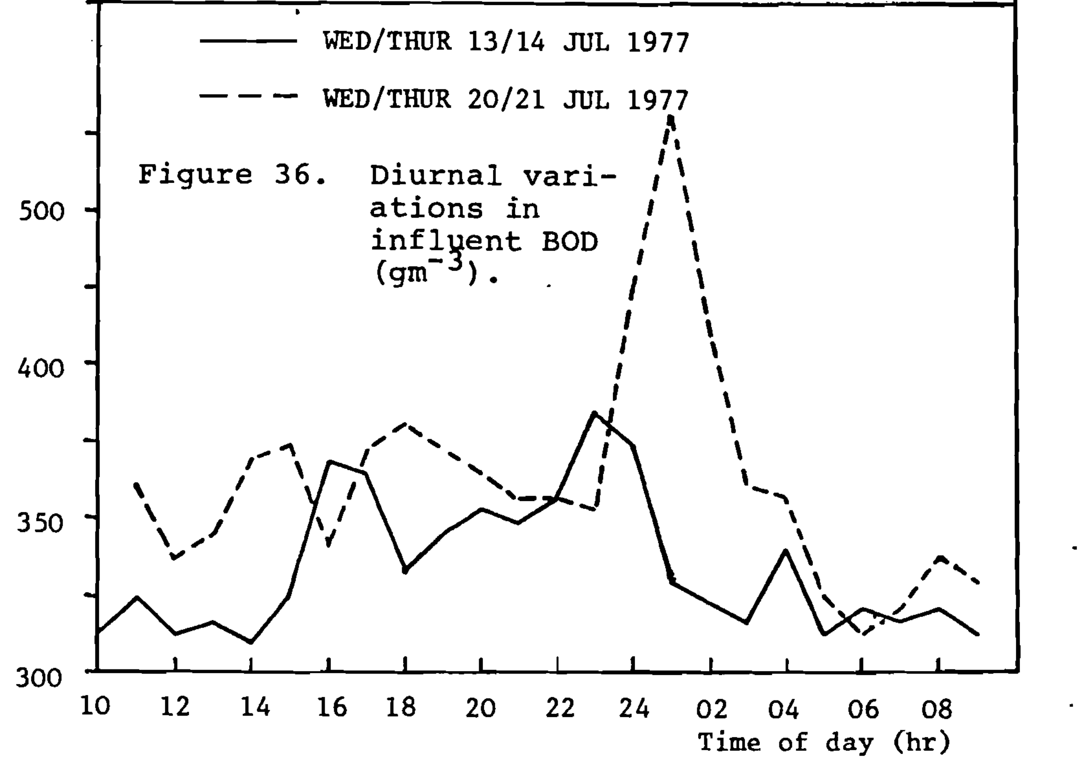


Figure 36. Diurnal variations in influent BOD (gm^{-3}).

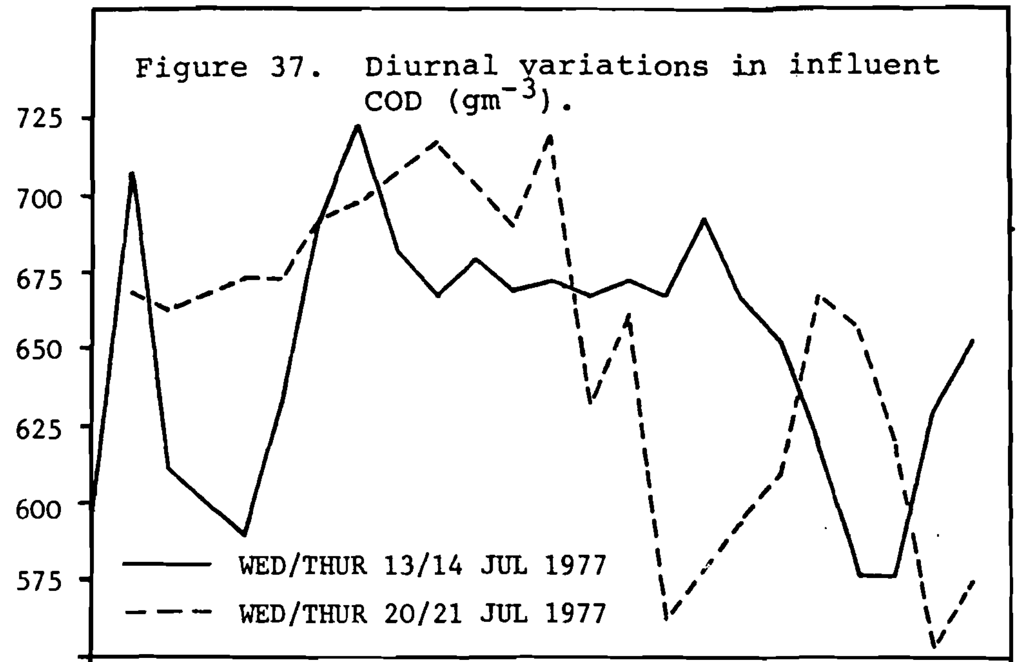


Figure 37. Diurnal variations in influent COD (gm^{-3}).

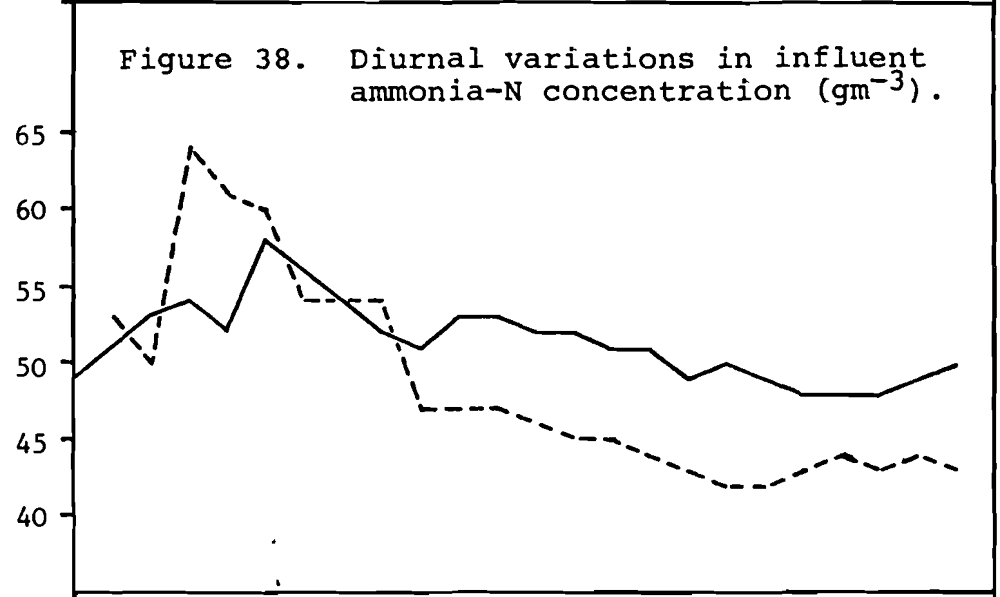


Figure 38. Diurnal variations in influent ammonia-N concentration (gm^{-3}).

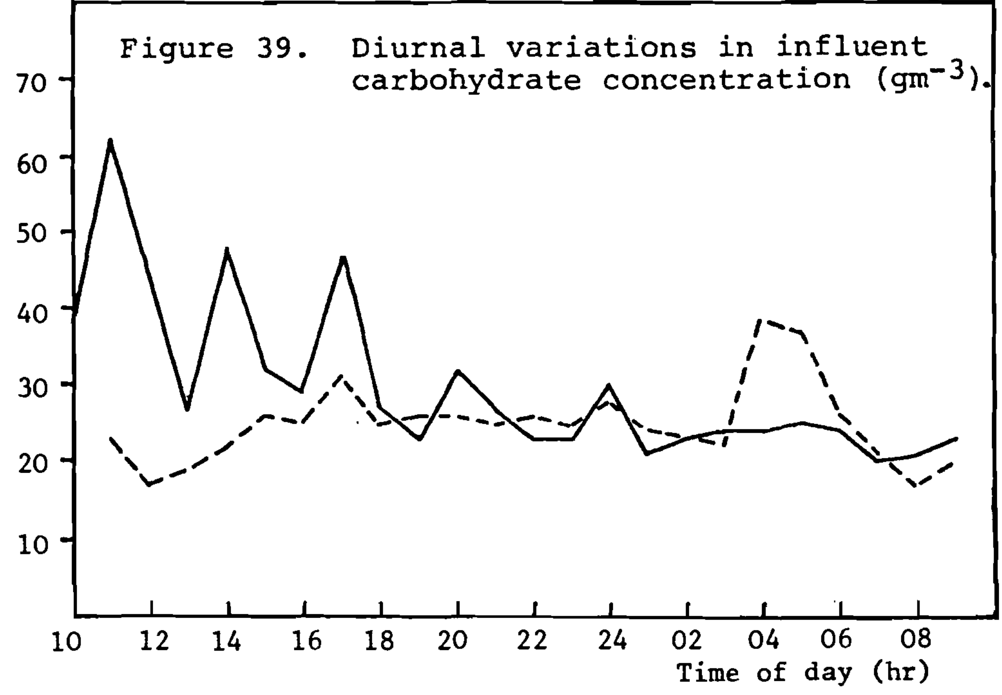


Figure 39. Diurnal variations in influent carbohydrate concentration (gm^{-3}).

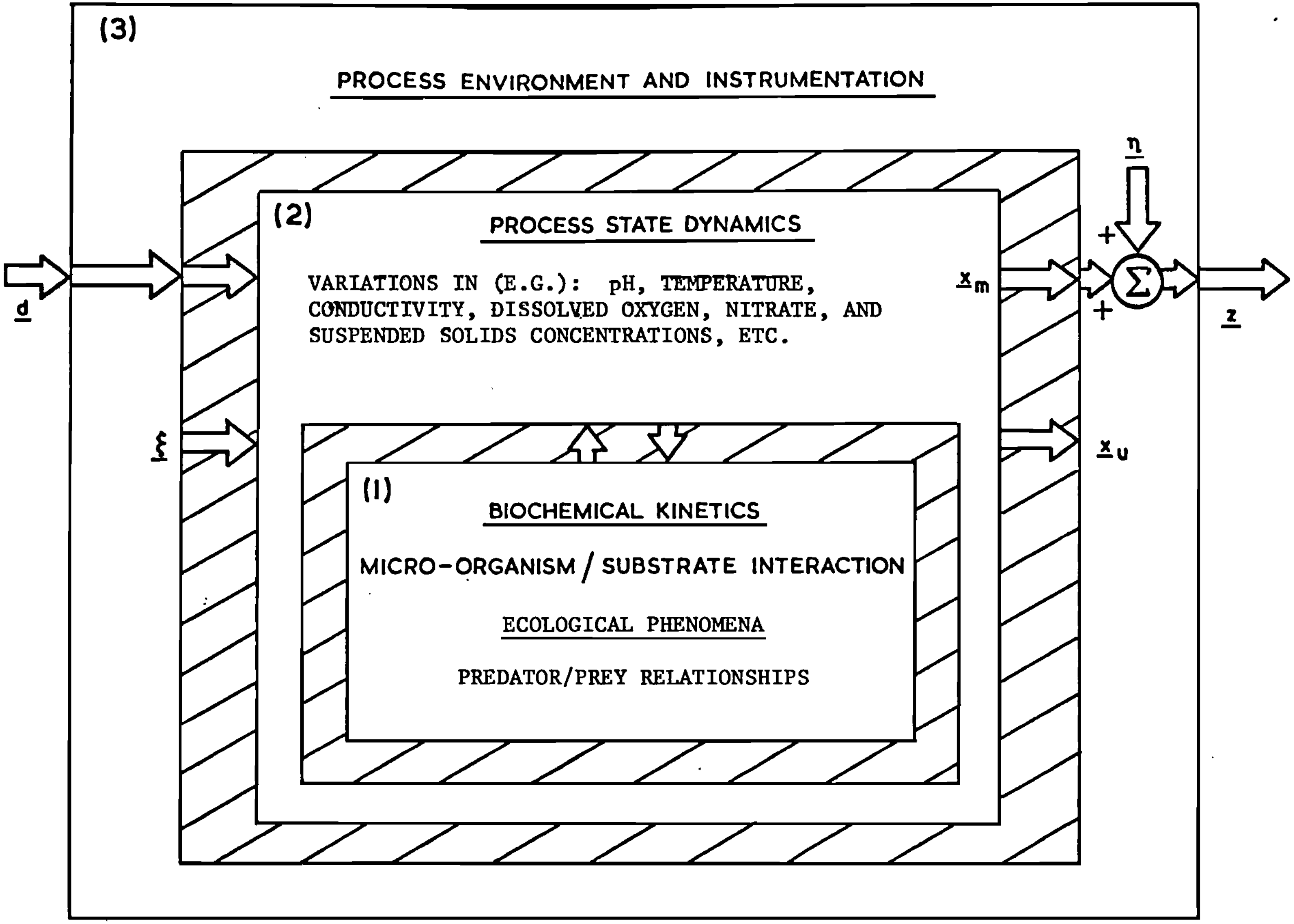


Figure 40. Observation of biochemical process kinetics.

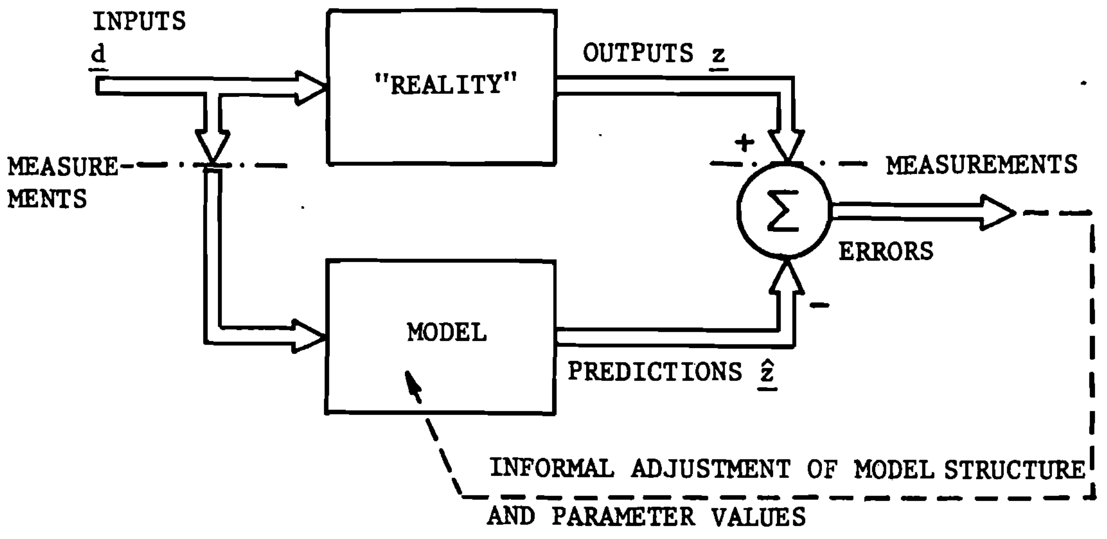


Figure 41(a). A rudimentary method of parameter estimation.

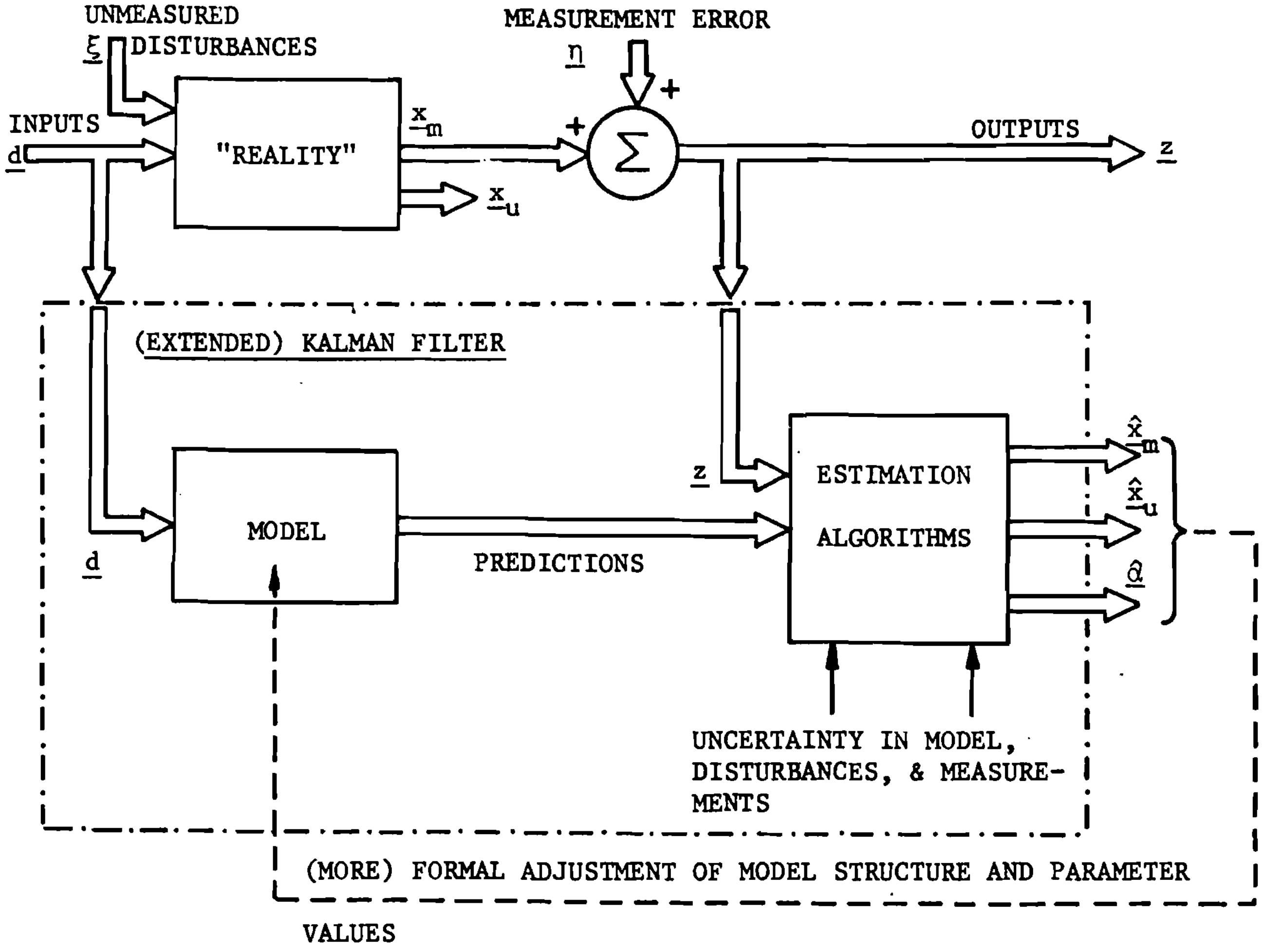


Figure 41(b). A formal method of parameter estimation (Kalman filtering).

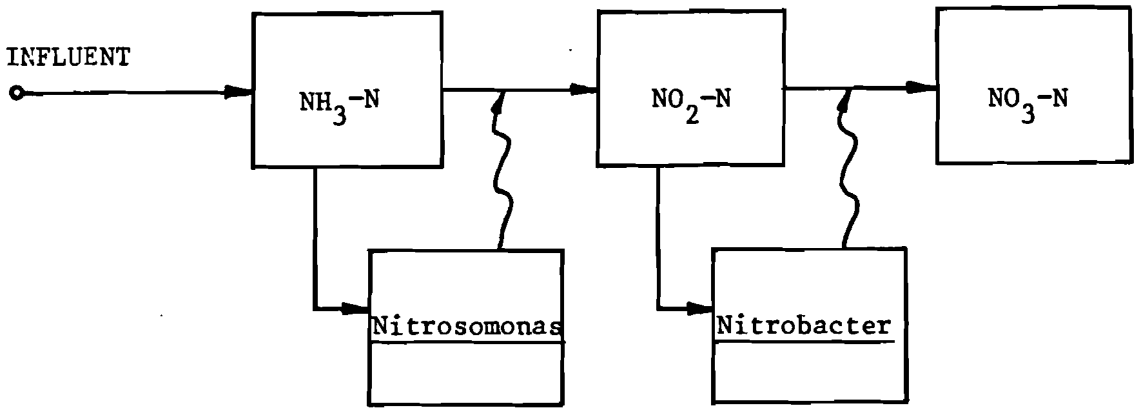


Figure 42(a). Biochemical model of nitrification in the aerator.

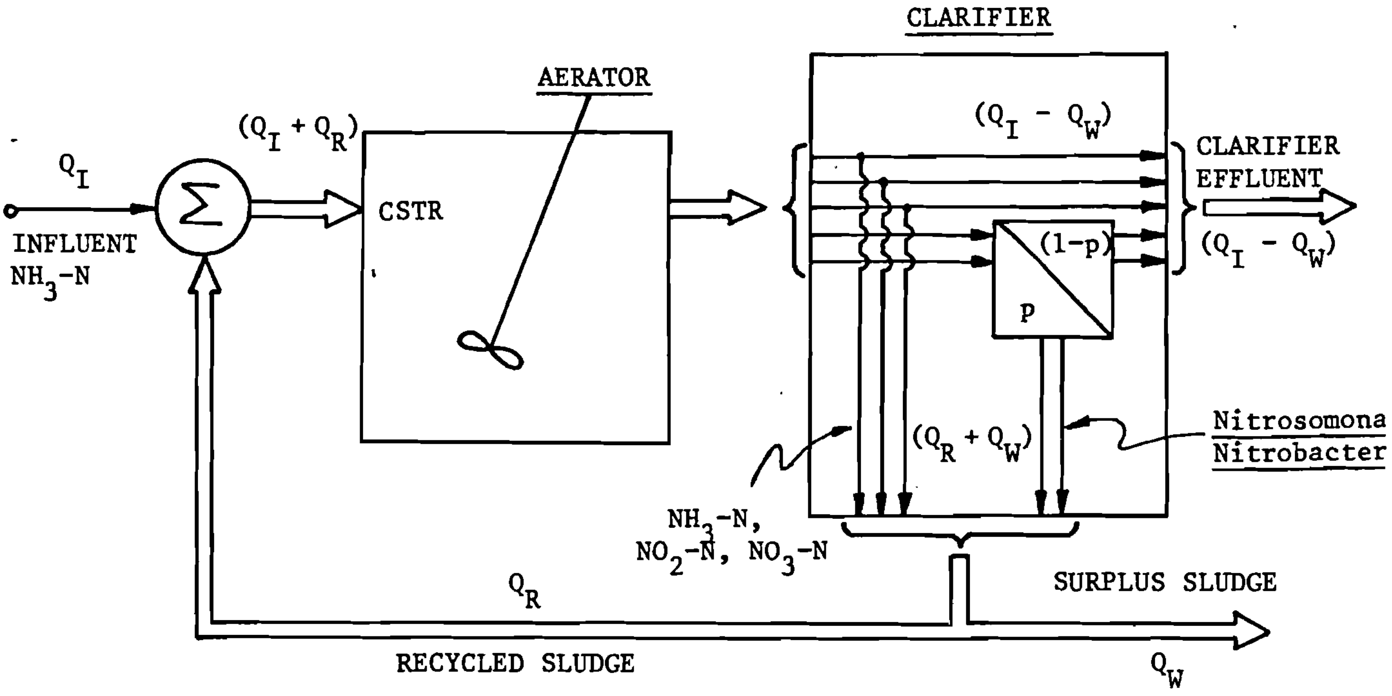


Figure 42(b). Mixing and transport models for the aerator and clarifier.

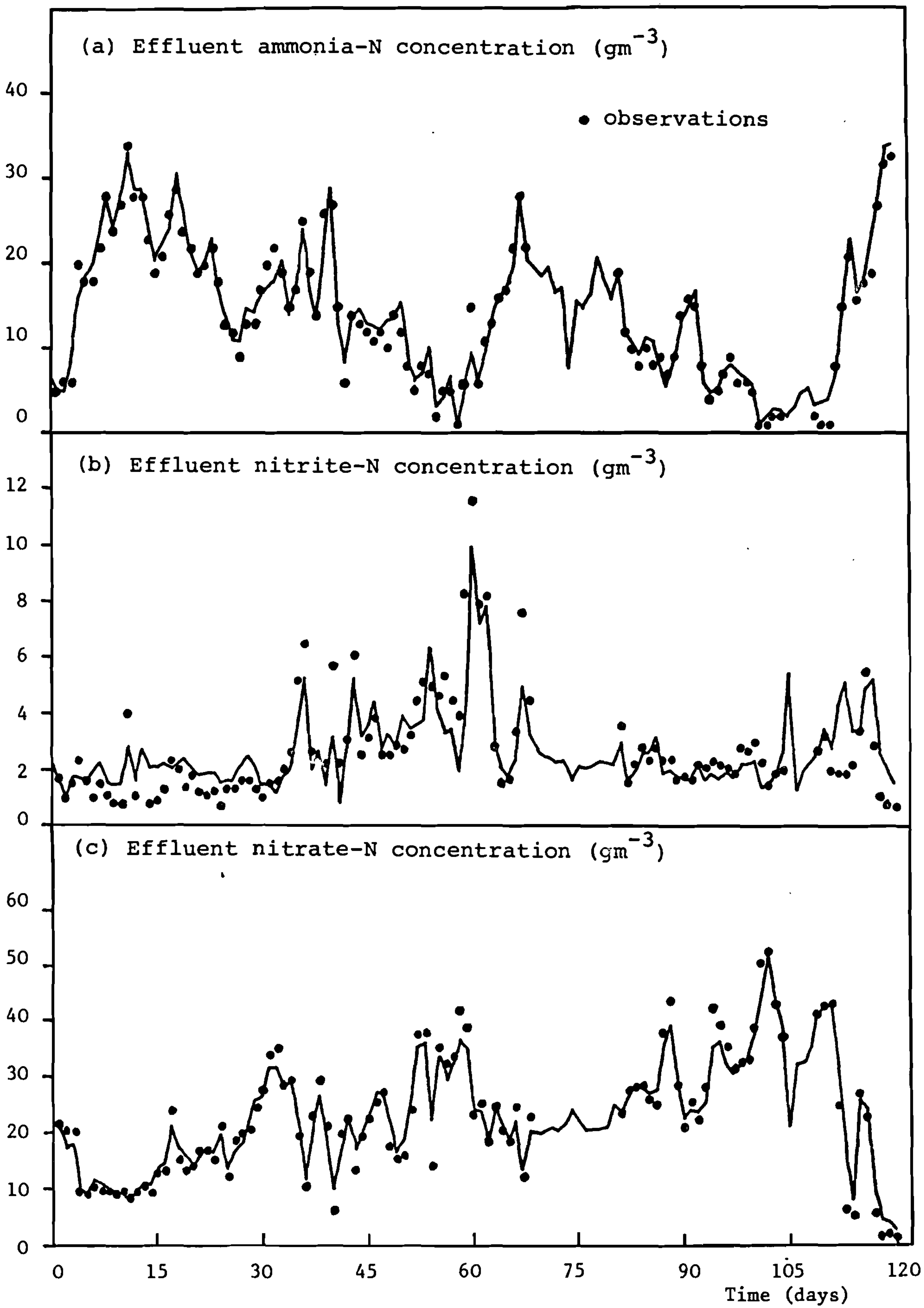


Figure 43. Nitrification model comparison of observations with filter state estimates $\underline{\hat{x}}_m$.

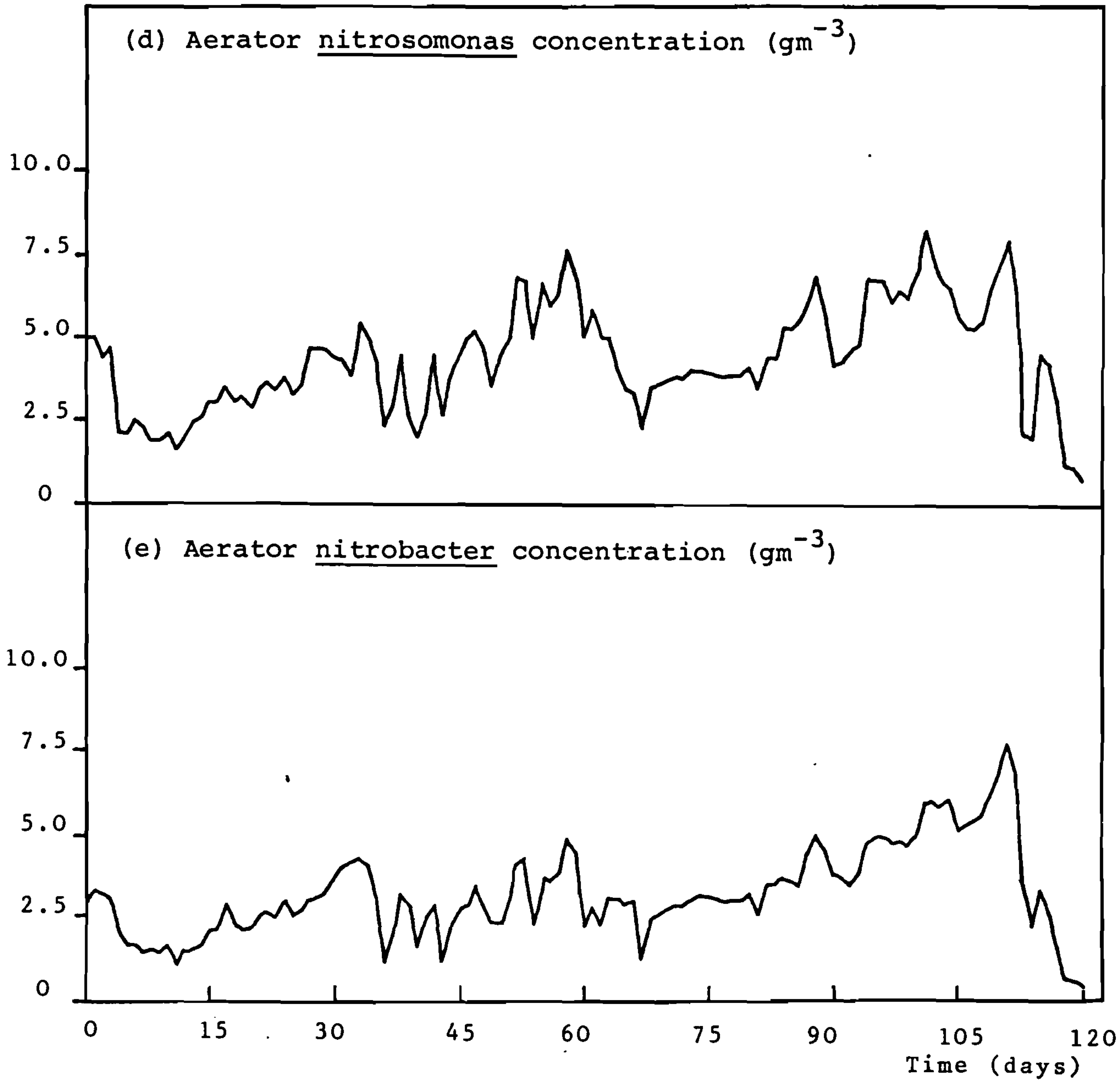


Figure 43 (contd.). Nitrification model-reconstructed state estimates $\hat{\underline{x}}_u$.

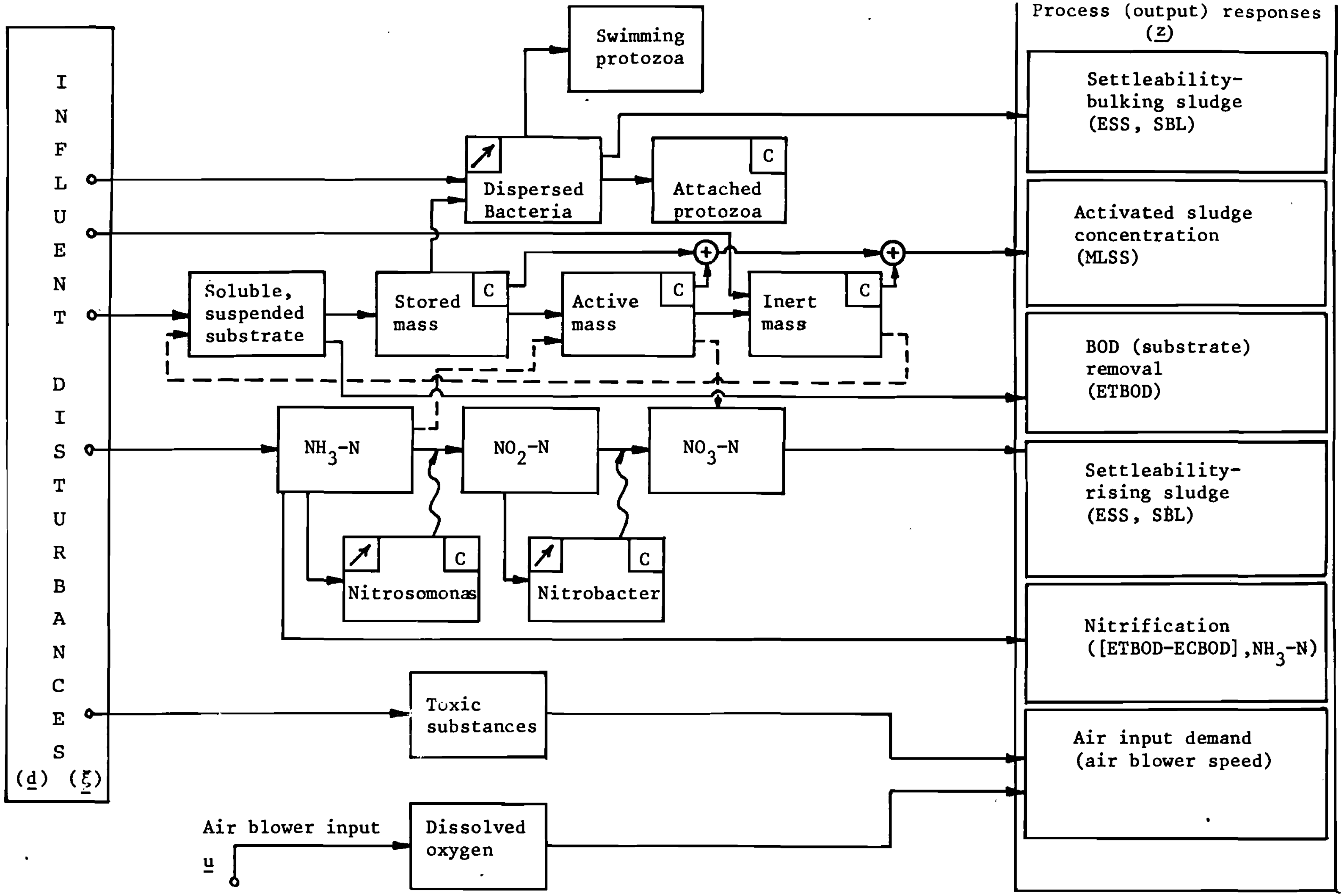


Figure 44. Aerator microbiological model; C denotes components which are compacted in the clarifier; ↗ denotes preferential enhancement of growth-rate at higher DO levels.

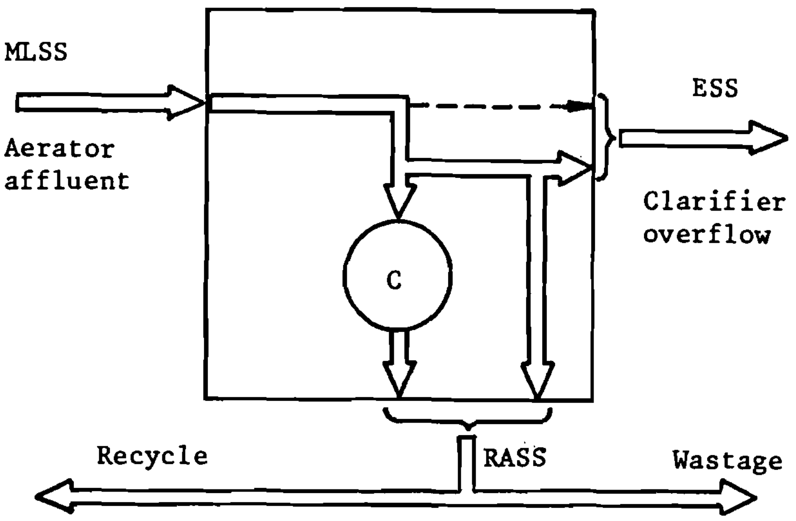


Figure 45. Model for compaction of solids in clarifier.

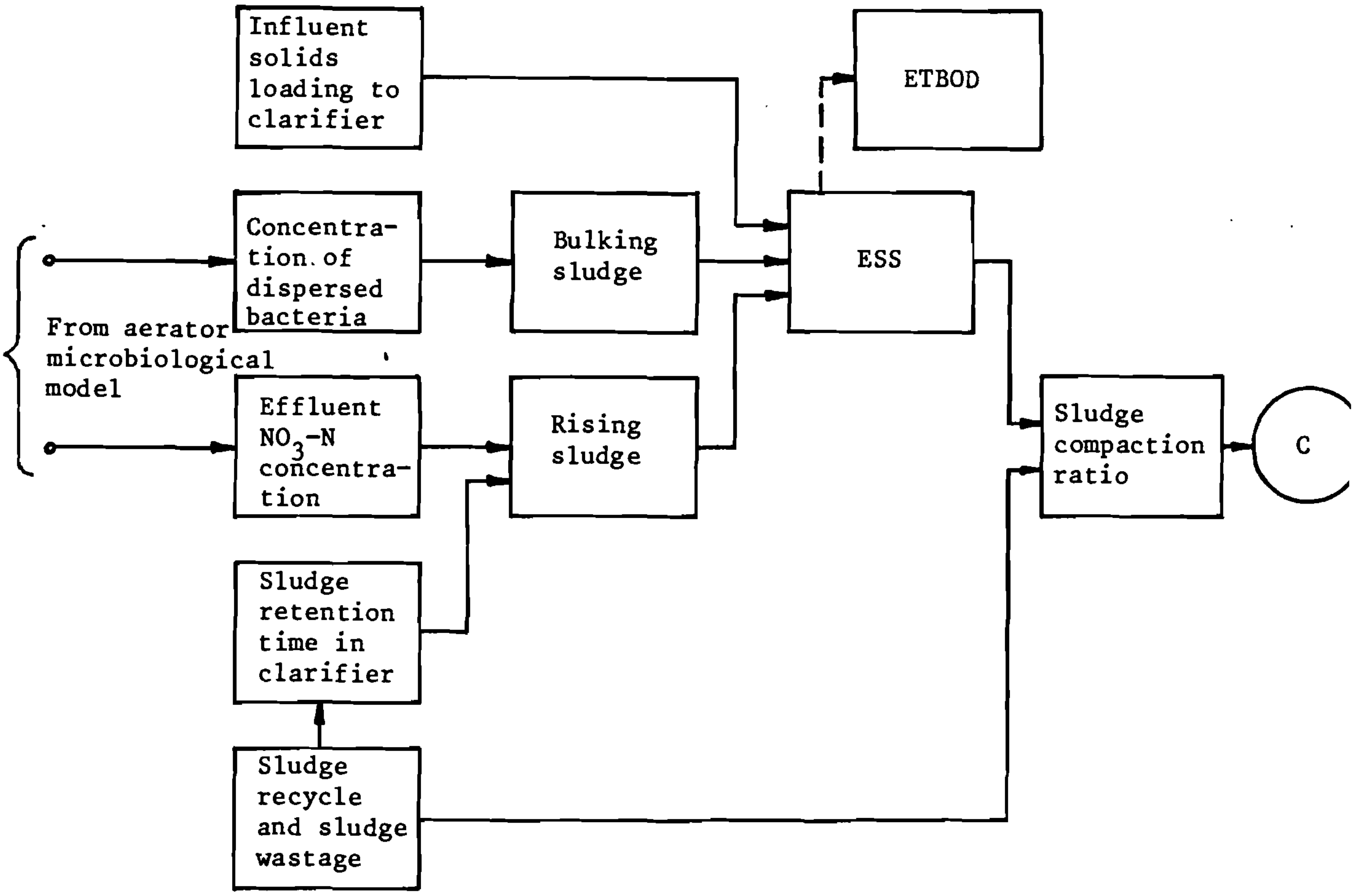


Figure 46. Determination of compaction ratio C in clarifier model.

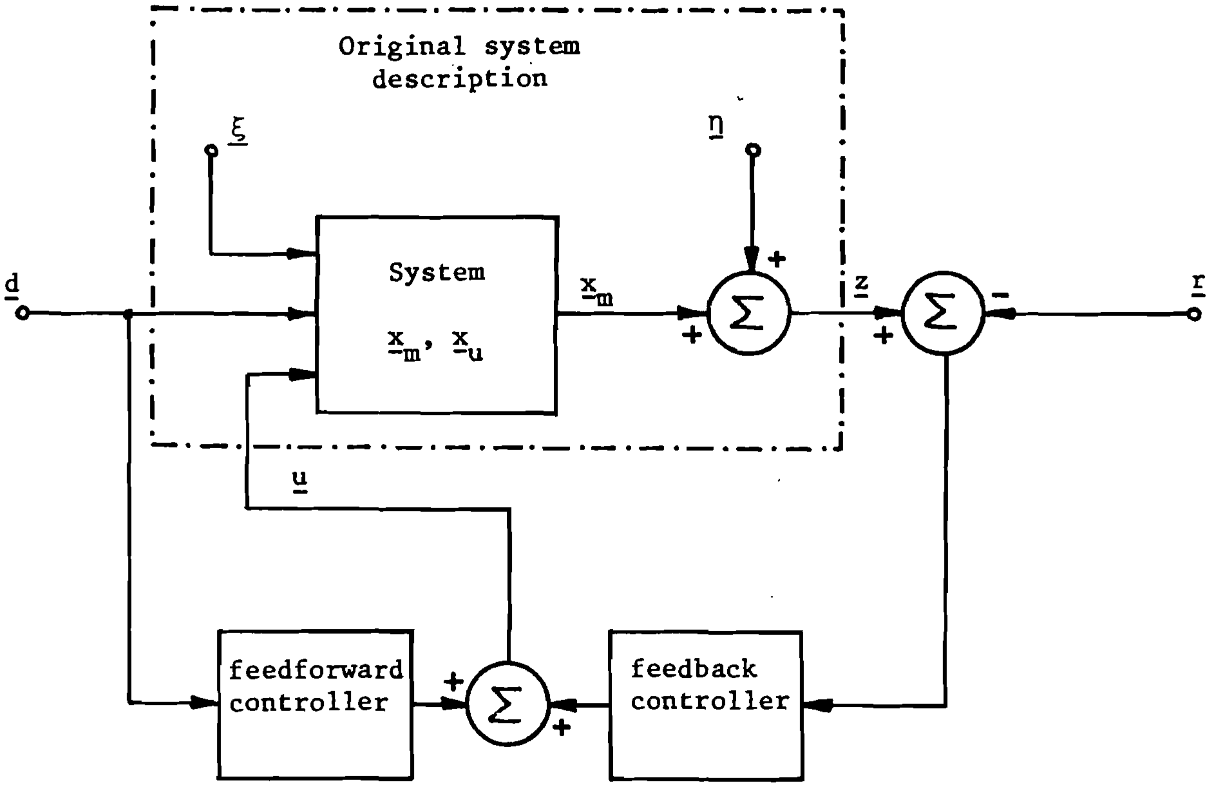


Figure 47. Principal elements of process control.

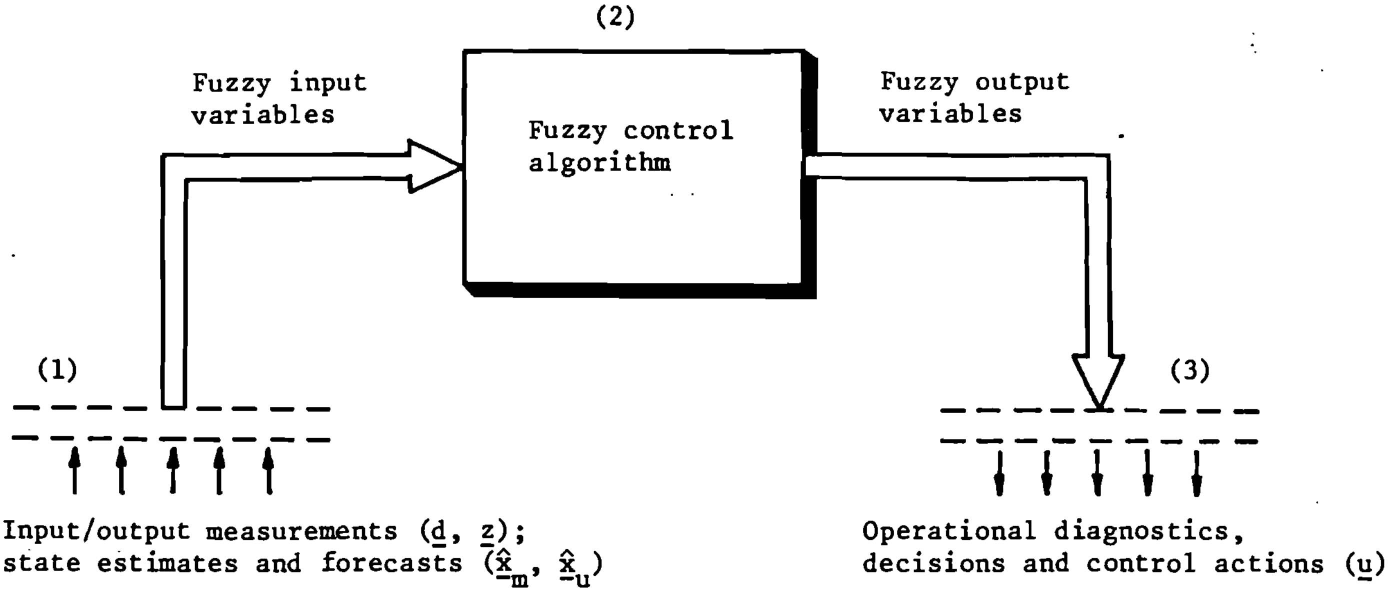


Figure 48. The fuzzy control system synthesis problem.

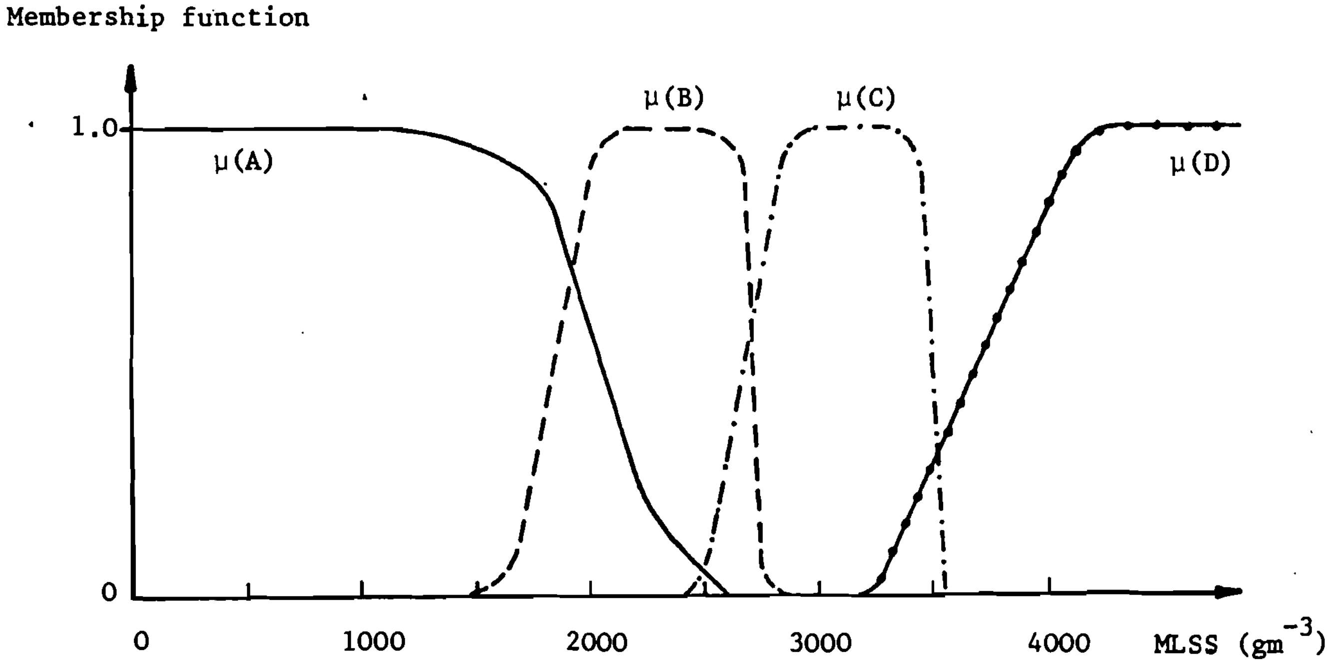


Figure 49. Membership functions for four fuzzy sets of MLSS concentration: A = (very low); B = (low); C = (medium); D = (high).

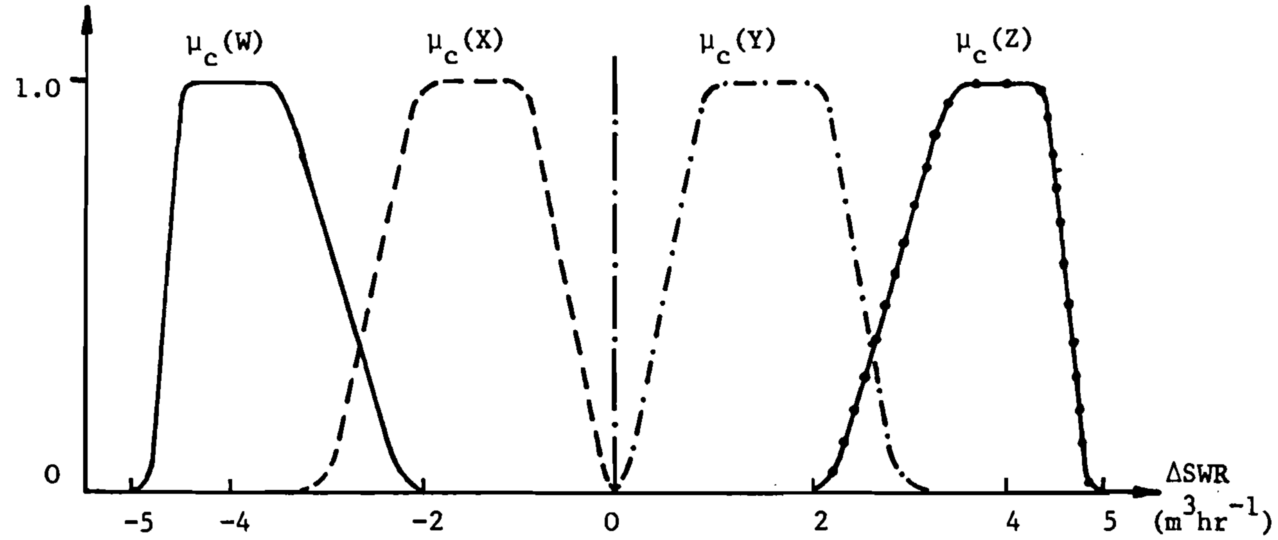


Figure 50. Membership functions for three fuzzy sets of change in sludge wastage rate.

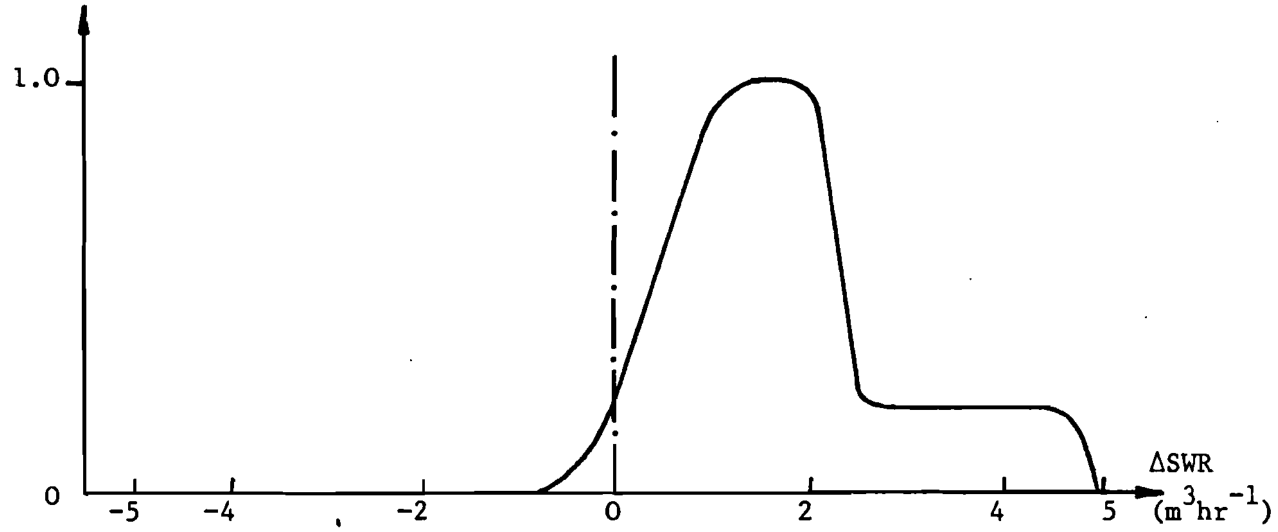


Figure 51. Example computed membership function for ΔSWR which is broadly unambiguous.

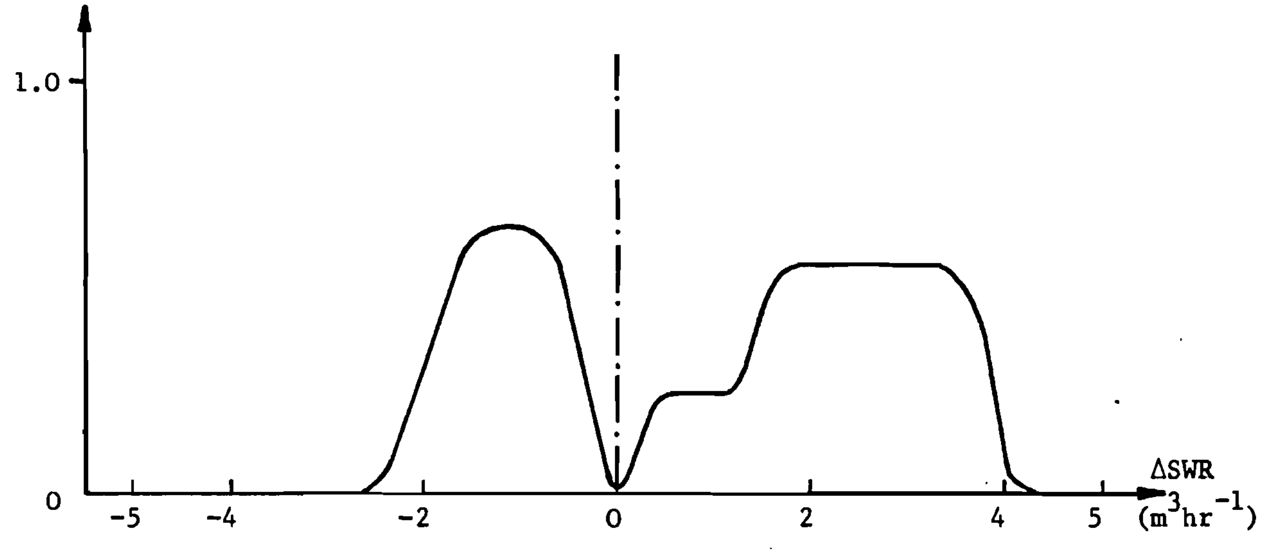


Figure 52. Example computed membership function for ΔSWR which is ambiguous.

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