Diagnosis Problems in Wastewater Settling

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Two different approaches have been investigated: parameter estimation and rule based reasoning. In this kind of application parameter estimation in time series models is not generally successful. Their drawbacks are displayed and discussed. Instead of a quantitative approach a qualitative rule based ditto is suggested. Several advantages of rule based methods are demonstrated, for example their capability to deal with unexpected situations that always appear in on-line applications. The ability to cope with on-line data is one crucial factor when looking for a methodology for diagnosis in wastewater facilities.

Odd situations with almost momentary disturbances in the return sludge flow and effluent suspended solids concentration are displayed and explained. Their appearance initiate a discussion of ways for active diagnosis, where peak disturbances may be purposefully injected to the return sludge flow in order to validate the settler operational marginal.

Key words

early warnings system; hydraulics; hydraulic impact; rule based diagnosis; return sludge control; risk analysis; settleability; settling properties.

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Occasionally the suspended solids concentration may display both large amplitude and unnaturally fast changes. If the sensor calibration has been found satisfactory, the abnormal appearance has to be explained by the process itself. There may be three principal reasons for such a behaviour: severe hydraulic conditions, poor floc separation properties or a high sludge blanket. During these circumstances it is very informative to qualitatively examine the relationships between the suspended solids concentration variations and important influencing variables, such as the flow rates and the sludge blanket level. It may be difficult to find accurate dynamical models for such extreme behaviour. However, a gross measure of the process state is often sufficient information to the operator to initiate further off-line or laboratory analysis in order to find the underlying cause.

Having found consistent data of flow rates and turbidity their dynamical relationships can be further analysed. Generally, there is an obvious dynamical causality between the hydraulic conditions, the sludge blanket level and the effluent suspended solids concentration.

Two different approaches have been investigated: parameter estimation and rule based reasoning. In this kind of application parameter estimation in time series models is not generally successful. Their drawbacks are displayed and discussed. Instead of a quantitative approach a qualitative rule based ditto is suggested. Several advantages of rule based methods are demonstrated, for example their capability to deal with unexpected situations that always appear in on-line applications. The ability to cope with on-line data is one crucial factor when looking for a methodology for diagnosis in wastewater facilities.

As in any parameter identification method, sufficient excitation of the system, e.g. by flow changes, is required. In other words, not all consistent data series are suitable for diagnosis. However, rule based methods may be applied to a significantly wider range of situations than parametric dittos. This is one important punch line of this work.

Odd situations with almost momentary disturbances in the return sludge flow and effluent suspended solids concentration are displayed and explained. Their appearance initiate a discussion of ways for active diagnosis, where peak disturbances may be purposefully injected to the return sludge flow in order to validate the settler operational marginal.

Contents

Preface

This thesis is presented for the degree of Licentiate of Technology[1] at the Department of Industrial Automation at Lund Institute of Technology.

An attempt has been made to present this thesis in a form that may be accessible for both people already familiar with the area of wastewater treatment as well as those with a general technological survey.

The starting conditions for this work was to use parametric methods in diagnostic purpose for the settling process of activated sludge. That methodology had already shown promising results when applied to pilot scale processes. The aim was to further develop and apply the methodology to on-line use under full scale operating conditions.

However, reality had some surprises in readiness. I was firmly struck by the pitfalls in on-line full scale data acquisition. In order to apply the assumed methodology the work started to focus on recognising, selecting and matching proper data. This process turned out to be far more complicated than expected and only a minor part of the data was usable.

At this time thoughts started to spin in new circles. The procedure mentioned above actually *knew* a lot more about the process than the parametric methods it applied. In order to find a suitable set of data it had to. It had to recognise process failures, abnormal conditions, etc. An approach for diagnosis based on simple features of the data started to evolve.

So much for a background introduction. The rest of the story is presented inside.

Lund, 1st of April 1996

Sven-Göran Bergh

[1] A Swedish degree that is intermediate between M.Sc. and Ph.D.

Between thought and expression lies a life time

Lou Reed

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1 Introduction

This work will focus on the applicability of two different approaches to diagnosis in the settling process. The aim is to be able to produce early warnings for deteriorating sludge separability properties. Often the evolution of such problems is a long term process, reflecting changing microbial conditions.

Those readers that are not familiar with the area of wastewater treatment will find a short survey in the first section. Those with previous experience in the field can skip this section. In the second section a short review of the area of sedimentation modelling is done. The basic conditions for this thesis are described in the third section. Then the practical limitations and the scope of the work are reflected. An overview of the work is given in the last section, and the content of the different chapters is outlined.

1.1 Novice Survey of Wastewater Treatment

A wastewater treatment plant can appear in many different fields, such as pulp and paper and chemical process industries as well as municipal systems. Consequently, there exist a wide range of process configurations. An appropriate introduction to the field of wastewater treatment is found in Henze et al. (1995), Eckenfelder–Grau (1992) or Andrews (1992). This work deals with some of the problems involved in municipal wastewater treatment. However, some of the results and conclusions might be applicable in other areas as well.

Large treatment plants are designed for an average flow throughput in the magnitude of 1-5 m^3/s. An ordinary configuration of a municipal treatment facility is given in Figure 1.1. Often the first step is some screening to remove large objects (the most unbelievable things may appear, like Christmas trees) and grit chambers to separate sand and gravel from the wastewater. Smaller particles are separated from the liquid in the primary sedimentation. The volume of such a settler may vary from 500 to 3000 m^3. Often there are two or more in parallel. Some dimensions of a large Swedish plant, the Rya wastewater treatment plant in Göteborg, is given in Appendix C.

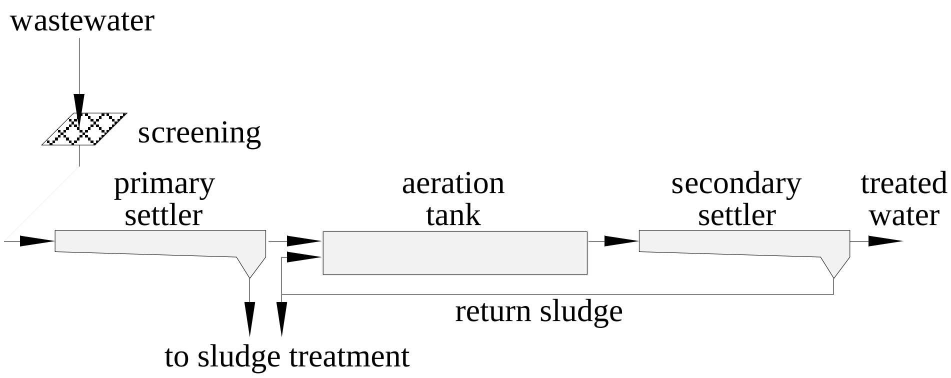


Figure 1.1 Schematic outline of a the main detachments in a municipal wastewater treatment plant.

The next major functional step is the biological treatment. Here, the purpose is to achieve good living conditions for the kind of micro-organisms wanted to do the work. The water contains organic components, nitrogen and phosphorus compounds. These nutrients are used by the organisms for their growth. For the organic removal the organisms need oxygen, and the organism growth produces more organisms, plus carbon dioxide and water. Hence, the term *activated sludge systems* often is used and these basins are also called *aeration tanks*. There is a challenge to create good conditions for the right type of organisms in the aerator.

Since the mass of micro-organisms grows continuously, there has to be a withdrawal of the relatively small amount of excessive sludge. This is arranged in the secondary sedimentation. Here the sludge containing the micro-organisms is separated from the liquid. Typically 0,5-3% of the separated sludge is considered as excessive and withdrawn, while the rest is recirculated back to the biological step. Since the sludge is the primary tool in a biological treatment facility it has to be handled with care and not unnecessarily wasted.

Several conditions in a treatment facility are reflected by the functionality of the secondary settler. Sludge flocculation properties as well as hydrodynamics influence the settler behaviour. Consequently, poor operating conditions in a wastewater treatment plant sooner or later cause settleability problems and unwanted loss of sludge.

1.2 A short review

The aim of this work is not to present a model that fully describes the settling process. However, a survey of existing models and their basic principles is still appropriate. This section gives a modest review of the evolution in this area.

The phenomena of sedimentation has been of interest ever since the beginning of the century, when Hazen (1904) presented a concept for overflow rates. In the middle of the century Kynch (1952) introduced a flux theory for hindered settling that still is generally accepted. It states that the suspended solids concentration should be considered when the relative settling velocity is calculated. This dependence may be expressed in different ways, but in general there are two empirically found relations that are used.

The relationship was first described by a power expression suggested by Yoshioka et al. (1955)

$$v_s = k_0 X^{-k_1} \tag{1.1}$$

where v_s is the relative settling velocity and X is the local concentration of suspended solids, while k_0 and k_1 are constants that have to be found for each sludge. However, the power function is not valid in the diluted region, as it approaches infinity for small concentration values.

The most common approach uses an exponential function instead. It was first explored by Thomas (1963) and Vesilind (1968)

$$v_s = k_0 e^{-k_1 X} \tag{1.2}$$

with the same notations as in (1.1). Even if the exponential function is valid in a wider range of solids concentration it does not describe low concentration settling, or small particles, very well. A more complicated numerical treatment is also required when it is used with the flux theory.

Both the power function and the exponential function must be calibrated to the current conditions and the actual properties of the specific sludge. Once the sludge properties change the calibration is no longer valid and has to be repeated. More convenient routines for calibration has been presented later, e.g. Härtel–Pöpel (1992), where a measure of the sludge properties, i.e. the sludge volume index (SVI), is used to obtain the parameter values.

While both approaches presented above were obtained empirically, Cho et al. (1993) used an analytical description of flows in porous media to derive their expression

$$v_s = k_0 \frac{e^{-k_1 X}}{X} \tag{1.3}$$

This expression does not suffer from the limitation of the power model, while it is easier to handle than the pure exponential approach.

In order to use the flux theory the settler has to be discretized and divided into elements. In 1-dimensional modelling the settler is divided into several horizontal layers. Every layer is considered to have a homogenous concentration of suspended solids. The flux theory is applied to describe the exchange between the layers. Furthermore, each layer has to fulfil the law of mass conservation. This is the case in Vitasovic (1989).

In order to overcome the problems with low suspended solids concentration several techniques have been suggested. Ossenbruggen–McIntire (1990) introduces a maximum restriction for the relative settling velocity. Takács et al. (1991) divides the concentration range into four regions and uses this restriction in one of them. Later Patry–Takács (1992) combined this restriction with a double exponential expression,

$$v_s = k_0 e^{-k_1 (X - X_0)} - k_0 e^{-k_2 (X - X_0)} \tag{1.4}$$

where X_0 denotes a non-settleable fraction of particles. The first term is recognised from (1.2) and dominates the expression for high concentrations of suspended solids, while the second term is dominating during more diluted conditions. The balance of the two terms is determined by the relation between the values of k_1 and k_2.

Other means of handling the slow settling micro flocs have been used. Parker et al. (1971) presented a distribution of the size of sludge particles entering the settler. Otterpohl–Freund (1992) made use of this and assigned the micro flocs a small constant settling velocity, while Dupont–Henze (1992) used zero settling velocity for the micro flocs.

However, there are several known phenomena that are not included in the 1-dimensional models mentioned above. Density currents and short circuiting from the inlet to the return sludge flow are effects that Dupont–Dahl (1995) incorporated.

In the models above a common basic structure is recognised, while a more analytical description of the sedimentation process was suggested in Diehl et al. (1990) and Diehl (1995).

Another obvious insufficiency of the 1-dimensional models is the ability to take the internal hydraulics into consideration. Instead, 2-dimensional models may achieve a more elaborate picture of the hydraulics, even though it is rough. Such an approach is presented by Krebs (1991) and Zhou–McCorquodale (1992).

Lately some excellent surveys have been presented. For a quick introduction to the principles of the different models and their limitations Krebs (1995) is recommended. A comparative study of models suited for on-line use is presented in Grijspeerdt et al (1995).

One common drawback of the models presented is that they are more or less complicated to calibrate. In order for a model to be implemented on-line it has to be easily updated. The most common way of handling this is by incorporating results from different kinds of test. The use of SVI in Härtel–Pöpel (1992) is already mentioned. Another example is found in Lee et al. (1996) that estimates the density and sizes of the flocs by free-settling tests. A different approach is presented in Tenno et al. (1995), where a relation between the suspended solids concentrations in the aeration tank and in the settler is used (Tenno–Pelkonen, 1994). The sampling and test is performed automatically in order to keep an on-line identification model up to date.

1.3 The Basic Problem for the Thesis

Solids-liquid separation is of crucial importance in all wastewater treatment systems, in particular in activated sludge systems. This is true in a wide spectrum of operating conditions. During severe hydraulic loading the settler becomes the bottle-neck. Likewise, the long term development of the microbial species determines the floc structure, and this in turn is directly reflected in the separability of the sludge. Due to these reasons, it is essential to find ways to automatically detect any changes in the settling properties.

Poor settleability properties will deteriorate the plant performance significantly. Typically the floc structure evolves very slowly. A deterioration is often not observed immediately in the effluent suspended solids. Rather, as long as there are only small disturbances in the plant a poor separability may be hidden, and the effluent suspended solids concentration may look acceptable. Any disturbance, however, may suddenly excite a large change in the effluent suspended solids concentration. Consequently, it is desirable to find early signs of poor performance. Here, the idea is to extract as much information as possible from available on-line sensors in order to predict plant failure.

As a first step diagnosis methods will be used to observe the settling process behaviour and try to detect odd changes. Just the knowledge that something is wrong may many times be a piece of useful information. Even if no reason or explanation can be found, this knowledge may initiate further actions to find it. Manual inspection might be enough, otherwise laboratory tests might give an answer. In this perspective, diagnosis is simply a tool for the operator to run the plant.

Depending on the method used for diagnosis, different possibilities may be offered. Some methods have the ability to try and find explanations for a process failure. Other methods may only be able to tell if the processes are working properly or not. The former methods can often be a complement to the latter. Possible explanations may of course be used first to guide the operator to examine the most likely causes and thereby hopefully gain some time. This time may be used to adjust the operating conditions and try to get the process on the right track again.

Since this field is highly interdisciplinary the terminology may differ depending on the background of the one using the words. For this reason it might be appropriate to try and explain what are meant by some expressions in this thesis.

When the term *settling process* is used the entire settler unit is considered. The settling process may then be divided in two sub-processes: the *clarification process* and the *thickening process*. In the *clarification process* the volume over the feed point is considered. Consequently, the *thickening process* is regarded as the volume below the feed point. The terminology is illustrated in Figure 1.2.

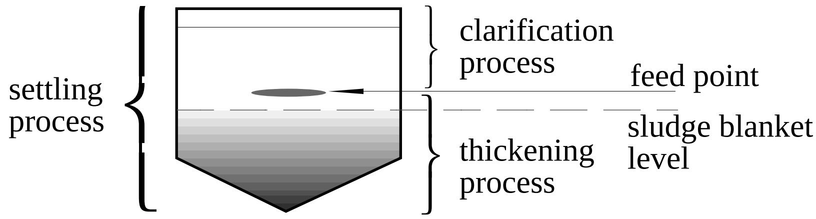


Figure 1.2 The settling process may be divided into a clarification process and a thickening process. The two are separated by the feed point.

It is harder to state a precise definition for the term *sludge blanket level*. A rough description is the depth in the settler where the magnitude of the suspended solids concentration gradient is at its maximum value.

Likely the term *normal conditions* will be used for the settler. Normal conditions include a regular acquisition of good reliable data describing a well functioning process. The interaction of the different parameters does not cause any major concern. Hopefully the settler would be in a normal condition most of the time, but this is not always the case.

A list of symbols is found as the first section of the Appendix.

1.4 Scope of the Work

It is assumed that flow rates and suspended solids can be measured on-line. The attempt is to find a diagnosis method that does not need any further sensor installations than already exist at most facilities. There are always some compromises. For example a sludge blanket detector may improve the information significantly, but has not been included in the method presented. This is due to the fact that sludge blanket measurements are not common in wastewater treatment plants.

There are two kinds of information that forms the basis for the diagnosis. One is qualitative and quantitative analysis of individual signals. This kind of information is mainly straight-forward to derive. The second is the interaction between different flow rates and suspended solids concentrations. To derive information from interactions and relationships more sophisticated methods are needed. In this work parameter estimation and rule based reasoning have been investigated.

A major problem in the beginning of this work was the quality of on-line data from full-scale facilities. No guarantees, what so ever, can be made regarding the data quality a diagnosis method will face. It is certainly not enough to validate the principles of an approach that only has been tested with laboratory or pilot scale data. This understanding was the core of a major change in the approach made during this work.

As in all data handling it is crucial to critically review the data for its consistency. It is suitable to use a simple knowledge based reasoning for this type of preliminary "filtering". The signals are examined with respect to extreme values, sudden changes, missing data, possible outliers, etc. A major message of this work is, that these qualitative features are of central value for the diagnosis and for predicting process upsets. The computational basis for this is described. Finally, some consequences of this kind of reasoning are shown. The results demonstrate, that qualitative analysis of data give a significant information for risk estimates.

1.5 Overview of the Work

Conditions for diagnosis and related problems are discussed in Chapter 2. Some of the related parameters are presented and the time aspect of different measurements is studied. General considerations of methods for diagnosis are also described. Some desired features for such a method are emphasised.

Hydraulic conditions are discussed in Chapter 3. The hydraulic propagation along the plant has to be understood properly in order to implement adequate diagnosis and control. Former unnoticed phenomena regarding the return sludge flow are presented and interpreted.

Parametric methods for diagnosis are examined in Chapter 4. Their suitability regarding the on-line conditions and desired features mentioned in Chapter 2 are considered.

In Chapter 5 it is shown how basic properties can be extracted from *normal* as well as exceptional data. In particular, the relationship between flow rates and effluent suspended solids concentrations are demonstrated.

Finally, the work is summarised and some conclusions are drawn in Chapter 6.

2

Diagnosis — Some Preliminaries

In this chapter conditions for on-line diagnosis will be discussed. It is generally considered to be a significant interaction between biological and settling properties. Sludge with compact flocs seems to settle faster than sludge with a lot of filaments. This relation is indeed complex and unknown, but it exists. In this work there are no ambitions to model this relationship, but to make further use of it. If a change in the settling properties is observed it is probably caused by some change in the biological properties.

Different parameters influencing the settling process will be discussed below. The matter of time is important in any process control application. Since there is such a wide time span to consider, such as biological, dilution and hydraulic effects, time is especially significant in waste water treatment. Influence of time aspects on the ability of diagnosis is described. Finally some general considerations are discussed.

2.1 Parameters Characterising the Settling Process

There are numerous parameters that influence the settling process. Some of them are hidden in different macroscopical tests, that do not explain their properties. A selection of these parameters is discussed below.

Sludge volume index, SVI, is a rough measure of the sludge settling properties. The test shows how far the thickening process has reached after 30 minutes. The settling velocity as a function of time is not monitored. Therefore, it is possible that two kinds of sludges with the same SVI show different settling properties. SVI is a standard test that is performed regularly on most major plants. Though it does not supply any complete information about the sludge it is a guideline for more sophisticated tests.

The main purpose of the settling process is to separate sludge and water. Information on how this aim is fulfilled is essential for the plant operation. This information is obtained with special gauges for the concentration of suspended solids in the effluent, here called C_{out}. The measurements are not simple and may imply some problems caused by failing gauges. Even if it is not common to find on-line sensors for secondary clarifier effluent, this work can prove the added value of having such a facility.

Diagnosis may also rely on suspended solids concentrations at various locations. Those of most interest are the suspended solids in the return sludge flow, C_r, in the bioreactor, C_{bio}, as well as in the influent to the settler, C_{set}. The suspended solids concentrations in the bioreactor are measured on-line at many plants.

Usually one would like to quantify the suspended solids concentration in weight per volume, e.g. mg/l. However, due to the principles of the measurements it is instead given as turbidity. Measurements of suspended solids are usually noisy and may include extreme changes, e.g. during a wash-out period. Sometimes it has to be thoroughly tested and reconsidered before used for any diagnosis purpose, otherwise it is easy to end up with wrong conclusions.

The hydraulics in the plant has a crucial influence on the settling process. Variations of the influent flow, Q_{in}, will propagate through the plant and affect the hydraulic conditions in the settler unit. The flow into the settler unit, Q_{set}, is not identical with the influent flow to the plant (Olsson-Stephenson, 1985). It will be subdued and delayed depending on the configuration of the plant. When Q_{set} is not measured it must be approximated or reconstructed so that an adequate opinion on the settling hydraulic conditions can be obtained. Due to practical reasons the effluent flow, Q_{out}, might be measured instead. The reconstruction of the various flow rates is shown in Chapter 3.

The under-flow in the settler affects the hydraulics as well. It is well known that variations in the return sludge flow, Q_r, will propagate through the aeration step and further on hit the settler (Olsson, 1985), and consequently the clarification process. Other phenomena, that previously have been disregarded, appear at rapid changes in the settler under-flow. Chapter 3 will give a closer view of these phenomena.

The level of the sludge blanket is rarely measured on a routine basis, but might append useful information on the settling process. Due to limitations in presently known models for the thickening process it is difficult to estimate the level of the sludge blanket. Available gauges have shown poor performance, and they are still too expensive to be of interest for minor or medium size plants. For this reason it is not recommended that methods for diagnosis rely on measurements of the sludge blanket, even if the information is valuable when it is present.

There are several other factors or phenomena that influence the settling process. Further investigations on their influence are found in Lumley (1985) or Pflanz (1969). The effects of most biological activities are for example still unknown. However, some are known and have even been incorporated in settling models. Henze et al. (1993) presents a settling model that accounts for the release of gas due to denitrification in the settler.

2.2 Time Horizons

The settling process is affected by various phenomena, each in its own time scale. A rapid change in the influent flow might appear within minutes, while the corresponding reaction in the effluent suspended solids appears after typically half an hour. The composition of the flocs is connected to micro-biological phenomena and will change slowly, during a period of weeks or months. Slow changes bring up a special problem of their own. They are difficult to detect at an early stage and it is hard to correct or control them when they have become obvious. Every method for diagnosis have to take these big differences of the time horizons into consideration.

Even an information flow has a time horizon. The time for a sample to be taken, treated, analysed and interpreted can represent this time horizon for information. Various information in a WWT plant are spread over a wide spectrum of time. Some variables are always available on line, while some other information might take a long time to get hold of. Then it may no longer be relevant.

A rough division of information depending on its availability might be on-line information, off-line information and information of difficult access.

On-line information is gained directly from some sensor. Alarms based on on-line information, such as flows, suspended solids, temperature or pH, are quick and simple to supply.

Off-line information call for on-line information, or manual samples, to be treated in one or several intermediate steps before it is presented. There are often well developed routines to gain the information. It might take from a few minutes up to days. Alarms based on off-line information are relatively simple and might eventually be manual. Common off-line information are respirometric analysis or simple tests of the sludge properties, such as sludge volume index. Note that the term off-line denotes a time aspect more than a procedure. Some respirometers operate on-line and are fully automated. Anyhow, there is a time delay for about half an hour of processing before any information is gained. Therefore respirometric information is considered to be off-line in this work.

Information of difficult access call for a more ambitious and purposeful piece of work, that demands longer time. There are seldom any standard routines to do this. For this reason it is hard to define any alarms. It takes a long time and must be done manually. Typical information of this kind are identification of micro-organisms and various floc properties.

Several of the parameters of difficult access influence the settling process, but the knowledge about them is limited. Furthermore, these parameters often change in a slow rate, which implies a slow change of the settling properties. The result of this is seen in the effluent suspended solids. The changes are difficult to detect at an early stage, which is illustrated in Figure 2.1. A major problem is to distinguish between changes of the effluent suspended solids concentration due to changing settling parameters and due to other variations. Since a treatment plant is a dynamical process and most often is in a transient state the outgoing suspended solids will vary.

To calculate how much of the variation that is due to a dynamic load and what is caused by changed floc settling properties is not a trivial task. The desire to try and detect changes in the floc structure under such conditions is well motivated. Even though, the change in the effluent suspended solids, C_{out}, in Figure 2.1 is quite potent it might be hard to detect it early. When the whole period is reviewed off-line there is an obvious change in the effluent suspended solids. However, assume that this was an on-line situation: when had the change been detected?

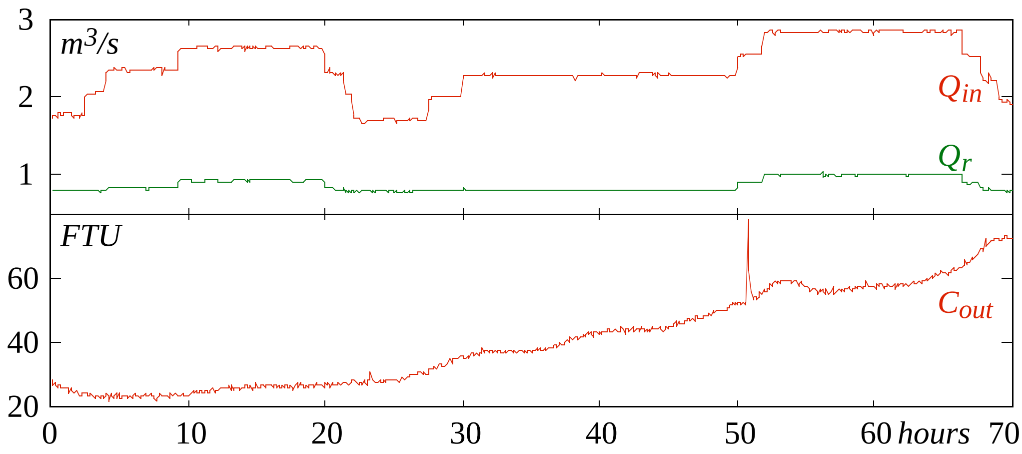


Figure 2.1 A situation of concern. An underlying change in the settling properties cause the effluent water quality to deteriorate.

2.3 General Considerations

Methods for early detection of changes in the settling properties should only involve the most essential measurement variables. It is not desirable to include variables that are not absolutely necessary since they will increase the complexity and make the method depend upon further measurements. Necessary variables are the effluent suspended solids, C_{out}, and some variables describing the hydraulic situation in the settler, for example Q_{set} and Q_r. The sludge blanket level is also highly relevant, but unfortunately it is rarely measured so it is not wise to incorporate it in a general method.

Some different data situations will be presented below to get a general feeling for what kind of data such a method might meet. The term *normal* conditions will be frequently used indicating situations without any serious problems. This is not necessarily the same as common conditions. Using this terminology some examples of both normal and abnormal conditions are discussed below.

Consider two crucial variables for the settler conditions, the plant influent flow rate, Q_{in}, and the effluent suspended solids concentration, C_{out}. For normal conditions the impact of the influent flow rate on the effluent suspended solids concentration is obvious. This is clearly demonstrated in Figure 2.2. The apparent dynamical relationship between Q_{in} and C_{out} has been described by Olsson-Chapman (1985). The gain and the time constant of this relationship is strongly coupled to the floc properties and may change slowly with time. For such normal data it is straight-forward to derive dynamical models using time series analysis or similar methods, see e.g. Ljung (1987). All settler models, steady state or dynamical, such as Pflanz (1969), Vitasovic (1989), Patry-Takács (1992) or Krebs (1991), rely heavily on such normal operating conditions.

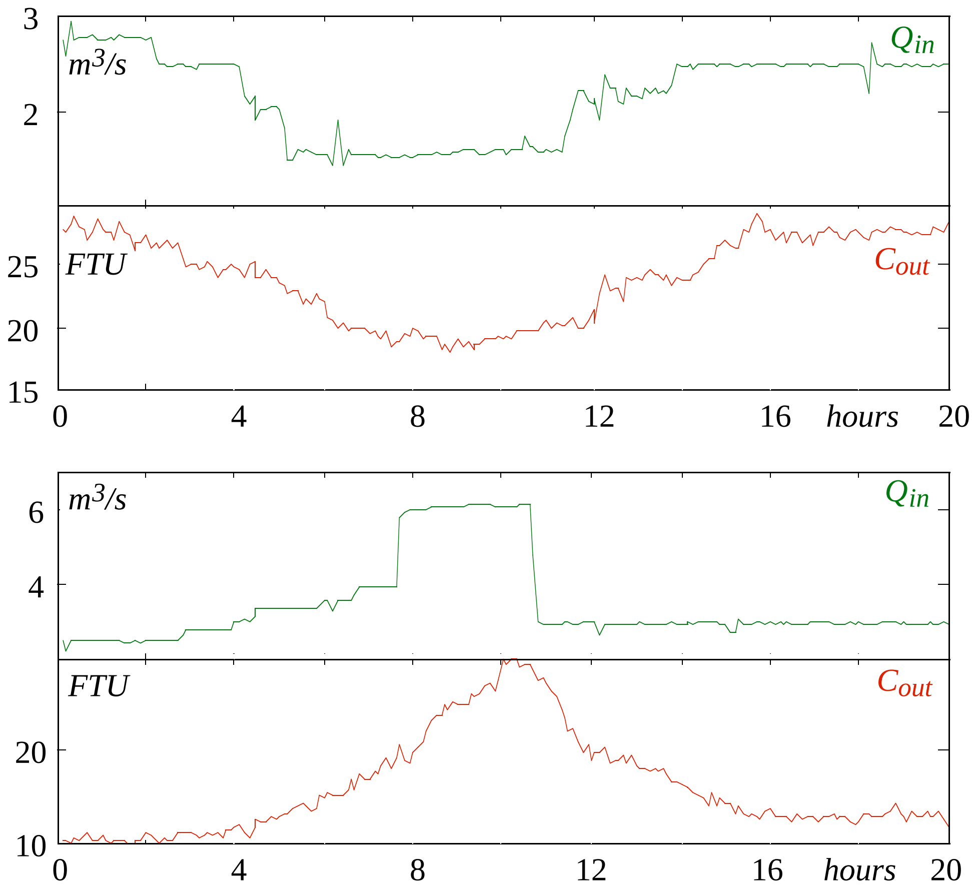


Figure 2.2 Two examples of so called normal conditions in a large municipal treatment plant. The distinct dynamical relationship between the influent flow rate Q_{in} and effluent turbidity C_{out} is typical for how "good data" should appear.

A common model structure for numerical estimation is the ARMAX-model, auto regressive moving average with external input,

$$C_{out}(t) = -a_1 \cdot C_{out}(t - \Delta t) - \ldots - a_{n_a} \cdot C_{out}\left(t - n_a \cdot \Delta t\right) + \\ + b_1 \cdot Q_{set}(t - \Delta t) + .. + b_{n_b} \cdot Q_{set}\left(t - n_b \cdot \Delta t\right) + e(t) \tag{2.1}$$

Most models that have been successfully used in earlier works, such as Olsson-Chapman (1985), are related to (2.1). These works have been carried out during favourable conditions. Often the data sets originate from pilot plant facilities. Since this kind of methods heavily rely on some excitation of the process it has been convenient to excite it manually. Even though the parameters *a* and *b* in (2.1) do not have any physical interpretation it was shown that changes in *a* are coupled to the changes in flocculation properties of the sludge.

At the start of this work the basic attempt was to adapt models like (2.1) and make further use of them to track the settling process on-line. This approach seems indeed reasonable for such normal data sets, as shown in Figure 2.2. However the adaptation to the on-line world introduce a whole new scenery of unexpected conditions.

A common situation in data acquisition is loss of data, illustrated in Figure 2.3. All of a sudden the data set is not updated any more. It is often simple to detect the situation, but how should an on-line method deal with it? For example, interpolation between existing data might be misleading. Furthermore, interpolation is not possible on-line. Extrapolation can be done but gives low reliability. It is apparent that missing data during a smooth period can be successfully extrapolated on-line, while missing data during transient conditions are certainly not advisable to replace. The most honest way for an on-line evaluation method to deal with missing data is probably to conclude nothing because lack of information.

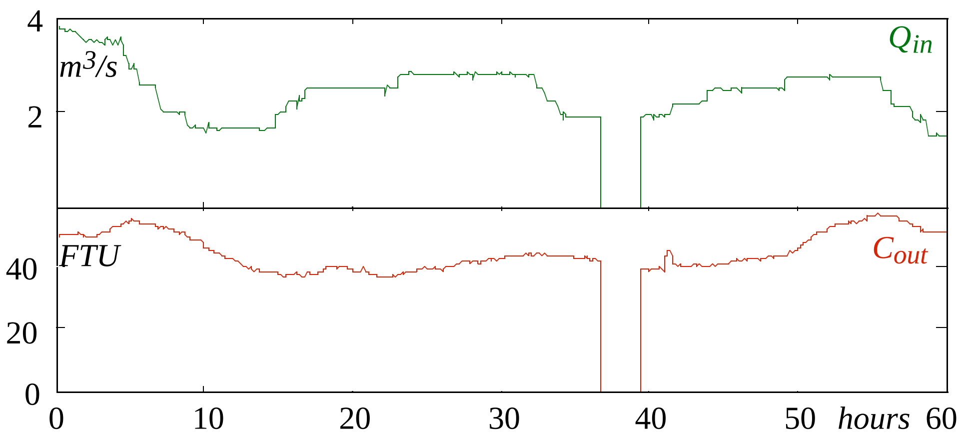


Figure 2.3 How should missing data be dealt with?

During periods of process operational problems the expected cause-effect relationship between the input and output signals may get completely lost. There are various reasons for this, such as failing sensors or upsets in the settler operation, due to e.g. bulking sludge. A period of bulking sludge is shown in Figure 2.4. Dramatic changes of the effluent suspended solids concentration appear. It may vary with a factor of 5 to 10 within minutes. An obvious reason could be an overloaded settler, where the sludge blanket level is close to the top of the settler unit. Such data sets are certainly not suitable for any numerical estimation method, since the apparent cause-effect relationship seems to have been lost.

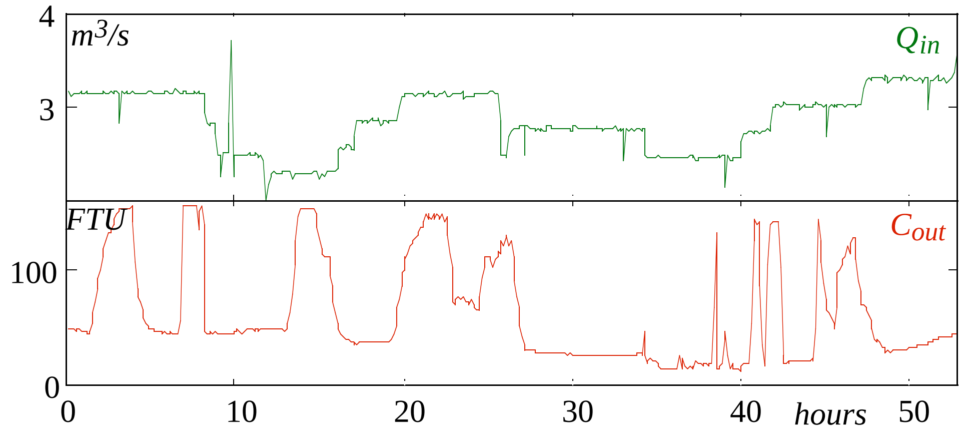


Figure 2.4 A period of settler failure in a full scale municipal treatment plant. The cause-effect relationship seems to be completely lost.

Another abnormal situation is peaks in the signal, as shown in Figure 2.5. Should a peak always be considered as an outlier? Even if it coincides with a peak in another measurement? Often a peak reflects the real process and contains valuable information. But if we do not understand why the peak appears it is easily considered to be an outlier and therefore eliminated. However, this is not just a matter of outlier elimination. The succeeding diagnosis or modelling method have to be suitable as well. Even if a peak is kept within the data set any model of the structure (2.1) will filter the peak and misrepresent its information. What might be useful information about the process state is instead misinterpreted or completely lost. Extraction of information from peak values is further discussed in Chapter 5.

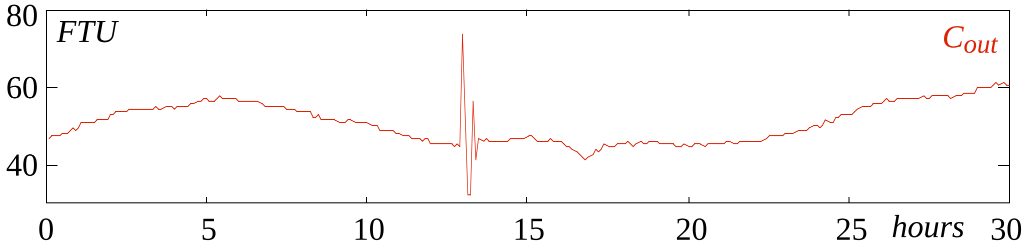


Figure 2.5 Often sudden peaks in a smooth measurement are considered as outliers. That might be true in the sense that they deviate from the surrounding data, but are they lying about the process?

It should be emphasised that many data sets are presented as average values. The data displayed in the Figures 2.2-2.5 are 6 minute samples, where each sample is a mean value of at least six measurements. This means, that if the signal suddenly jumps significantly it is not only a single value that changes abruptly but an average value. This of course increases the reliability of the data set. Consequently, a traditional outlier elimination has to be used with great care.

On entering the on-line world a number of questions occur. If numerical estimation should be used on-line the problems above have to be solved automatically in some way or another. How are suitable data sets detected and selected on-line? To be able to extract information about the process such suitable data sets must involve some kind of excitation. Process excitations never occur in an identical fashion. How should they be detected and selected on-line? By rejecting unsuitable sets of data the total amount of information is automatically reduced. Considering on-line conditions only a minor part of the data is suitable for numerical estimation. Even though, data not suitable for time series analysis may contain a great deal of information. In Chapter 3 such abnormal, but most adequate, data will be presented and discussed.

Any method used for on-line diagnosis should be prepared to meet all possible kinds of data. Even situations with extreme data, like the ones in Figures 2.3-2.5, must be recognised and suitably handled automatically. Consequently, there has to be some preliminary analysis that prevents a data sequence like the one in Figure 2.4 to be used directly for time series analysis. An easy way for a method to deal with inconvenient situations might be to ignore them, and consequently not gain any information. Such a neglect may lead to missed diagnosis possibilities. This is of course not a desirable feature of a method and should be avoided as much as possible. Instead, methods that actively evaluate the data sets and extract information during as many circumstances as possible should be encouraged.

3

Hydraulic Propagation and Return Sludge Control

Often the dynamical aspects are overlooked in the design of waste water treatment plants. Instead of a "money talks" philosophy a "concrete talks" ditto is used. Every now and then this results in a plant designed for steady state conditions at maximum flow, since that is considered to be the worst case. However, it is not. Transient conditions, at any flow situation, might be even more severe. This chapter will focus on the hydraulic conditions for the settler, because of its sensitivity to such disturbances.

First an analytical approach to return sludge control is given. Only the settler function is considered from a pure mechanistic point of view and no biological effects are discussed. However, a well functioning settler will of course improve the overall operation, and thus even the biology.

Later some strange phenomena on settler transients are shown and discussed. At a beginning they seem almost unaccountable, but certainly not coincidental. Instead an explanation has to be sought in the understanding of the physical process.

In order to explain these phenomena a dynamic model for hydraulic propagation is presented. Hydraulic differences in plant design and configuration are also discussed.

Hydraulic conditions for the settler are studied, using the described model. While two return sludge control strategies are compared and discussed from the hydraulic point of view, a simple tool to judge the settler hydraulics is suggested and used.

When the physical circumstances for the settler are dealt with, a reflection of the settler transient phenomena is done. While considering the relations between the involved measurements, a natural conclusion appears due to the settler conditions discussed earlier.

The basic principles of the phenomena discussed are verified in a couple of settler hydraulics simulations. In order to perform these simulations a beta-release of a new software package called Clarity has been used.

Since the hydraulic consequences of a proportional return sludge control strategy is questioned, an alternative strategy is suggested. Implementation of the proposed control law is then studied and discussed.

3.1 General Aspects

There has been a lot of effort spent on control of the return activated sludge (RAS) flow rate. Some consequences of different strategies are shown in Olsson (1985). A common strategy is to keep the return sludge flow constant. This is a rather sensible strategy, since there are many constraints on how the return sludge flow may vary.

Controlling the return sludge flow proportional to the influent flow rate is a rather common control law as well. The most important aspect for this control is to vary the return sludge flow as the load of the entire waste water treatment plant changes. One purpose of the proportional control is to keep the sludge blanket in the settler at a relatively constant level. Unfortunately there are some disadvantages as well. Some concerns of the return sludge flow are discussed below.

Analysis of the return sludge flow rate

Start by considering a steady state mass balance for the settler in Figure 3.1 (see further Olsson–Andrews, 1978).

Referring to Figure 3.1 a steady state mass balance is formulated:

$$Q_{in} \cdot (1+r) \cdot C_{set} = Q_{in} \cdot (r+w) \cdot C_{set} \cdot \gamma + Q_{in} \cdot (1-w) \cdot C_{set} \cdot \varepsilon \quad (3.1)$$

where the left hand side denotes the mass input and the right hand side denotes the mass output.

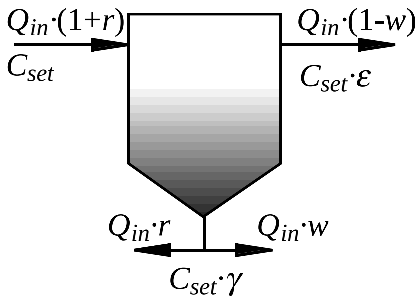


Figure 3.1 A settler, that is the subject for a steady state mass balance. The symbols used are defined in the first section of the Appendix.

The mass balance in (3.1) may be rearranged into:

$$1 + r - r \cdot \gamma = w \cdot \gamma + \varepsilon - w \cdot \varepsilon \tag{3.2}$$

Furthermore, the sludge retention time in the entire system, θ_χ, is defined by:

$$\theta_\chi = \frac{\text{Total amount of sludge in the bioreactor}}{\text{Sludge flow rate out of the system}}$$

$$\theta_\chi = \frac{m_{bio}}{Q_{in} \cdot C_{set} \cdot (w \cdot \gamma + \varepsilon - w \cdot \varepsilon)} \tag{3.3}$$

Considering (3.2) expression (3.3) may also be written as:

$$\theta_\chi = \frac{m_{bio}}{Q_{in} \cdot C_{set} \cdot (1 + r - r \cdot \gamma)} \tag{3.4}$$

If we assume that the aeration tank effluent suspended solids concentration C_{set} is representative for the average concentration of the aerated system, the suspended solids concentration leaving the bioreactor may be expressed as:

$$C_{set} \approx \frac{m_{bio}}{V_{bio}} \tag{3.5}$$

where V_{bio} is the hydraulic volume of the bioreactor. Note, to assure steady state condition, we have to consider concentrations and flow averages of typically more than a week.

The hydraulic retention time, θ_h, is defined by:

$$\theta_h = \frac{V_{bio}}{Q_{in}} \tag{3.6}$$

which also can be expressed as:

$$\theta_h = \frac{m_{bio}}{Q_{in} \cdot C_{set}} \tag{3.7}$$

Rewrite (3.4) using the hydraulic retention time instead:

$$\theta_\chi = \frac{\theta_h}{(1 + r - r \cdot \gamma)} \tag{3.8}$$

Now we have to define the constraints for the system. For example, the sludge retention time has to exceed a certain minimum value, $\theta_\chi > \theta_\chi^{\min}$. This yields:

$$(1 + r - r \cdot \gamma) < \frac{\theta_h}{\theta_\chi^{\min}} = \delta \tag{3.9}$$

where δ is the relation between the hydraulic and the minimum sludge retention time. This implies a restriction on the return sludge flow ratio, r.

$$r > \frac{1 - \delta}{\gamma - 1} \tag{3.10}$$

The second constraint is that the system should be able to treat the water, i.e. produce sludge (w>0) and separate the sludge (γ>1). The constraint, $w \cdot \gamma > 0$, is applied to the right hand side of (3.2) which result in:

$$r < \frac{1}{\gamma - 1} \tag{3.11}$$

Thus the return sludge flow ratio should be held within certain limits for a sustainable operating system,

$$\frac{1-\delta}{\gamma-1} < r < \frac{1}{\gamma-1} \qquad (3.12)$$

To get a feeling for the size of this range we illustrate with a numerical example:

θ_h = 6 hours
θ_χ = 200 hours ≈ 8 days
γ = 3

This gives δ=0,03 and the restriction

$$0,485 < r < 0,5$$

It is a remarkable small span that the return sludge flow rate are allowed to vary within, for the constraints in our example. Note that steady state is assumed and that γ has to be established for each steady state operating condition.

Limitations for the return sludge flow rate

Dynamically the return sludge flow rate may vary, but the ratio r has to be kept within narrow bands in order to keep the mass balance of the settler. If it varies too much, then the sludge blanket will drift outside its permitted range. A result of this is that the mass transport is dramatically restricted.

The statement that an increased return sludge flow rate will increase the mass transport out from the settler is thus not always true, since a higher return sludge flow rate will dilute the sludge in the settler. In other words, there exist a maximum limit for the possible mass transport of sludge out from the settler.

It is also important to take the hydrodynamical effects of the return sludge flow into consideration. This is especially true when the return sludge flow rate is variable, e.g. controlled proportionally to the influent flow rate. It will amplify an external hydraulic disturbance on the system. From a control point of view a proportional control law may be considered as a positive feedback. Changes in the influent flow rate will be amplified by the return sludge flow, yielding more drastical changes hitting the bioreactor and, after a while, even the settler. When a proportional control strategy is used the return sludge flow ratio, r, may be constant but set to a value anywhere between about 0,3 to 3.

Another hydrodynamic effect, that has not been that well studied, is the internal conditions in the settler. Rapid changes in the return sludge flow may generate internal shock waves. These disturbances will propagate from the bottom to the top of the settler within seconds. This phenomenon will be further discussed in the sections 3.2, 3.5 and 3.6.

3.2 Some Observations on Return Sludge Control

During manual scanning of a large amount of data from the Rya waste water treatment plant in Göteborg some unexpected phenomena were detected.

In the beginning the phenomena were hard to explain, but too well structured to be coincidental. They were not caused by defective sensors or outliers. Therefore some other explanation was sought.

Three representative situations are shown in Figure 3.2. At about $t \approx 2$ hours in Figure 3.2a the influent flow rate, Q_{in}, suddenly decreases. As a result of a proportional control law the return sludge flow rate also decreases rapidly. The result is seen in the effluent suspended solids concentration that immediately increases.

The Figures 3.2b-c show similar phenomena when disturbances in the influent flow rate are passed on to the return sludge flow by a proportional control law. The reaction in the effluent appears in the order of minutes.

First it is important to emphasise that it is not the influent flow that hits the settler. This flow is moderated during its propagation through the preceding basins. The actual flow change that hits the settler is lagged and dampened as will be shown in sections 3.3-3.4. However, the control strategy is such that the return sludge flow changes are directly proportional to the plant influent flow rate. This affects the hydraulics of the settler before the change in the influent flow has fully reached the settler. The hydraulic propagation time constant for a plant of this size is about 30 minutes. Thus, the rapid changes in the effluent quality can not be explained by the influent flow. Instead the effects of the return sludge flow has to be considered.

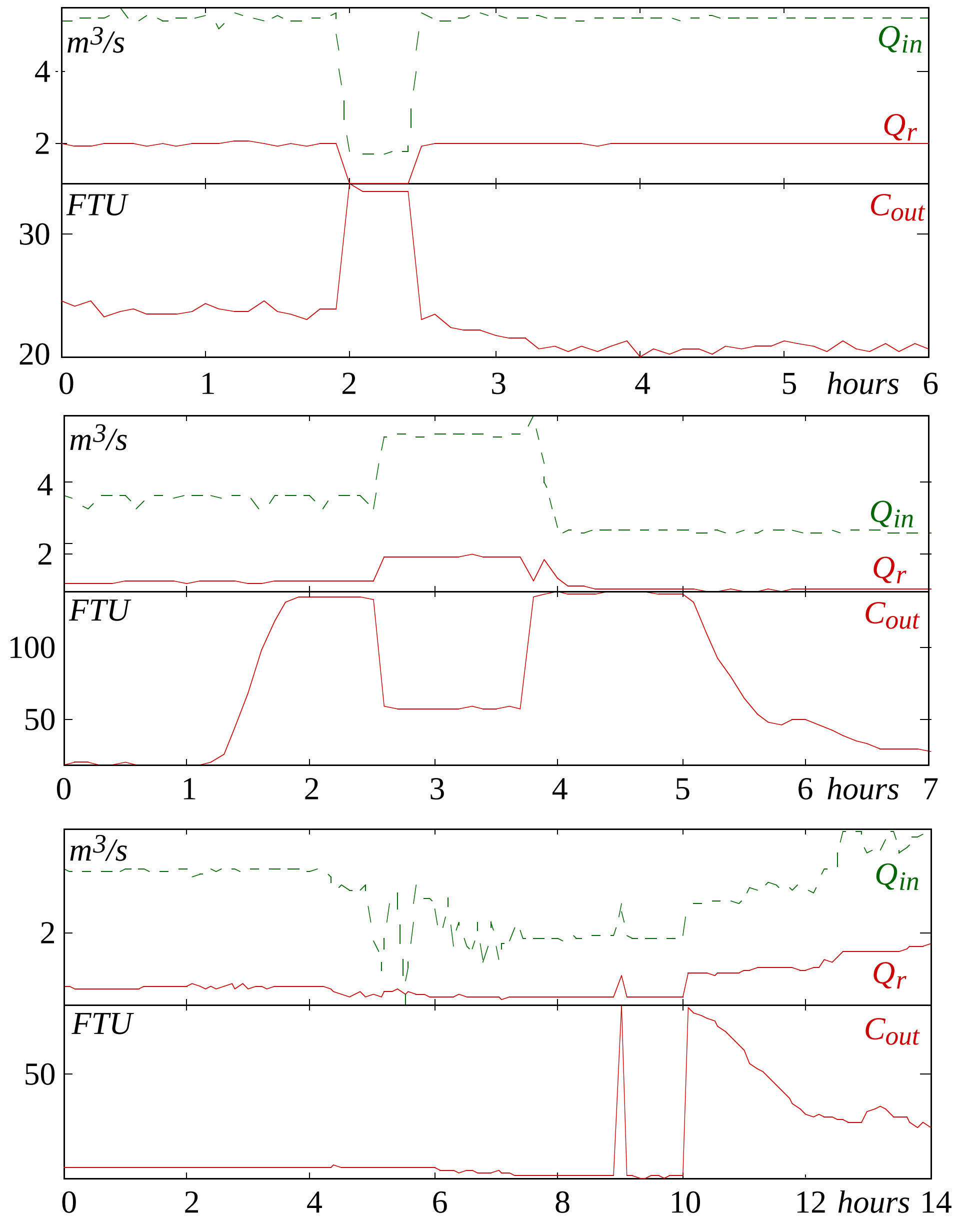


Figure 3.2 Three similar course of events from different periods during the Fall of 1991 at the Rya wastewater treatment plant in Göteborg. The proportional control law is clearly revealed in all three cases. The effluent suspended solids is affected momentarily.

The phenomenon shown above does not always occur. It has been detected during, or just before, known severe conditions, but not during periods with stable settling properties. A reasonable conclusion is that sludge with good settling performance is not as easily disturbed as sludge with deteriorated settling properties. This discussion will be continued in section 3.5.

3.3 A Dynamical Model for Hydraulic Propagation

To better understand the phenomena shown in the previous section a hydraulic consideration is done below. A model for hydraulic propagation is presented and the properties of different weirs are discussed. In the next section this model will be used for a case study on the settler hydraulics.

The dynamics of flow rates are often neglected when a waste water treatment plant is designed. Not only the flow magnitude, but also their changes have an important impact on the clarification as well as the thickening process. The relationship between the influent flow rate, Q_{in}, and the flow into the settler, Q_{set}, will now be investigated.

When modelling the hydraulics of a waste water treatment plant three basic elements have to be considered: basins, transportation channels and pipes. However, the basins are the crucial ones. Changes in the flow into a basin will be moderated as they leave the basin. Channels may be modelled as long and narrow basins. Propagation through pipes, on the other hand, is considered to be momentarily. The reason for this is that the propagation in a water filled pipe will travel with the speed of sound, which is approximately 1500 m/s in water.

Any waves on the surface of a basin are not regarded, but only the water mass balance over the basin. Since a qualitative picture of the dynamics are sought these are two reasonable simplifications. An early modelling approach is found in Olsson–Stephenson (1985).

Consider a basin with an influent and an effluent flow. The effluent flows over the weirs and the magnitude depends on the amount of water in the basin.

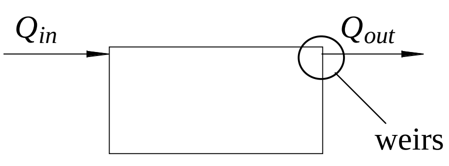


Figure 3.3 An outline of a single basin with an influent and an effluent flow, where the latter depends upon the water level and the profile of the weirs.

A total mass balance over the basin yields

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{3.13}$$

where V is the water volume. The flow, Q_{out}, is a function of the water level in the weirs, h, as well as their profile and number, N. The geometry for calculating the flow through one single weir is illustrated in Figure 3.4.

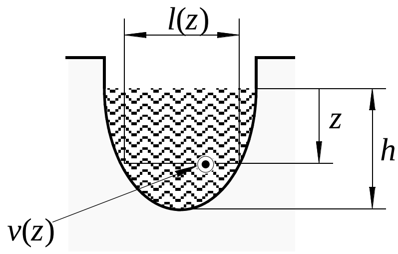


Figure 3.4 The flow geometry for a weir with arbitrary profile. $l(z)$ denotes the weir width at the depth z, and $v(z)$ the water velocity at this depth.

The total flow through all weirs is obtained by integration,

$$Q_{out} = N \int_0^h l(z) \cdot v(z) \cdot dz \tag{3.14}$$

An expression for $v(z)$ can be derived by using the Bernoulli equation,

$$p_{stat} = p_0 + z\rho g - \frac{1}{2}\rho v^2 \tag{3.15}$$

where ρ is the water density, g the acceleration due to gravity, p_0 the reference pressure just above the water surface and p_{stat} the static pressure after the weir passage. In the case of a surface located weir we get

$$p_{stat} = p_0 \tag{3.16}$$

Thus, an expression for the water velocity as a function of the depth, z, is obtained,

$$v(z) = \sqrt{2gz} \tag{3.17}$$

Using (3.14) and (3.17) the total effluent flow can be expressed as:

$$Q_{out} = N \cdot \sqrt{2g} \int_0^h l(z) \cdot \sqrt{z} \cdot dz \tag{3.18}$$

where the width, $l(z)$, at the depth z is derived from the profile of the weir.

The two most common weir profiles in waste water treatment plants are the V-notch and the rectangular, shown in Figure 3.5a-b. A third profile that also may be used is called Sutro. It is not as common and is less known than the previous two ones, but still a good option. A Sutro weir gives a flow that is proportional to the water level, h. For this reason it has mostly been considered as a simple way of measuring flows (Singer–Lewis, 1966).

If (3.18) is solved for these three weir profiles it may be rewritten in a more general way.

$$Q_{out} = k + \alpha \cdot h^{\beta} \tag{3.19}$$

Where α, ß and k are constants depending on the type and number of weir used, as well as their geometry. For V-notch and rectangular weirs k=0. The exponent, ß, is essential for the weirs hydraulic performance and is 2,5 for V-notch, 1,5 for rectangular and 1,0 for Sutro.

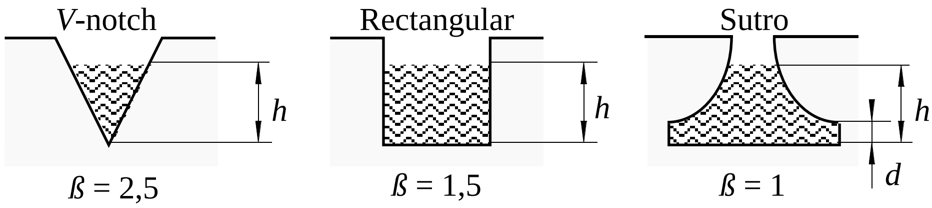


Figure 3.5 Three weir profiles used in treatment plants: V-notch, rectangular and Sutro.

For the Sutro weir to be linear it is necessary that $h \geq d$ (see Figure 3.5c).

The calculations above are theoretically based and does not consider any side effects. Consequently the real effluent flow will be less, mainly reduced by friction and contraction in the weirs. However, these losses can be compensated for with pretty good accuracy, (Tyllered, 1981). Let expression (3.19) denote the ideal effluent flow, without any losses. Then we can introduce a compensation, called the flow coefficient, ϕ:

$$Q_{comp} = \phi \cdot Q_{ideal} \tag{3.20}$$

where ϕ may be described as consisting of two factors:

$$\phi = \psi \cdot \Gamma \tag{3.21}$$

The first factor, ψ, is called the velocity coefficient and compensates for the friction in the weir. The typical range for the velocity coefficient is $0{,}9 \le \psi \le 1{,}0$.

The second factor in (3.21), Γ, compensates for the contraction and is consequently called the contraction coefficient. The most narrow point of the flow jet will appear just after the actual passage through the weir and is called *vena contracta*. The contraction coefficient denotes the ratio between the jet area in vena contracta, A_c, and the jet area in the weir, A_w.

$$\Gamma = \frac{A_c}{A_w} \tag{3.22}$$

Depending on factors as the weir type the parameter Γ usually varies in the relative narrow range, $0{,}61 \le \Gamma \le 0{,}65$. Thus, in this kind of implementation, it is reasonable to assume a constant value for the flow coefficient, $\phi = 0{,}6$.

The compensation in (3.20) is now used in relation (3.19). This yields a new expression for the effluent flow rate:

$$Q_{out} = \phi\left(k + \alpha \cdot h^{\beta}\right) \tag{3.23}$$

Assume that the surface area of the basin is constant for any level in the weir. Then the volume change, dV/dt in the mass balance equation (3.13), is related to the surface area, A, of the basin and the weir height variation, dh/dt. Substituting this relation in expression (3.13) and using the relation for Q_{out} in (3.23) will yield:

$$A \cdot \frac{dh}{dt} = Q_{in} - \phi\left(k + \alpha \cdot h^{\beta}\right) \tag{3.24}$$

As is shown, some information is needed to use the above model to reconstruct an arbitrary flow in a treatment plant. Measurements of the influent flow rate and any other flow entering or leaving the plant as well as any controlled flow, such as the return sludge flow, are needed. Furthermore the surface area and weir configuration for every basin have to be considered. With this information the flow rates downstream in the plant can be calculated.

Weir properties

There is an essential difference between the hydraulic properties of the three weirs. This is reflected by the different *ß*-constants in (3.19). It is illustrated by the simulation shown in Figure 3.7, where the hydraulics for the same basin have been modelled with different weir configurations. A weir has the ability to smooth hydraulic disturbances into the system. Still the possibility to use weir configuration as a design tool for hydraulic damping is often overlooked.

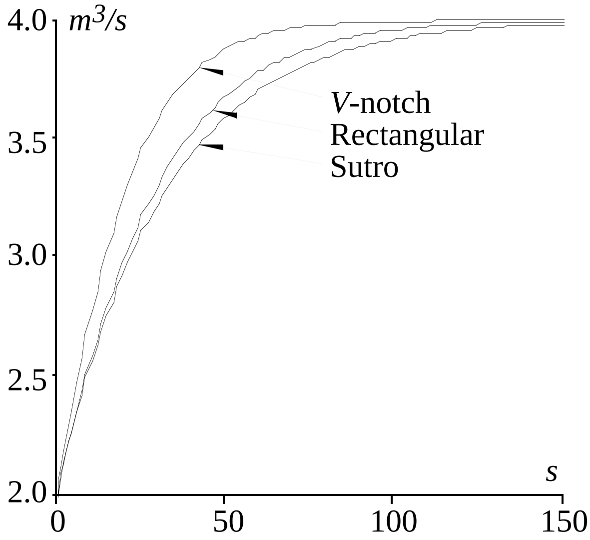


Figure 3.7 A comparison of the hydraulic performance for the same basin with different weir configurations. The influent flow rate is increased as a step at t=0. The curves show the corresponding effluent flow rate profiles. The damping for the V-notch weir is the lowest.

The prerequisite of the comparison in Figure 3.7 is that the surface width in the weirs should be the same for all three cases at a reference flow of 0,5 m^3/s. Below the reference flow the Sutro weir configuration will behave identical to the rectangular one. The volume of the basin is relatively small, which gives rather fast responses for all three cases. However it is possible to upscale the result and to use it for comparison of the different types of weirs.

It is evident that rectangular and Sutro weirs are far more suited to deal with hydraulic disturbance rejection than V-notch weirs. The time constant for the Sutro configuration is about 50% higher than for the V-notch.

In order to accomplish good hydraulic damping the volume of a basin must be allowed to vary somewhat. Often volume variations have been considered as undesirable. One reason e.g. has been that the aeration of the biological step could be disturbed. This is not a relevant objection in a system with adequate dissolved oxygen control. If a constant volume is considered to be the main goal the V-notch weirs are most suitable, but the price for this concern is an inferior hydraulic performance.

With the depth of the basin in the simulation above assumed to be 4 m and its surface area assumed to be constant the corresponding relative volume variations are shown in Figure 3.8. Note that the relative variations in pressure at the bottom are identical to the relative volume variations.

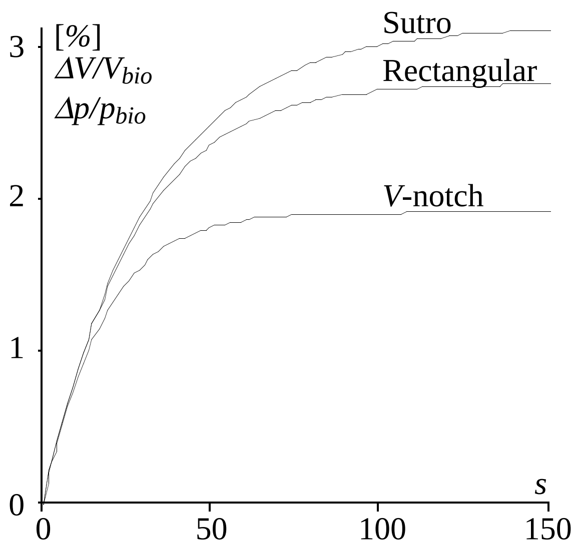


Figure 3.8 A comparison of the relative volume variations for the different weirs discussed. Note that this is equal to the relative pressure variations at the bottom, where the aerators are located.

In summary, the difference in relative volume or relative pressure at the bottom, between Sutro and V-notch weirs is 1,2%, while the hydraulic moderation is about 50% better for the Sutro weir. In other words there is no reason to consider the volume variations as more important as the hydraulic performance when weirs are to be chosen.

More active measures could also be considered to improve the hydraulic handling of a plant. The option to install controllable weirs is seldom considered. However, the most common use of controllable weirs is in distribution of flows. For example to balance the influent to several parallel basins. The design of such a system is presented by Csépai–Kastanek (1992). It has been successfully built and implemented, and is reported in Csépai–Kabelka (1996).

In the internal design of individual sedimentation basins 2-dimensional settling models, such as Zhou–McCorquodale (1992) or Szalai et al. (1994), can be used to compare different options. However, the hydraulic options for the system as a whole is seldom as thoroughly investigated.

It should also be emphasised that oxygen control is a feature that is being implemented more often. If there are any effects of the variations in volume, as shown above, a proper oxygen control compensates for them.

3.4 Hydraulic Conditions for the Settler

The hydraulic propagation model developed above will now be used to exemplify what can happen in the settler for different conditions. In a hydraulic simulation the two most common strategies for return sludge control will be studied during an incoming hydraulic disturbance. A third control law will be presented and compared to the previous two ones in section 3.7. The simulations below are implemented and performed in Simnon™ (SSPA Systems, 1991).

The first two strategies for the return sludge control to be compared are constant and proportional control. When only the term *proportional* control is used, proportional to the influent flow rate is implied. The consequences of the different strategies can be explained by qualitative reasoning and simplified models of the plant, as in Figure 3.9. Any primary treatment is disregarded and the influent flow is assumed to join the return sludge flow and enter the biological step directly.

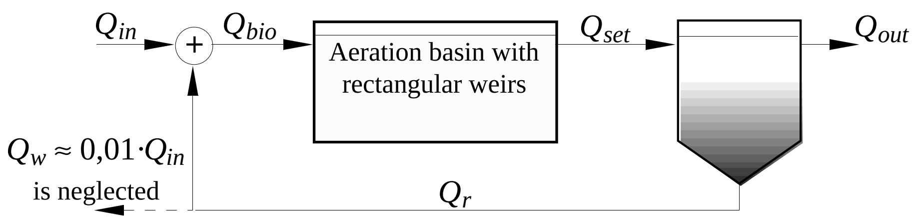


Figure 3.9 Layout of the configuration for a small simulated plant. The aeration basin has an area of 150 m^2 and 100 rectangular weirs, each with a width of 20 cm.

The configuration is assumed to have rectangular weirs in the aeration basin. This will supply a better hydraulic damping than the V-notch weirs.

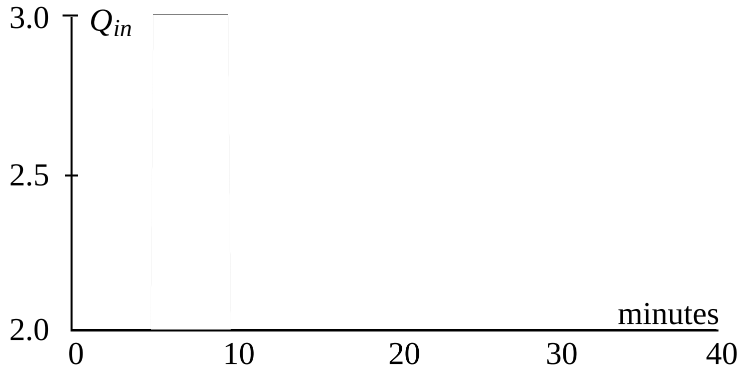


Figure 3.10 Assumed hydraulic profile for an influent disturbance to the simulated plant in Figure 3.9.

It is assumed that the influent flow rate, Q_{in}, will increase from 2 to 3 m^3/min for 5 minutes and then return to the original 2 m^3/min as illustrated in Figure 3.10. Since the waste sludge flow rate might be about 1% of Q_{in} its hydraulic effect is disregarded.

Consider the two cases below:

(I) $Q_r = 0{,}6$ m^3/min = constant;

(II) $Q_r = r \cdot Q_{in}$

where the return sludge ratio in case (II) is quite low, $r = 0{,}3$.

By accompanying the disturbance through the plant its profile will be shown for some different locations. The first location is immediately before the bioreactor. The return sludge flow have now joined the influent flow forming the influence flow to the biological step, Q_{bio}. Since the return sludge flow will differ for the two cases, so will Q_{bio}, as shown in Figure 3.11. With a constant return sludge flow the increase caused by the disturbance is still 1 m^3/min, while it will be amplified by 30% for case (II).

To calculate the flow rate propagation for the two cases through the biological step the hydraulic model (3.24) is used. The resulting influent flow to the settler, Q_{set}, is shown in Figure 3.12. The differences between the two cases have decreased compared to the influent location, because of the dampening effect of the aeration basin. Still the disturbance is significantly larger for the proportional case.

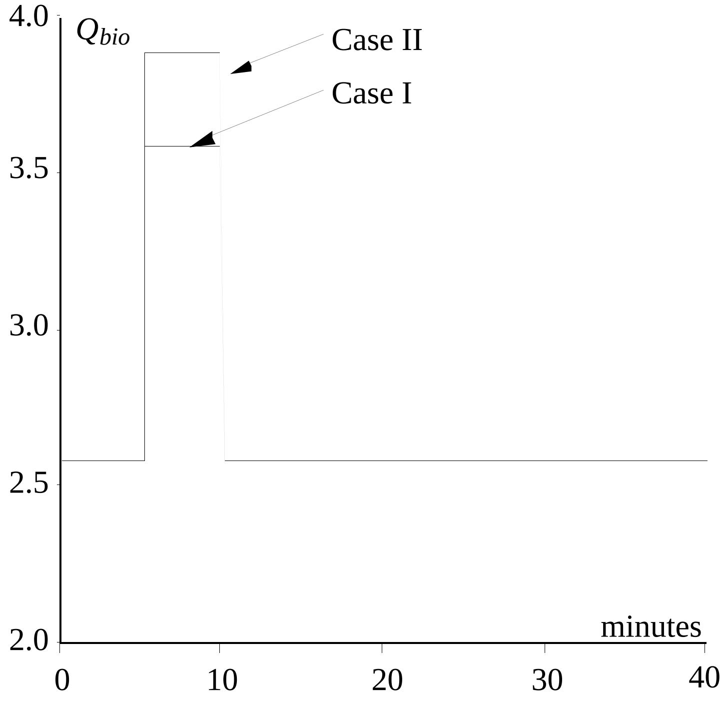


Figure 3.11 Resulting influent flow to the bioreactor, Q_{bio}. The return sludge flows are added to the influent flows.

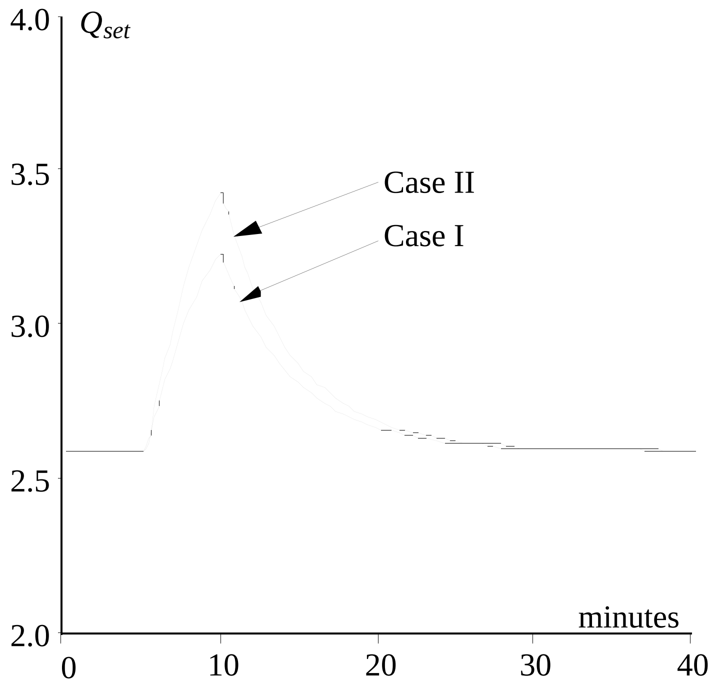


Figure 3.12 After the propagation through the aeration basin the flow profiles have changed according to dampening effects. This is the settler influent flow rate, Q_{set}.

The influence from the return sludge flow on the settler has been studied elsewhere, see e.g. Samstag et al. (1992). The main emphasis is usually the long term effects on the sludge blanket level and the thickening ratio (Ossenbruggen–McIntire, 1990). The immediate hydraulic impact from rapid changes in the return sludge flow are not dealt with.

To analyse the hydraulic conditions for the settling process a simple model will be used. A more elaborate analysis will call for models describing the internal circulations as well as its geometrical design. In order to qualitatively explain the phenomena seen in Figure 3.2 this kind of coarse model is sufficient. The purpose is not to completely describe the internal hydraulics of a specific settler, but to point out some general features.

Both the influent flow to the settler, Q_{set}, and the return sludge flow, Q_r, have to be taken into consideration. The latter will show a decisive influence on the internal hydraulics of the settler. A simple liquid mass balance over the settler will yield:

$$\frac{dV_{set}}{dt} = Q_{set} - Q_r - Q_{out} \tag{3.25}$$

where V_{set} is the volume of the settler. Considering expression (3.13), (3.25) indeed looks similar. These two expressions are closely related.

The return sludge flow is considered as a manipulated variable. It is apparent that the total hydraulics cannot differ between an increase in Q_{set} or a decrease in Q_r, or vice versa. The water level h and consequently the effluent flow rate Q_{out} does only depend upon the net influent flow to the settler. Therefore the term *settler net influent flow* Q_{set}^{net} will be used describing the sum of all external hydraulic influent flows, i.e. Q_{set} and Q_r, on the settler,

$$Q_{set}^{net} = Q_{set} - Q_r \tag{3.26}$$

Furthermore, the effluent flow Q_{out} in (3.25) is a function of the weir design and their water level h according to the previous discussion starting with (3.13) and resulting in (3.23). If the same calculations that led to (3.24) are performed on (3.25) and the settler net influent flow in (3.26) is used the result will be:

$$A_{set} \cdot \frac{dh_{set}}{dt} = Q_{set}^{net} - \phi\left(k + \alpha \cdot {h_{set}}^{\beta}\right) \tag{3.27}$$

where the subscript *set* refers to the settler. Remembering that *k*=0 for non-Sutro weirs, expression (3.27) can be simplified into:

$$A_{set} \cdot \frac{dh_{set}}{dt} = Q_{set}^{net} - \phi \cdot \alpha \cdot h_{set}{}^{\beta} \tag{3.28}$$

where α and *ß* depend on the weir type, number and design. The flow coefficient ϕ is considered constant as mentioned earlier.

In order to get a survey of what is going on inside the settler the net influent flow will be used. Since Q_{set} and Q_r are not located at the same point in the settler, this approach is not realistic for the internal state, but it can offer a reasonable examination of the overall behaviour. Consequences of the difference in location between Q_{set} and Q_r will be commented on in section 3.5.

The net influent flow offers a simple tool for comparing different hydraulic operating conditions for the settler. It will now be used to compare the two cases constant (I) and proportional (II) return sludge control. The result for case (I) is shown in Figure 3.13, while the result for case (II) is shown in Figure 3.14.

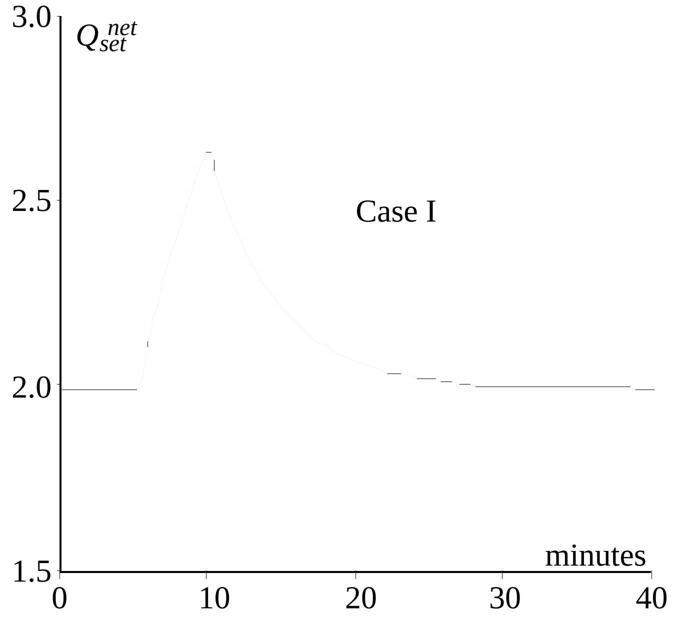


Figure 3.13 The settler net influent flow, Q_{set}^{net}, from equation (3.26), is a convenient tool for evaluation and comparison of different hydraulic situations. Here shown for case (I)

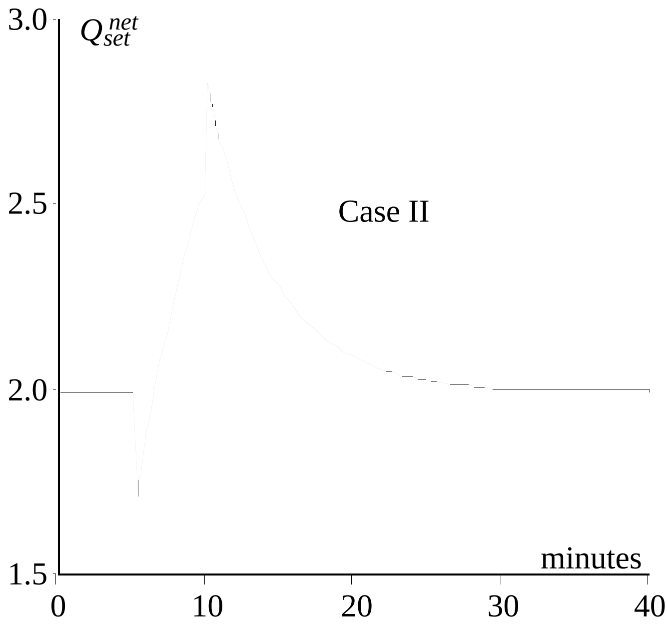


Figure 3.14 The settler net influent flow for case (II). Compare the profile with case (I) shown in Figure 3.13. The difference between constant (I) and proportional (II) return sludge flow control is significant.

The method of using Q_{set}^{net} for comparison reveal some new insights about the proportional control strategy. It does not only cause a higher flow into the settler, but a much worse flow profile. The peaks in the flow profile originate from the sharp edges of the disturbance introduced directly to the settler via the proportional return sludge control.

3.5 Qualitative Explanation of the Settler Transients

The simulation results in Figures 3.13-3.14 clearly show, that a constant return sludge flow is superior to the proportional control from a hydraulic point of view. The proportional control strategy may introduce severe hydraulic disturbances into the bottom of the settler. The settler underflow obviously affects the settler internal hydraulics. A reasonable conjecture is, that powerful variations do not favour the settling process dynamics. Here, the underflow is manipulated so as to generate unwanted disturbances that may deteriorate the settling process. The drastical changes in the return sludge flow will propagate from inside the sludge and upward like a shock wave. If such an impact shock wave is introduced it will propagate with the speed of sound. For a settler that is about 60 m long such a impact will spread in the entire basin within 40 ms. That is to be considered as momentary compared to any of the mass transportation.

Since the model used is quite simple it cannot explain what happens inside the settler. However, the underflow disturbances interfere with the settling process. In the case of poor settling sludge, the settler will become more sensitive to underflow disturbances and some of the settled sludge is stirred.

There might be a slight uncertainty about using the net influent flow for this kind of evaluation. Q_{set}^{net} is produced as an algebraic sum of the two flows Q_{set} and Q_r even if they are not located at the very same point in space. However, due to the fact that the disturbances in Q_r are introduced inside the settled sludge, they may cause even more damage than an equivalent influent flow similar to the one in Figure 3.14. If the shock waves exist they do not affect the total hydraulic behaviour for the settler, i.e. the effluent flow Q_{out}, but they probably have a negative influence on the effluent water quality, C_{out}, e.g. by causing turbulence.

There are other possible approaches to explain the phenomena in Figure 3.2. One line of argument is to consider the internal steady state flow profile for a certain return sludge flow rate.

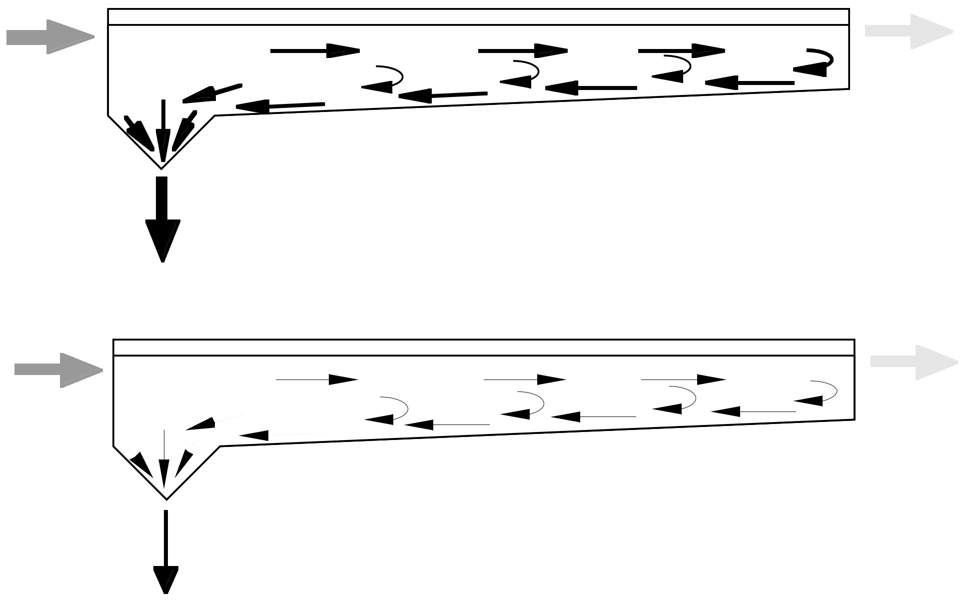


Figure 3.15 Two fictitious internal steady state flow profiles for a settler. Each corresponding to a certain return sludge flow. Shown on in the upper outline is a profile for a high Q_r and in the lower outline a low Q_r profile.

Qualitatively, it is apparent, that the spatial distribution of the local water velocities depend strongly on the magnitudes of Q_{set} and Q_r.

Therefore, if Q_r changes the internal steady state flow profile has to change as well. Two fictitious profiles are shown in Figure 3.15. They are qualitative but can serve as an illustration to this line of thought.

Consider a sudden decrease in the return sludge flow. Due to the laws of momentum the internal flow profile of the settler cannot change as quickly as Q_r. One of the consequences is that all the water set into motion cannot change velocity and direction momentarily. Since the exit in the bottom has been reduced there is a considerable amount of water, heading that way, that all of a sudden has to go elsewhere. It causes internal circulation that upsets the sludge, see Figure 3.16. This is an intermediate state of turbulence before a new steady state is achieved.

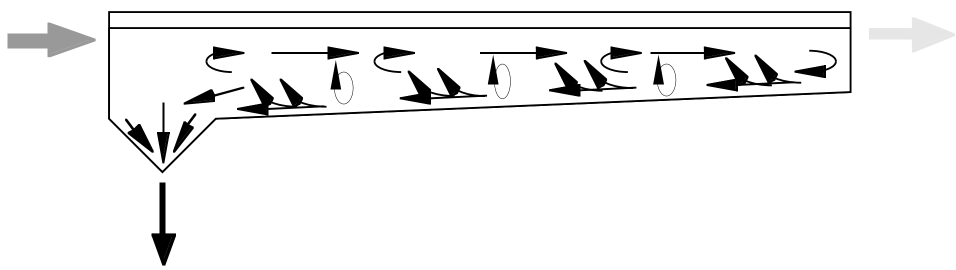


Figure 3.16 A transient state of internal chaos in-between the two steady state conditions shown in Figure 3.15.

3.6 Hydraulic Simulations

Some hydraulic simulations have been performed in order to try and verify the qualitative assumptions regarding the settler hydraulics in sections 3.4-3.5. The simulations were carried out with a beta release of a recently developed clarifier hydraulics simulation software called Clarity. A short description of the software is found in Appendix D.

A circular basin configuration was simulated, since the support for rectangular basins was not ready in this version of Clarity. However, the phenomena previously discussed should appear in a circular settler as well. Thus, a qualitative interpretation of the simulation results can be done. The volume and depth of the basin were set to the same values as for the basins in which the phenomena were detected, see Figure 3.2 and Appendix C.

Three hydraulical cases were considered in the simulations,

(1) decrease of the return sludge flow rate;
(2) increase of the return sludge flow rate;
(3) peak in the return sludge flow rate.

First the hydraulics were allowed to approach steady state during a period of 300 minutes. Then the change in the return sludge flow was performed. The change was linear with the duration of one minute, which is more realistic than a momentary change. The lower and upper values of the return sludge flow rate were set to 150 m^3/h and 300 m^3/h respectively, similar to the values for one basin in Figure 3.2a.

For these three cases three positions in the settler were monitored. The positions were all located in the clarification zone of the settler. A radial cross section of the settler, with these locations marked, is shown in Figure 3.17.

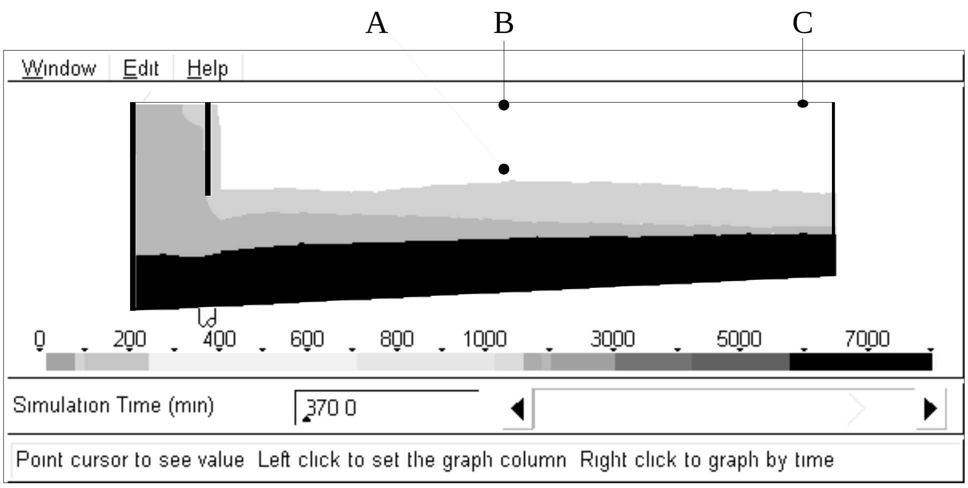


Figure 3.17 A radial cross section view of the simulated settler. The three positions monitored are marked A, B and C.

All simulation were performed with good sludge characteristics, e.g. SVI was set to 100. Likewise the sludge blanket was less than 1 m thick. In other words, there were no extraordinary conditions implemented in the simulations.

The suspended solids concentrations for the first case, reduced return sludge flow, is illustrated in Figure 3.18. At *t*=300 minutes the return sludge flow is decreased from 300 m^3/h to 150 m^3/h. This is intuitively considered as the worst case.

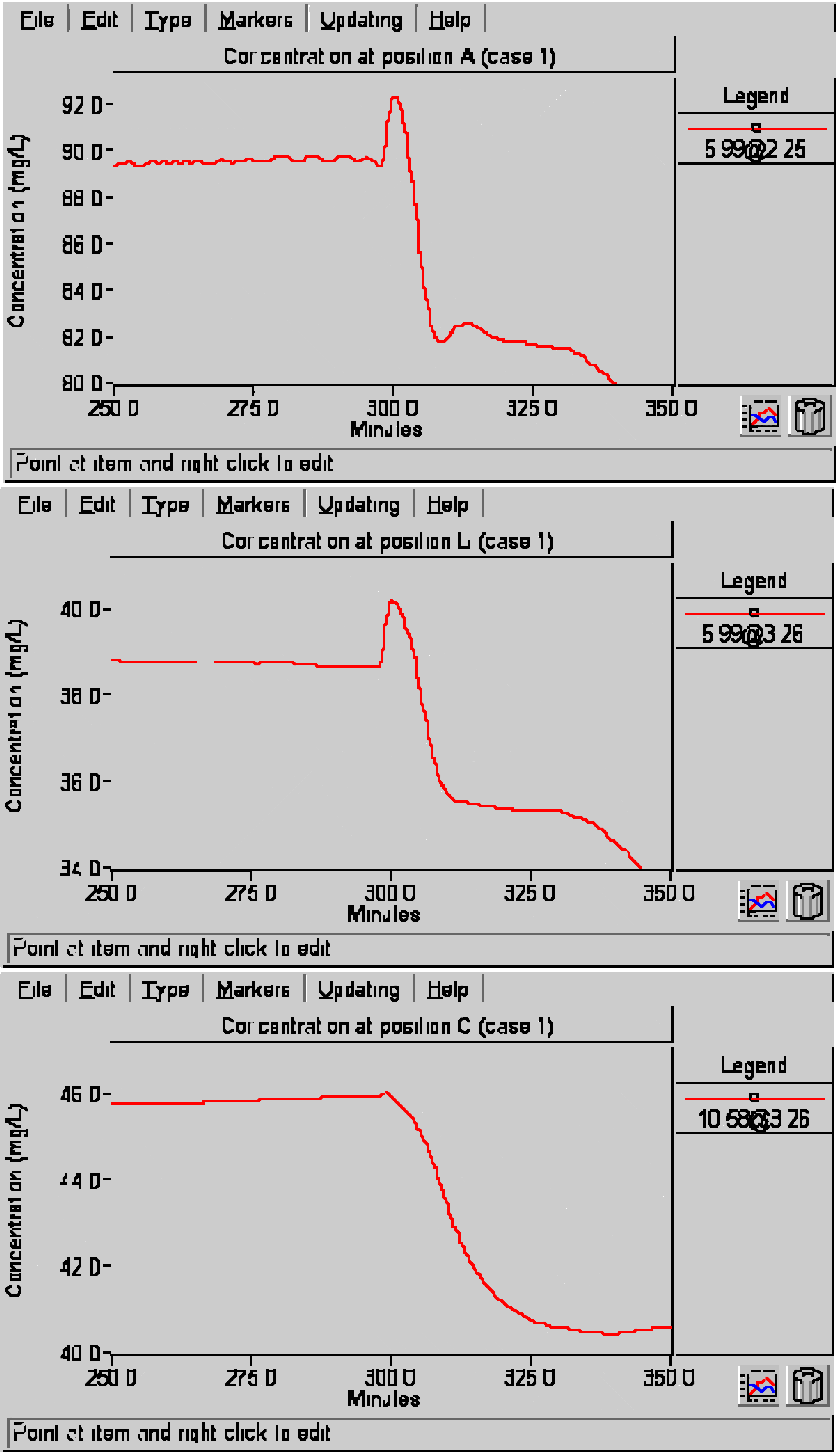


Figure 3.18 The suspended solids concentrations when the return sludge flow rate is decreased at *t*=300 minutes.

The suspended solids concentrations at position A (the upper curve of Figure 3.18) and B (the middle curve) display indisputable peaks when the return sludge flow was reduced. At the effluent, i.e. position C (the lower curve), the disturbance is not quite as obvious, but there is a distinct change when the return sludge flow is decreased.

In the second case the return sludge flow was increased. The intuitive assumption that this is not as severe as the first case was confirmed, Anyhow, there are still clear reactions in the suspended solids concentrations at positions A and B, as seen in Figure 3.19. For position C, the reaction is still seen but not as apparent as for the other two positions.

The third case involved a peak disturbance in the return sludge flow. The driving force for a change only exists for 2 minutes and then disappears. However, the simultaneous irregularities in the suspended solids concentrations are still there, see Figure 3.20. They even appear to be more severe than for the second case.

Despite the fact that good settling properties were assumed in all three cases it is apparent that the concentrations at positions A and B can change very rapidly when the return sludge flow is changed at t=300. Also for position C the concentration change is rapid, even if it is not as apparent as in positions A and B.

In order to get a hint about the hydraulic forces in the cases above, the horizontal velocities were monitored for position A as well. The results are illustrated in Figure 3.21. There is no doubt about the fact that the changes in the return sludge flow cause hydraulic irregularities.

A qualitative evaluation indicates that all three cases are bad for the settler hydraulics. There is no sign of that any one case should be significantly different than the others.

The indication in the second case, that a increasing return sludge flow also affects the suspended solids concentration confirms the phenomena shown in Figure 3.2c. In Figure 3.2a a reduced return sludge flow momentarily affects the effluent water quality. Figure 3.2c shows the opposite case with an increasing underflow, but the process still reacts quickly.

The simulations above may be used in a discussion of principles, despite some shortcomings. Even if the geometry of the basins are different, the same phenomena as shown in Figure 3.2 appear in these simulations. The main purpose of the simulations was to serve as a basis for such a discussion.

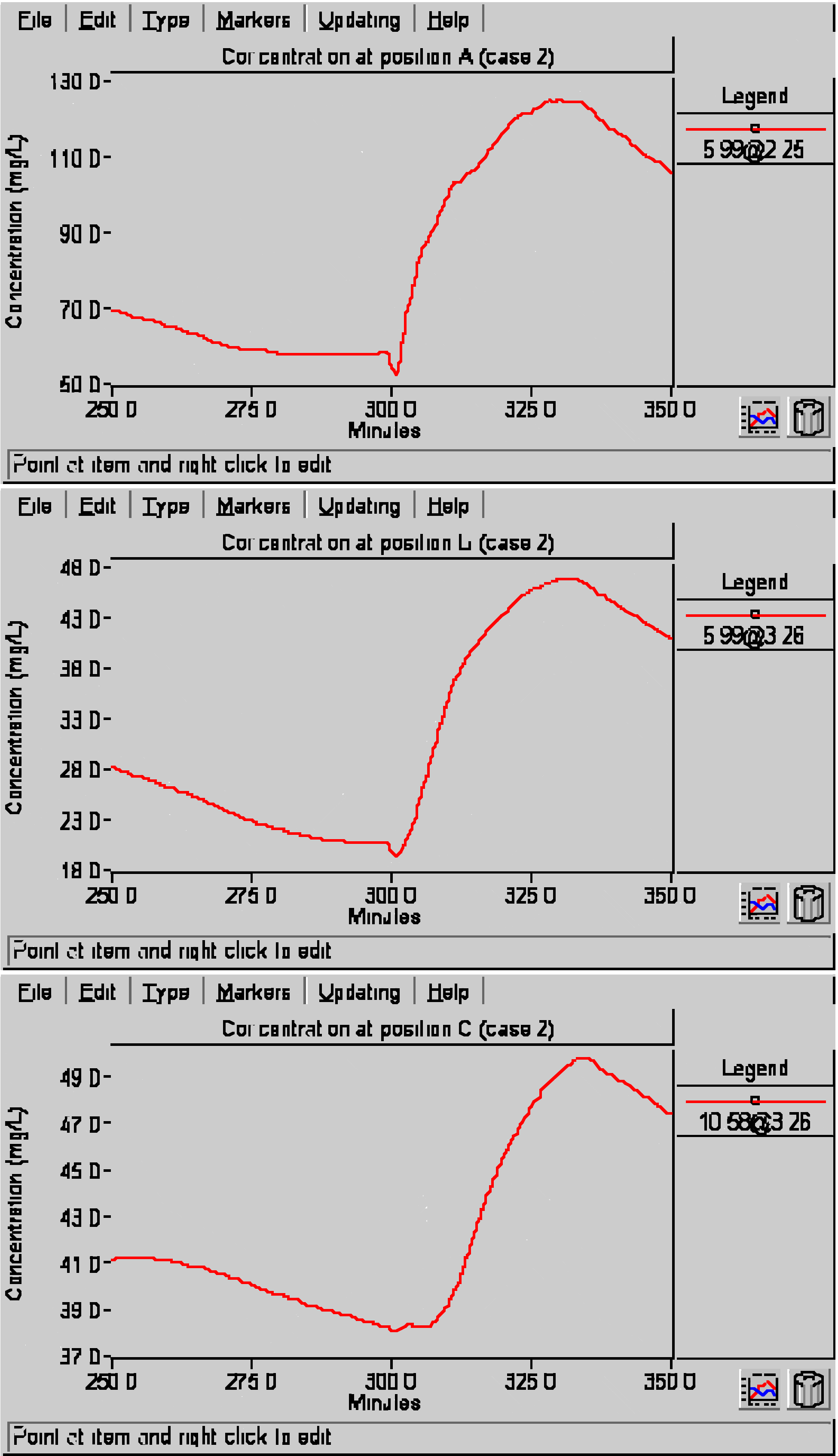


Figure 3.19 The suspended solids concentrations at positions A, B and C during an increase in the return sludge flow rate.

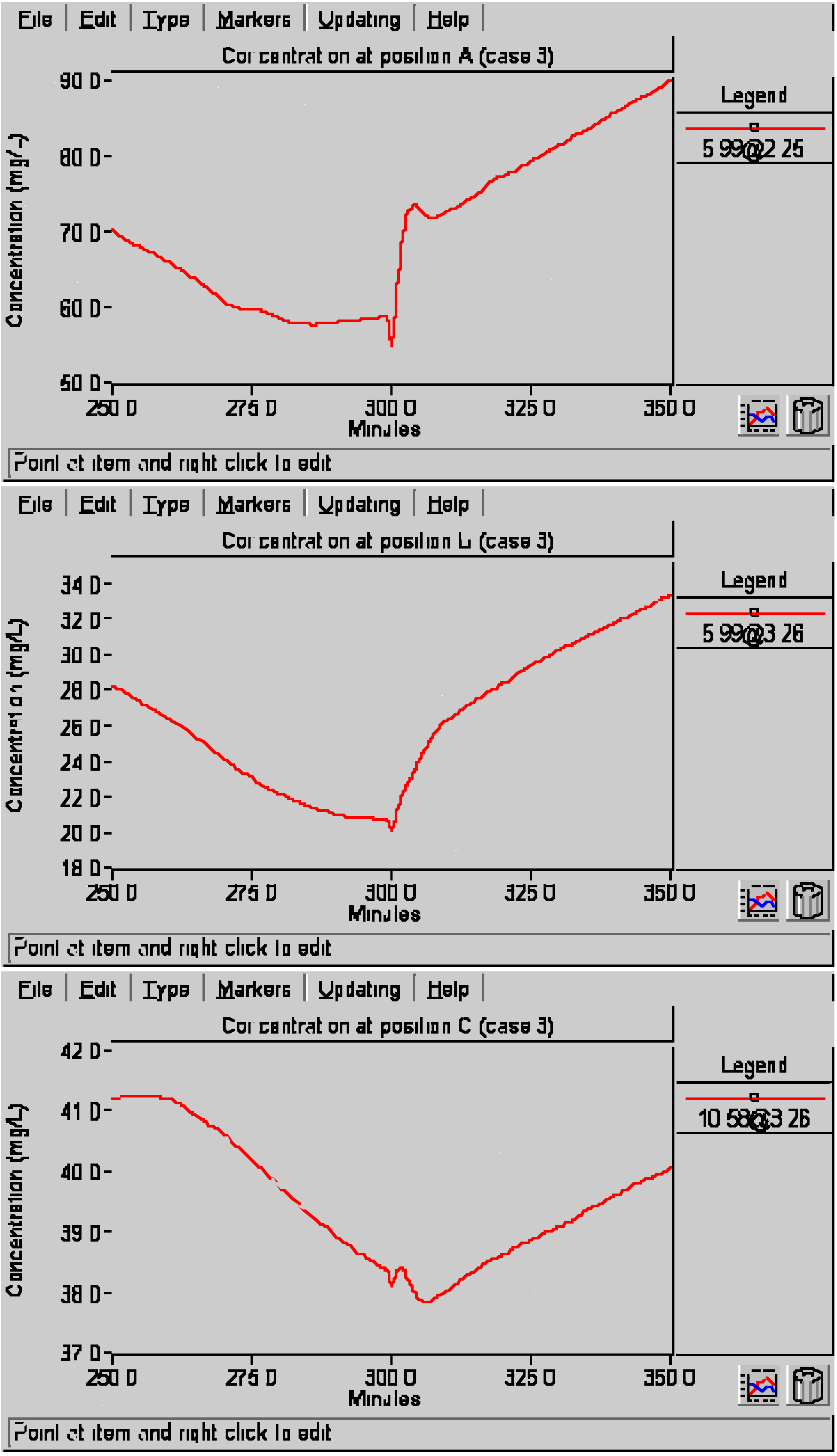


Figure 3.20 The suspended solids concentrations respons for a peak disturbance in the return sludge flow.

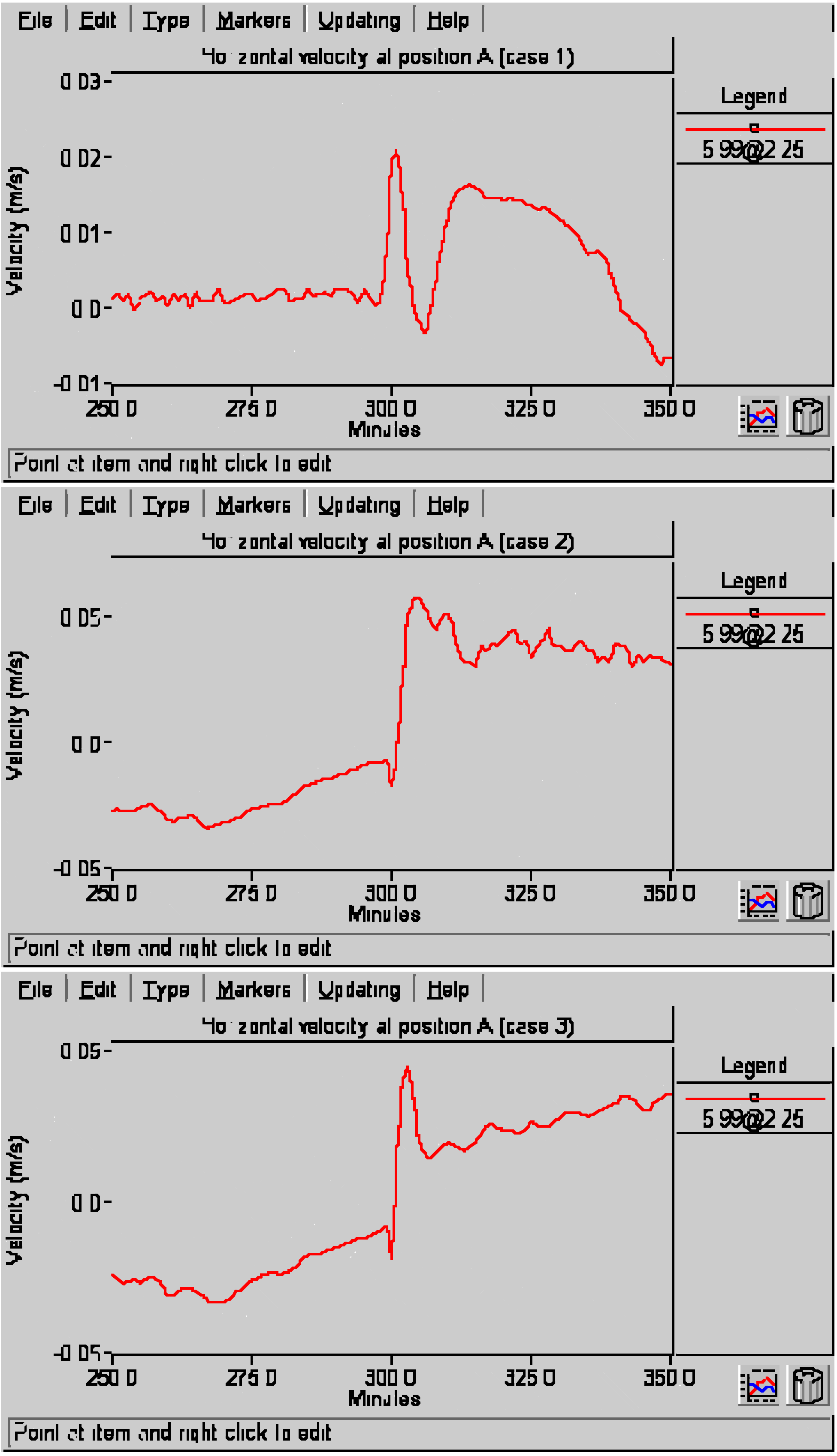


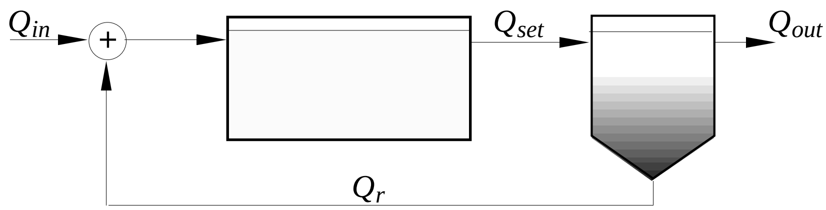
Figure 3.21 The horizontal velocities for all three cases at position A. Apparent hydraulic irregularities are revealed.

3.7 An Alternative Control Law

In the previous sections some shortcomings have been observed in the strategy of controlling the return sludge flow proportional to the influent flow rate. The limitations and restrictions on the control has also been noted. An alternative control law, where the return sludge flow is controlled proportional to the settler influent flow Q_{set} instead of proportional to the influent flow Q_{in} is presented below. The basics of these ideas were presented in Bergh–Olsson (1994).

Consider the settler net influent flow described in (3.26). In order to minimise hydraulic disturbances on the settler, then (3.26) says that a return sludge control that produces a Q_r that mirrors the behaviour of Q_{set} should be preferred. Such a strategy would reduce the effects of hydraulic transients on the influent flow, Q_{in}, instead of increasing them or generating new ones. This new strategy will be called case (III), when compared with the previous two cases.

Since the return sludge flow will recirculate through the bioreactor and affect the settler influent flow, Q_{set}, a control based on Q_{set} will indirectly amplify itself, as shown in Figure 3.22.



case (II): $Q_r = r^{(II)} \cdot Q_{in}$ *case (III):* $Q_r = r^{(III)} \cdot Q_{set}$

$Q_{set} = (1 + r^{(II)}) \cdot Q_{in}$ $Q_{set} = Q_{in} + r^{(III)} \cdot Q_{set}$

Figure 3.22 In case (III) Q_{set} will amplify itself by means of the alternative return sludge flow control strategy.

In order to do a relevant comparison with case (II) in section 3.4, the steady state amplification has to be equal. This means that any steady state condition should yield the same magnitude of Q_r and Q_{set} for case (III) as for case (II). Forcing Q_{set} to be equal for the two cases gives $1+r^{(II)}=1+r^{(III)}(1+r^{(II)})$, referring to the notation in Figure 3.22. That yields the relation:

$$r^{(III)} = \frac{r^{(II)}}{1 + r^{(II)}} \tag{3.29}$$

Consequently an alternative law should be formulated as:

$$Q_r = \frac{r}{1+r} \cdot Q_{set} \tag{3.30}$$

where r=0,3 as in the previous simulations. Meaning that Q_r=0,23·Q_{set} for case (III).

A comparison of the return sludge flow profile for the cases (II) and (III) is illustrated in Figure 3.23. Since Q_{set} has a softer profile than Q_{in}, the profile of Q_r will become softer for case (III).

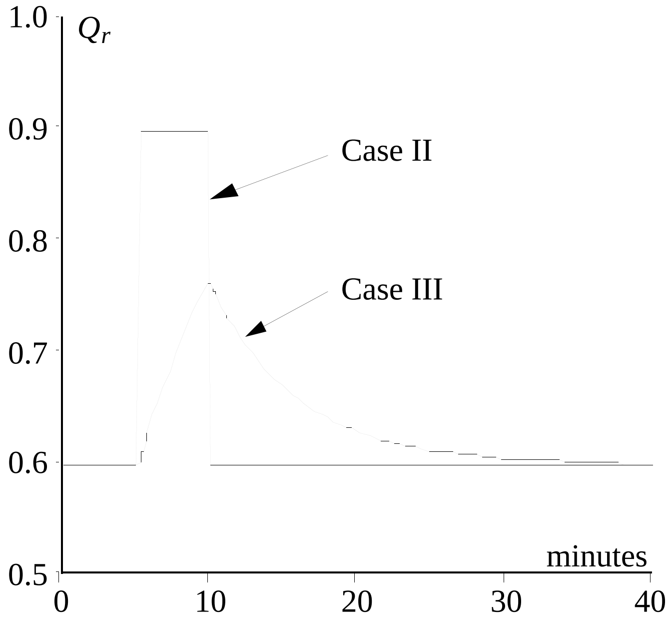


Figure 3.23 A comparison of the return sludge flow for two control strategies. For case (II) the control is proportional to the influent flow, Q_{in}, while the control for case (III) is proportional to the settler influent flow, Q_{set}.

The resulting settler net influent flow, Q_{set}^{net}, for case (III) is compared with the previous two cases in Figure 3.24. Notice the considerable hydraulic improvement compared to case (II) as well as to the constant flow case (I).

Note that the result of this comparison cannot state which control strategy that will achieve the best settling properties. Parameters like the thickening ratio and the sludge blanket level do not only depend on the hydraulics. However, it is clear that the proposed alternative control law will cause less harmful hydraulic effects on the system.

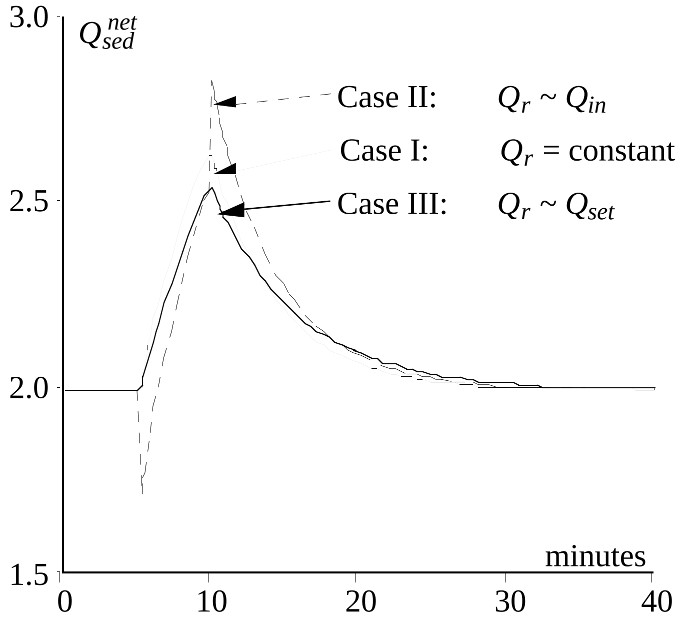


Figure 3.24 For the purpose of comparison, the settler influent flow, Q_{set}^{net}, for all three cases are shown together in the same graph.

In order to implement an alternative control law according to (3.30), it is essential to have good information about the settler influent flow rate Q_{set}. This can be achieved in two ways. The most obvious is on-line measurements, but unfortunately this is seldom performed in today's wastewater treatment plants. On some plants it might be possible to incorporate a measurement for Q_{set}, but it is usually not economically feasible. The other way is to calculate Q_{set} on-line based on Q_{in}, using the model derived in section 3.3.

A general model based on the principles of hydraulic propagation have been implemented into a software, called Hyprosim (Bergh, 1994). As long as there exist sufficient input data, any arbitrary flow rate may be estimated by the software. As a pure on-line simulator Hyprosim lacks an user interface. Instead it is "hidden" in the data collecting system and its output appears together with all "real" measurements. The input, i.e. plant configuration and flow measurements, are read from one configuration file and one import file respectively. Once the calculations are performed the output is written to an export file. Hyprosim has been installed and tested at the Rya treatment plant in Göteborg, Sweden. A rough description of this plant is found in Appendix C.

Since Hyprosim is a general package, it may be installed on any plant as long as corresponding input data is supplied and its interface is adjusted to the surrounding computer system environment. An user manual is presented in Bergh (1994).

As for any modelling software the quality of the output heavily depends on the quality of the input. This is essential if an on-line model, such as Hyprosim, is to be used for control purposes. While control actions may be close to continuous in time, measurements and results of on-line modelling are discrete. The more measurements, the better modelling, the better control and vice versa. In order to base the return sludge flow control on a simulation it should run at least once a minute, but a 10 second sampling interval may improve the performance.

4

Conditions for Parameter Estimation

In this chapter conditions for different methods for parameter estimation are discussed. Parameter estimation spans a wide spectrum of models. One example is time series (Box et al., 1994 and Ljung, 1987), neural networks is another (Hopensteadt, 1986 and Farvell, 1996). A common feature for these models is a black box structure, see Figure 4.1, i.e. there is no physical interpretation of the process parameters. Rather, inputs and outputs are used to mimic its behaviour. This approach is suitable for unknown sub-processes, where it is not essential to understand the process itself, but its interaction with the surrounding environment.

Figure 4.1 A black box modelling approach.

Some of the basic demands and desires on an early detection method were stated in section 2.3. It should be emphasised that most conclusions drawn in this chapter only apply to time series methods used for the purposes of diagnosis mentioned in this thesis. Whether the conclusions apply to processes outside wastewater treatment facilities depends on the quality of the on-line data, the modelling purpose and, of cause, the process.

First a rough survey over common parameter estimation models will be presented and short comments on there functionality in applications like wastewater treatment will be given. In the next section the comments will be expanded to concern implementation aspects. Difficulties in implementing this kind of models will be investigated. Some main criteria will be outlined regarding the models discussed. The topics of interest is the length of a data sequence, the excitation needed, classification of the measurements and timing of the excitation.

4.1 Empirical Model Structures

In time series analysis there is a wide variety of model structures. For this reason it is possible to calibrate and adapt a time series model to many classes of continuous processes. However, it is hard, sometimes impossible, to identify models including many interactions and several inputs and outputs. Time series models have been described by many authors, Box et al. (1994) is a classic, and Söderström–Stoica (1989) and Johansson (1993) are more recent texts on process identification.

Consider a general form of a linear time series model, equation (4.1).

$$A^{\#}\left(q^{-1}\right)\cdot y(t)=\frac{B^{\#}\left(q^{-1}\right)}{F^{\#}\left(q^{-1}\right)}\cdot u(t)+\frac{C^{\#}\left(q^{-1}\right)}{D^{\#}\left(q^{-1}\right)}\cdot e(t) \tag{4.1}$$

There are quite a lot of special cases of (4.1).

The variables *y* and *u* in expression (4.1) are the process output and input respectively, while the superscript # denotes a polynomial. Both the process and the measurements are influenced by some level of unpredictable disturbances, or noise. In order to model this random influence the variable *e* is used to reflect the presence of white noise.

The capital letters in (4.1) describe polynomials of individual and arbitrary order. Meaning that the number of terms can be freely chosen and may differ between the polynomials. The time shift operator *q* is used to emulate the polynomials distribution in time. In order to demonstrate how the polynomials of q^{-1} may be expanded $A^{\#}(q^{-1})$ will be used. The left hand side of (4.1) might as well be written:

$$\left[a_0\cdot q^{-0}+a_1\cdot q^{-1}+\ldots+a_{n_a}\cdot q^{-n_a}\right]\cdot y(t) \tag{4.2}$$

Usually a_0 is cancelled and the first term set to 1.

When the time shift operator is replaced, expression (4.2) will be transformed into:

$$y(t)+a_1\cdot y(t-\Delta t)+\ldots+a_{n_a}\cdot y\left(t-n_a\cdot\Delta t\right) \tag{4.3}$$

First it is important to choose a proper structure of complexity for the model. Since it is a model without physical interpretation it is wise to make the number of parameters as small as possible, while still describing the characteristics of the physical process. In wastewater treatment a common derivative of (4.1) is the *ARMAX*-model (Hiraoka–Tsumura, 1988 and Novotny et al., 1991). ARMAX, *auto regressive moving average with external input*, is the result of eliminating the denominators in (4.1). Often it is modified by means of internal reshuffling. Expression (4.4) shows a full transcription of the ARMAX-model.

$$\begin{aligned} &y(t)=-a_1\cdot y(t-\Delta t)-\ldots-a_{n_a}\cdot y\left(t-n_a\cdot\Delta t\right)+\\ &b_0\cdot u\left(t-t_d\right)+\ldots+b_{n_b}\cdot u\left(t-t_d-n_b\cdot\Delta t\right)+\\ &c_0\cdot e(t)+\ldots+c_{n_c}\cdot e\left(t-n_c\cdot\Delta t\right)\end{aligned} \tag{4.4}$$

where a time delay of the process may be described by the optional parameter t_d.

Once the structure of the model is chosen the model order has to be established. That is, which terms in each polynomial should be used. Insight in the physical process is a valuable tool for this. Often some different model orders are considered for evaluation.

When a model of the proper structure and order is chosen it has to be calibrated, or trained. An appropriate set of data, representative for the process, is chosen for this purpose. Then the different model parameters are adjusted to minimise the modelling error. After that the model hopefully describes the set of calibration data as good as possible. Last of all the model should be verified on another independent set of data. If the modelling error is found acceptable the model, and its parameters, may be approved.

Once this is done a model for the process is obtained and may be implemented on-line, in parallel with the physical process, as shown in Figure 4.2. However, the model is only relevant for conditions similar to the set of data used for calibration. For other operating conditions the model output is undefined.

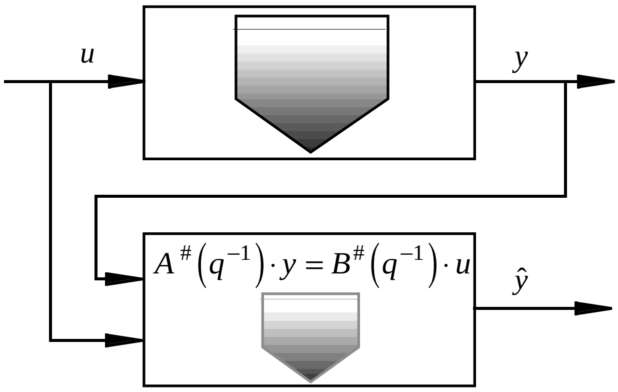


Figure 4.2 An on-line implementation of a time series model.

Furthermore, it is often desirable to have small simple models instead of big complex ones. Even if it might be possible to maintain one general time series model for a wide range of operating conditions it is probably not advisable. The complexity of a model reduces its ease of use. This is especially true for black box models. It is difficult to calibrate a complex model, but its even more difficult to verify if it has been properly calibrated. Complexity without any physical interpretation is hard to handle.

Since the settling process is highly non-linear it is preferred to replace a general complex model with a set of small linear ones. Each linear sub-model is then used in a limited range of operating conditions, e.g. one model for near steady state conditions, one for increasing flow, one for decreasing flow, etc.

If such a set of small linear models is to be used on-line two main demands have to be fulfilled. Some kind of classification method must be used to choose the proper sub-model for the actual situation. Furthermore, the switching between sub-models has to be done in a smooth manner. It might be a tricky task to sort the current operating condition into a predefined set. But the worst part is probably to determine accurate parameters for a new sub-model in order to achieve a bumpless transfer between the models.

Simplicity should be honoured before complexity, as well when the structure of a sub-model is chosen, as when its order is determined. One important aspect is to reduce the number of parameters that have to be prefit when a new sub-model design is engaged on-line. If a time series sub-model should be used for the settling process, the best choice is probably a first order ARMA, or ARMAX, model.

However, the physical process is likely to change somewhat, as time goes by. This is especially true for the settling process with its wide range of different time horizons, as described in section 2.2. The settling process depends upon microbiology as well as hydraulics. For these phenomena the difference in time scales might be in the order of weeks. Even if an almost perfect model is found in the first place it may only describe a limited range of process behaviour. The model parameters probably need to be re-calibrated from time to time, in order to make sure that the model maintains an adequate description of the process. It is possible to accomplish this on-line by means of recursive estimation (Ljung–Söderström, 1983).

A common way to deal with this task is to use a Kalman like filter to keep the process parameters up-to-date (Åström–Wittenmark, 1990). Every sample of the model output is compared with the actual process output. The error is then used for a smooth correction of the model parameters for the next sample. A more serious error renders a more forceful correction, while a minor error probably does not show. An illustration of recursive estimation is shown in Figure 4.3.

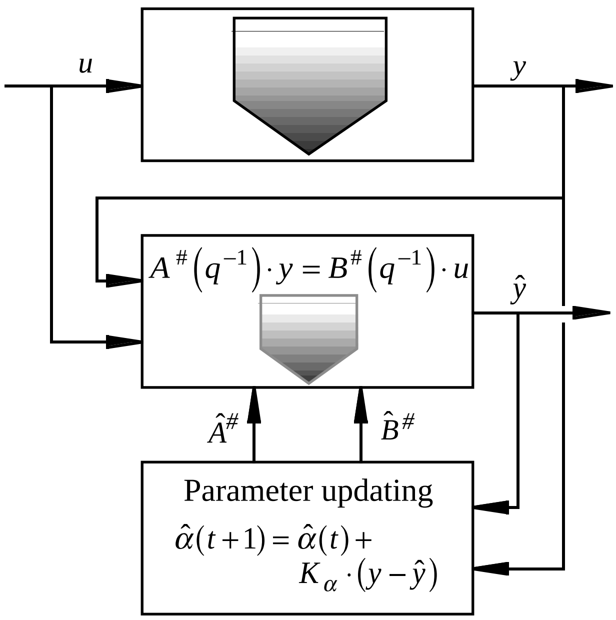


Figure 4.3 Recursive estimation is when a model (estimate) is updated over and over again (recursively). Here, a time series model is updated on-line by a Kalman like filter.

A qualitative explanation of Figure 4.3 could be that the time series model tries its best to observe and mimic the settling process. However, it is not perfect, especially when some process properties change over time. Thus, the recursive filter is used for an on-line calibration of the model parameters. This increase the accuracy of the observation made by the time series model. Figure 4.4 use symbols, rather than equations, to obtain an analogous version of Figure 4.3.

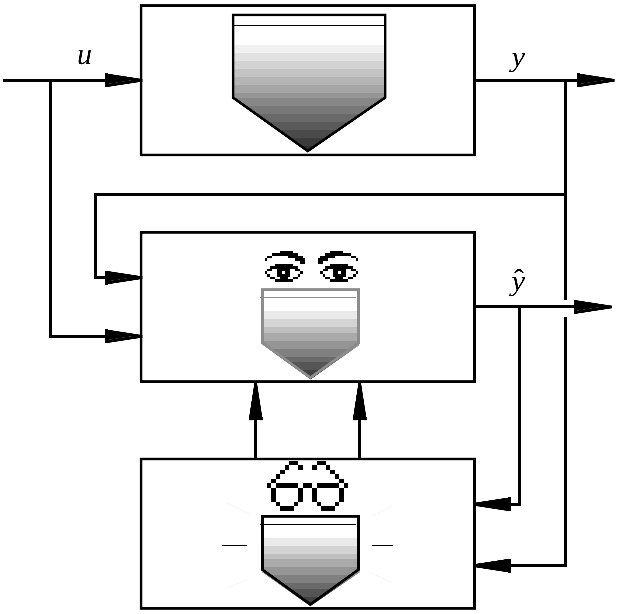


Figure 4.4 An analogous explanation of recursive estimation.

The résumé about time series analysis given above shows one line of possible methods for observing the evolution of the settling process. However, there are several other possibilities, both more complex and more simple. Measures for comparing different situations could be both static and dynamic relations. A static relation could be the gain between two process parameters, e.g. the influent flow rate Q_{in} and the effluent turbidity C_{out} as shown in (4.5),

$$G(t) = \frac{P_Q^{\#}\left(q^{-1}\right) \cdot Q_{in}(t)}{P_C^{\#}\left(q^{-1}\right) \cdot C_{out}(t)} \tag{4.5}$$

where both the numerator and denominator should be interpreted as a weighted average over the last few values of Q_{in} and C_{out} respectively.

The expression (4.5) is a simple measure, but it might be powerful enough to detect a disproportion in the process. Another simple tool is to keep track of the process time constant for typical situations. This may be done by observing the parameter a in expression (4.6),

$$C_{out}(t) = \hat{a} \cdot C_{out}(t - \Delta t) + \hat{b} \cdot Q_{in}(t - \Delta t) \qquad (4.6)$$

where C_{out} and Q_{in} are measurements and both $\hat{a}$ and $\hat{b}$ are estimated values.

Even though it has no physical interpretation, the parameter $\hat{a}$ will reflect changes in the process time constant. The absolute value of the time constant is of minor interest for the diagnosis.

4.2 Implementation Aspects on Time Series Models

Time series methods put quite high demands on the quality of the data to be used. On-line data sets often suffer from some defects that disqualify them from being used in time series models. As a matter of fact it is seldom a defect in the measurement itself. Mostly the measurements reflect the physical process. However, even when the measurements show a true picture of the process, the data set might be unsuitable for other reasons, such as missing data, process related problems or sudden peaks, as described in section 2.3.

Data sequence length

Even a data set consisting of high quality data, where all samples are adequate, may be unsuitable for these modelling methods. One crucial property is the length of the data set. Depending on the structure of the model chosen the data set has to consist of a minimal number of acceptable samples. Otherwise the whole set might be useless. Any time series model needs a certain time, i.e. number of samples, to converge. During this period of adaptation the model does not produce any reliable output.

An example of too small data sets, whose lengths are restricted by deviating data is shown in Figure 4.5. Often the sampling rate at a wastewater treatment plant is as low as one sample every sixth minute. The low sampling rate in combination with the demand that there should be a minimum of acceptable samples tells us that a data set probably must enclose several hours in order to be useful.

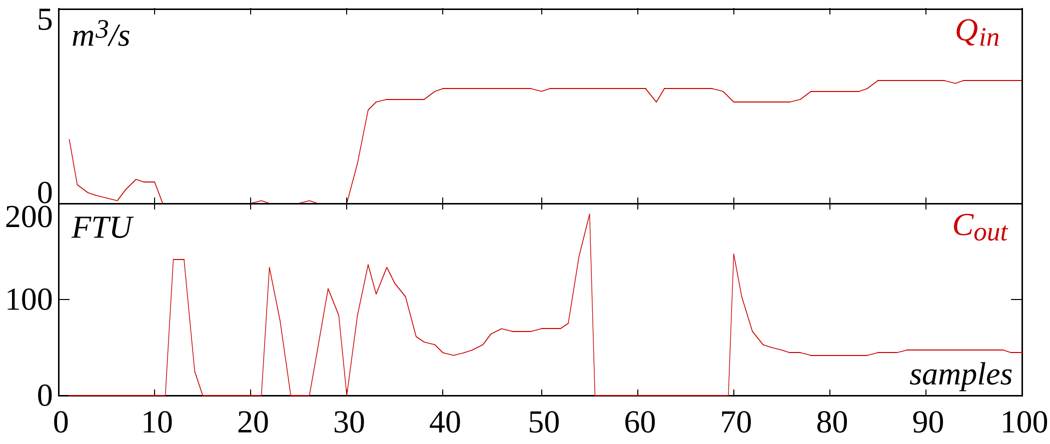


Figure 4.5 There are no intermediate intervals that are useful for parameter estimation. The measurement is too scattered by deviated and missing values.

Excitation

A high quality data set with a sufficient length may also be unsuitable for time series analysis. In order to get some useful result it is important to have sufficient excitation of the physical process. In other words, smooth operating conditions, without any hydraulical disturbances, might be good for the process, but for the purpose of diagnosis such conditions are more or less to be considered as loss of data. There is no information gained about the process state. A period of such smooth operating conditions is shown in Figure 4.6.

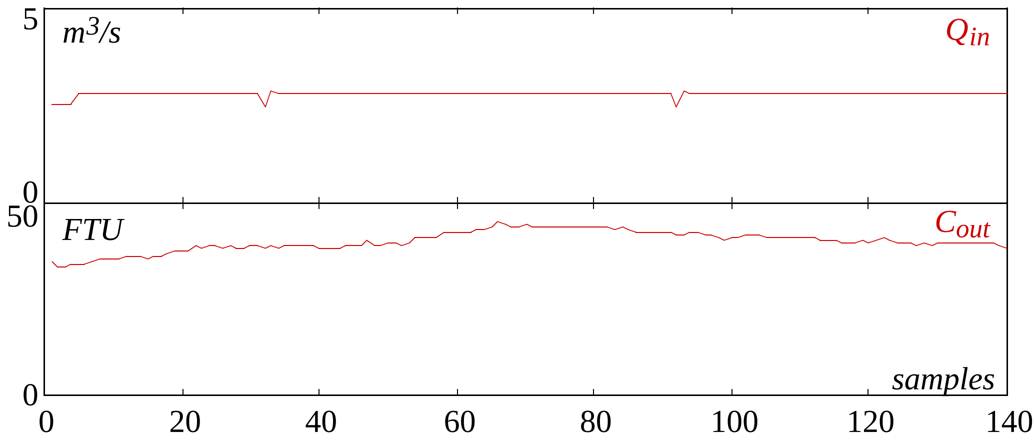


Figure 4.6 A period of no excitation. There is no available information about the reliability of the process.

In order to make use of an excitation it must be properly detected. This detection has to be done on-line and as fast as possible. Otherwise the entire diagnosis method will suffer from an undesired time delay. A good excitation for diagnostic purposes is a step disturbance in the hydraulics. It is fairly easy to detect as well. However, this is also the worst case disturbance of the settling process, so it is not likely to occur often. Instead responses to different degrees of hydraulic variations have to be considered. A typical hydraulic excitation might look as shown in Figure 4.7.

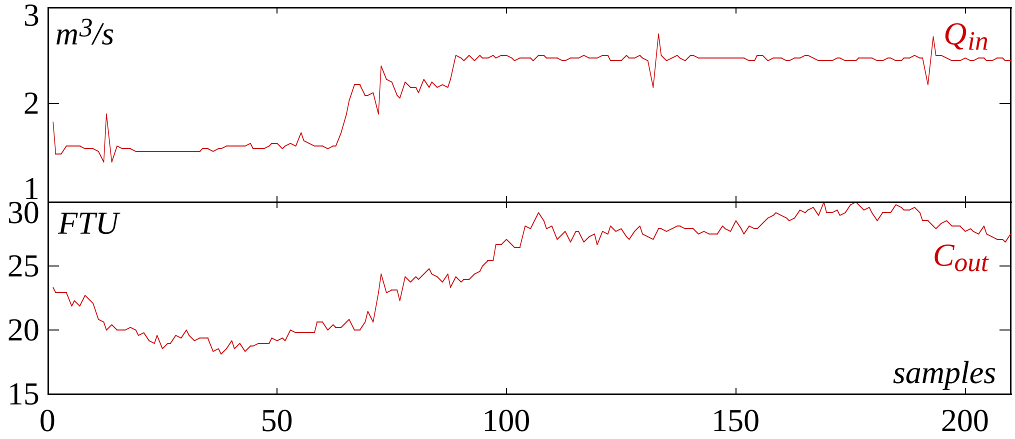


Figure 4.7 A typical effluent suspended solids response to a hydraulic excitation.

The tricky part is to detect an excitation as the one in Figure 4.7. It is easy for the human eye, but not as trivial for a data processing routine. It is even harder to determine when the excitation starts and ceases. To be able to compare different excitations and gain any information from them on-line, this problem has to be solved accurately.

Classification

As mentioned earlier it is not wise to try and use the same model for all possible kinds of operating conditions. Instead typical situations should be investigated with specialised models for various operating conditions. In order to do this, excitations have to be classified in some way. It is probably good to differ between a minor and a major excitation, as well as if it is increasing or decreasing. To do this, four different cases have to be considered,

- small excitation, increasing flow rate
- small excitation, decreasing flow rate
- large excitation, increasing flow rate
- large excitation, decreasing flow rate

It might be hard to detect an excitation, but it is even more difficult to classify it. To differ between increasing or decreasing is easy.

However, to determine if it is a minor or major excitation could imply serious problems.

The discussion illustrates that there is a contradiction between what we want to do and what we are able to achieve. On one hand we want to divide the operating conditions into as many specialised sets as possible, in order to use simple time series models. On the other hand, the more refined the classification is, the harder it is to perform accurately.

Timing

When an excitation has been detected and properly classified a limited set of data for the corresponding model has to be chosen. This implies the question: Where in the data set should the excitation occur? This is a problem of timing the excitation in the window used for modelling. Two alternative timings of the excitation in Figure 4.7 are shown in Figure 4.8.

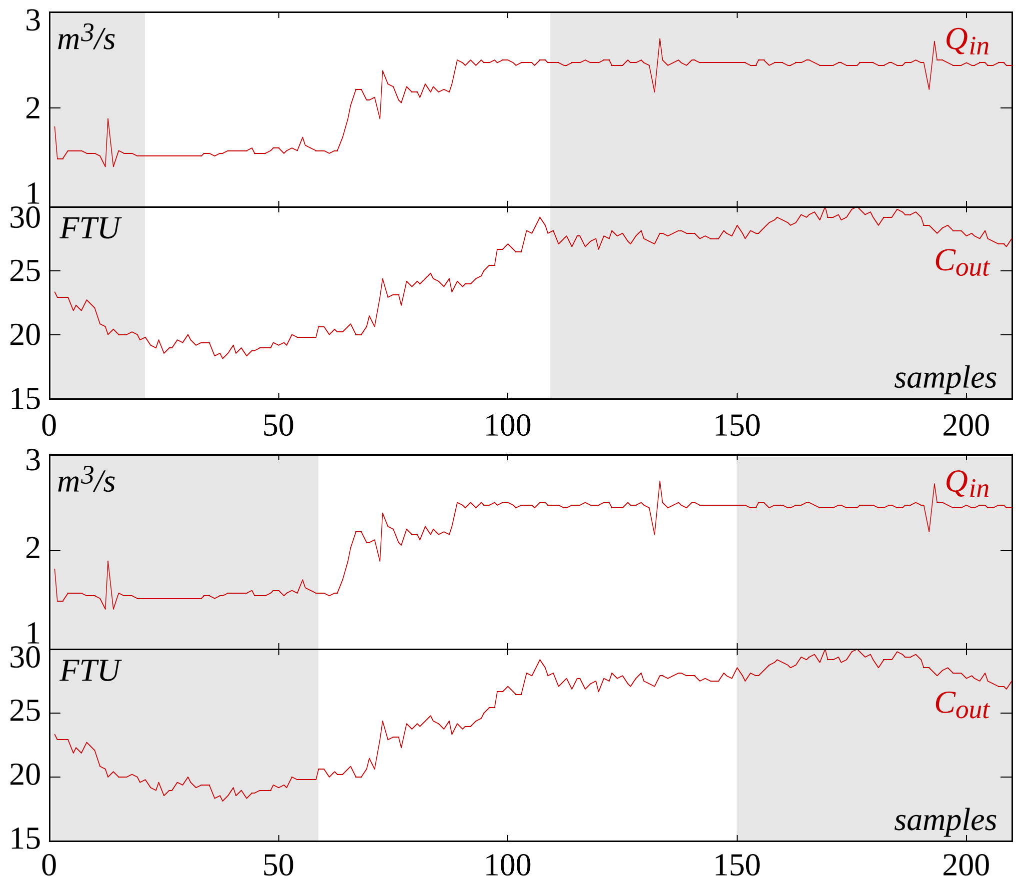


Figure 4.8 Two alternative timings of the same excitation yields different modelling results.

The modelling result will not be the same if the excitation appears in the beginning of the data set as if it occurs in the end. Although the difference is small, it is in the same order of magnitude as the difference between two separate operating conditions.

In the cases of detecting, classifying and timing an excitation on-line it is sensible to recall that the human eye is superior to any routine for data processing. What seems trivial for the human eye often leads to a complex calculation with an inferior result.

Most works regarding time series methods for the purpose of diagnosis in wastewater treatment plants, such as Olsson–Chapman, 1985 and Olsson et al. (1986), have been performed on laboratory or pilot scale facilities. That gives the opportunity to manually excite the system, which also has been done. Instead of waiting for a random disturbance to appear, a more precise one is introduced manually. However, this is not a realistic approach for a full scale facility, where a manual excitation is as undesirable as any other disturbance. When manual excitations are used the problems of detecting, classifying and timing them are of no concern.

All together, there are several properties that may disqualify data sets from being used in time series analysis. Table 4.1 summarises some considerations that affect a data set negatively.

Loss of data	One or more samples lack information, see Figure 2.3.
Extreme data	One or more samples present extreme values, mainly caused by process problems, see Figure 2.4.
Peaks	One or a short sequence of samples performs a significant deviation from the normal operating level, see Figure 2.5. Peaks are mainly caused by some process phenomenon.
Too few samples	The sequence of samples is too short for the method to adapt and start producing an usable output, see Figure 4.5.
Lack of excitation	There are no disturbances introduced to the process and consequently no response to consider, see Figure 4.6.
Detecting excitations	It is hard to detect a proper excitation on-line, as shown in Figure 4.7.
Classifying excitations	It is hard to determine which subset a detected excitation should be sorted into.
Timing excitations	The timing of the excitation does matter for the modelling result. Consequently, it is important to perform a repetitive and accurate timing.

Table 4.1 Summary of potential inconsistencies or problems in full scale experimental data.

When the conjunction of all these properties is considered, one realises that many data sets have to be neglected. As a matter of fact, most recorded measurements in a wastewater treatment facility have to be neglected, leaving a minor part of the data that is considered suitable for time series analysis.

A basic condition for parameter estimation is that the characteristics of a data set should not be too deviating from what the model has been trained to deal with. Using the term *normal conditions,* as explained in section 2.3, one might say that parameter estimation should certainly not be used for abnormal conditions, i.e. for conditions outside the definition range of the model. Even if the method does produce an output the result is erroneous. For this reason, if a model is to be used on-line it is essential not to feed it with inadequate data. Since there are no quality guarantees for on-line data it is necessary to implement some kind of primary evaluation procedure that decides if the data is suitable for the model or not. The models themselves have to be embedded into some kind of intelligent shell routine. There is a significant amount of factors to consider. Thus, the shell routine appears to become quite advanced and requires more effort than the actual modelling.

4.3 Filtering Data

Below the need for filtering is discussed. However, it should be recognised that the following discussion applies to the use of time series methods. Some conclusions drawn here are directly wrong when some other technique for diagnosis is used. This will be further emphasised in chapter 5.

A more thorough description of the most common filtering techniques is given by Olsson-Piani (1992) and Haykin (1989).

Need for filtering

Some measurements in wastewater treatment facilities can be rather noisy. There are mainly two sources of noise. Either the noise originates from the process itself or is introduced by the measuring devices used. These two sources of noise may also be superimposed or combined. Typically, most noise introduced to measurements of suspended solids is combined. Some of the noise originates from the process or principles measuring, but the measuring devices adds to the noise level.

For example, light is used to measure the turbidity in one single point in space. While the sludge is not homogeneously distributed, flocs of different sizes and shapes are formed. For this reason a suspended solids sample may differ between two points, close in space, even in a reactor that is considered as totally mixed. Likewise, when suspended solids are measured in a stream, e.g. a pipe or a channel, two subsequent samples in time may differ somewhat. These fluctuations are considered as noise. In order to get a smooth measurement, some kind of average sampling technique for a predefined volume should be used. Similar explanations are found for the noise in flow rate measurements, even if the noise–to–signal ratio in flow rate measurements is generally smaller and thus of minor concern.

Limitations of causal filters

In order to apply some diagnosis method on noisy measurements it might be desirable to filter them first. It should be recognised that all kinds of filtering cause a loss of information. It is important to find the proper balance between eliminating the noise and keeping the signal information content.

In on-line diagnosis, only causal filters are of interest. A well known phenomenon about causal filters is that they lag the output in time. The length of this time lag may vary depending on the filtering technique used. To exemplify this time lag and loss of information a moving average filter using n=10 samples is considered in Figure 4.9. The filter produces an output lagging the input n/2=5 samples. The loss of information is demonstrated in the way a signal looses its shape. By only looking at the filtered outputs in Figure 4.9 it is hard to tell whether the corresponding inputs was triangular waves or a sinusoidal dittos.

The time lag is especially severe when a significant noise reduction is desired. For common filters it is true, that the more effective filtering the longer time lag. In order to achieve both good noise reduction and a small time lag the order of the filter has to be increased. However, a basic condition is that the noise frequency sufficiently differs from that of the signal information content. Often this law of causal filters leads to a compromise. It has to be decided what is most wanted, a small time lag or a good noise reduction. This dilemma is illustrated in Figure 4.10, where the input from Figure 4.9 is given a superimposed level of noise.

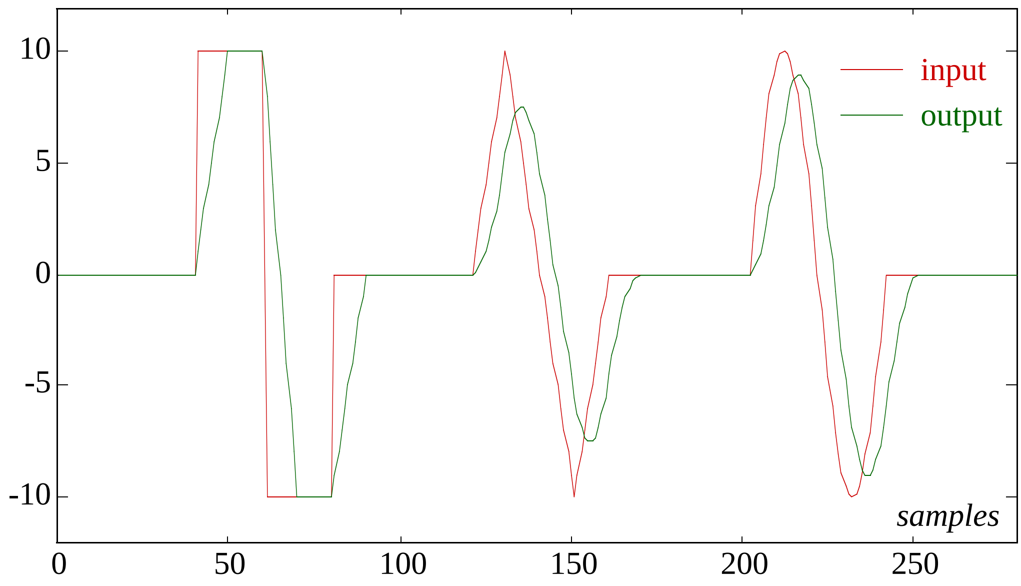


Figure 4.9 Demonstration of the loss of information and time delay when causal filters are used. Here a MA-filter producing an average over 10 samples is used on an artificial input.

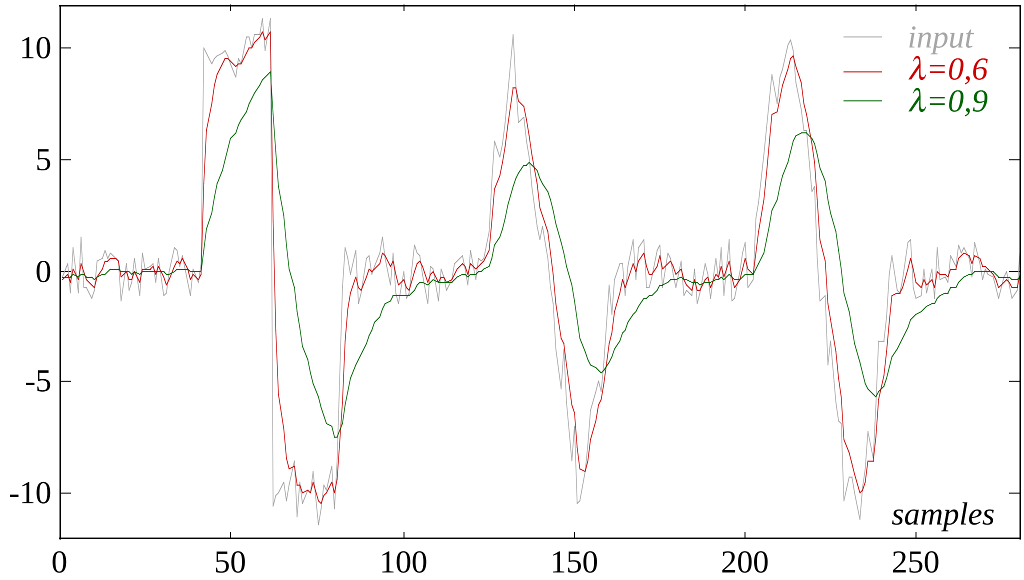


Figure 4.10 The input from Figure 4.9 is repeated with a superimposed noise. An exponential filter is then used twice with two different time constants to demonstrate the compromise in causal filtering.

In Figure 4.10 a first order exponential filter, according to expression (4.7) is used,

$$\hat{y}(t) = \lambda \cdot \hat{y}(t - \Delta t) + (1 - \lambda) \cdot y(t) \qquad 0 \leq \lambda \leq 1 \qquad (4.7)$$

where λ is the filter constant. The filter constant is used to tune the filter to the desired level of filtering.

Consider the principal difference between the two cases in Figure 4.10. In the case of a small filtering constant, the noise level in the output is significant. In the case of a large filtering constant, the noise level might be satisfactory, but the time lag and loss of information are close to unacceptable.

It should be emphasised that there is always a time lag between the input and output for a causal filter. Some, more or less sophisticated filters manage to reduce this lag, but not totally eliminate it. In order to reduce the time lag different kinds of calculations are used, that demand both time and processing power. Thus, depending on the application and sampling rate some filtering techniques are unsuitable. The calculations may become too complex and there is not enough time or processing resources available to perform them. However, computing time is not a problem of major concern in wastewater applications.

During periods with large signal variations the signal change is more apparent than the noise. Since the signal detection is crucial the noise level reduction should be low, i.e. a small λ. On the other hand, during periods with small signal variations the noise becomes a more dominating part of the signal. Thus, a more efficient noise level reduction, i.e. larger λ, should be applied.

One way of achieving this behaviour for an exponential filter is to make use of its residuals, i.e. the differences between its inputs and outputs. If the residual, $y - \hat{y}$, has the same sign over a predefined number of samples, the filter constant is decreased in order to get a faster response. On the other hand when the residual sign shifts the filter constant is gradually increased to effectively reduce the noise. This is a quite simple but effective way of dealing with the time lag. The strategy is applicable to most filters, but the ease of implementing it may differ.

On-line filtering often ends up in some compromise, where available time and resources have to be considered when choosing a proper filtering algorithm. Most research and development done regarding filtering technique have been dealing with relatively high sampling rates. Thus, they have to consider the time constraints. If the sampling interval is 1 or 6 minutes, as in most wastewater facilities, there is seldom such constraints limiting the choice of filter to be used.

Another, more uncomfortable, effect of the low sampling rates in wastewater applications is that details might get lost or misrepresented. For example a signal peak might disappear in the output, while a change with an actual duration of 3-4 minutes appears like a momentary step.

A new filter design — the max-filter

A new filtering technique, called max-filter, was developed for this type of applications (Bergh, 1992). The purpose has been to rapidly detect significant changes, while still achieving a good noise reduction. It is a combination of three common filtering techniques: moving average, adaptive and exponential filtering.

The time lags for conventional filters, in wastewater treatment plants, or other slow processes, may be a couple of hours. This is due to the low sampling rates used. A typical measurement of a flow rate is presented in Figure 4.11. It is apparent that high frequency noise is no problem in this case. Instead some process disturbances with a time constant in the same order of magnitude as the process itself occur.

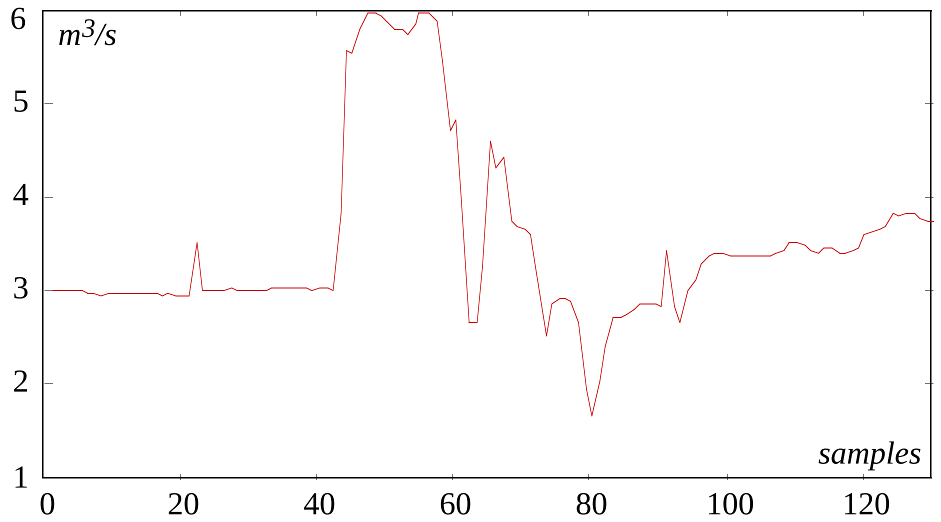


Figure 4.11 Typical flow rate measurement without any high frequency noise, but with some process disturbances.

The max-filter uses knowledge about its own internal structure together with estimates of the input properties to determine a proper output. Its performance is based on simple logical tests of the form `if…then…else…`. Most calculations are straight–forward and performed when needed, e.g. mean values and standard deviations. The time consumption is instead caused by a number of calculations and logical tests that are repeated for each sample. The internal steps of the filter is illustrated in Figure 4.12.

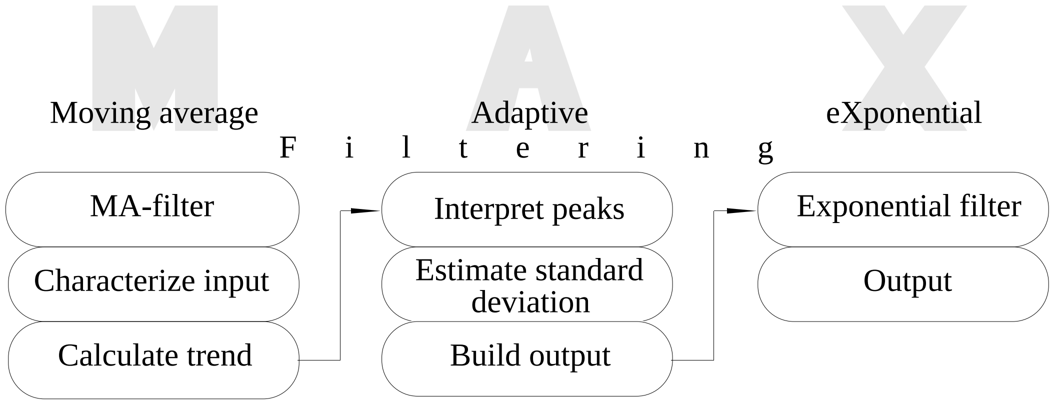


Figure 4.12 For every sample there is a schedule for the max-filter to work through. Here the different internal phases of this schedule are shown.

First an internal MA-filter is used to easily smooth the signal. That is done in order to get a reference signal. The input is then characterised in order to roughly determine its current state, e.g. increasing, decreasing, etc. If there is a trend of the signal it is approximated.

The next internal step starts to examine if there is a peak in the input. In order to do this the standard deviation is determined and a multiple of it is used as a threshold value. If this threshold is exceeded a dramatical deviation in the input, possibly a peak, can be detected.

If a larger deviation is recognised two alternative cases must be considered. In the case that the deviation appears in a limited number of samples it is probably an outlier and is neglected. The trend for the preceding samples is then used to guide the output. In the other case when a deviation exceeds a predefined number of samples it is probably no peak, but a step in the input. In this case a similar step is performed by the filter in order to reduce the delay. This is especially obvious in the comparison to conventional filters done below in Figures 4.13 and 4.14.

Since the preceding step might involve some "cut and paste" actions on the signal in order to build a representative output, small unintentional disturbances might be introduced. Therefore, a final touch is performed by exponentially filtering.

Comparison

The max-filter is meant for applications where the sampling rate allows more calculations without adventuring the function. First of all it is an effort to reduce the time lag for a causal filter. A characterising property is to recognise principal changes in the input as fast as possible in order to adopt a new strategy. A comparison with conventional causal filters performed on the signal in Figure 4.11 is shown in Figure 4.13.

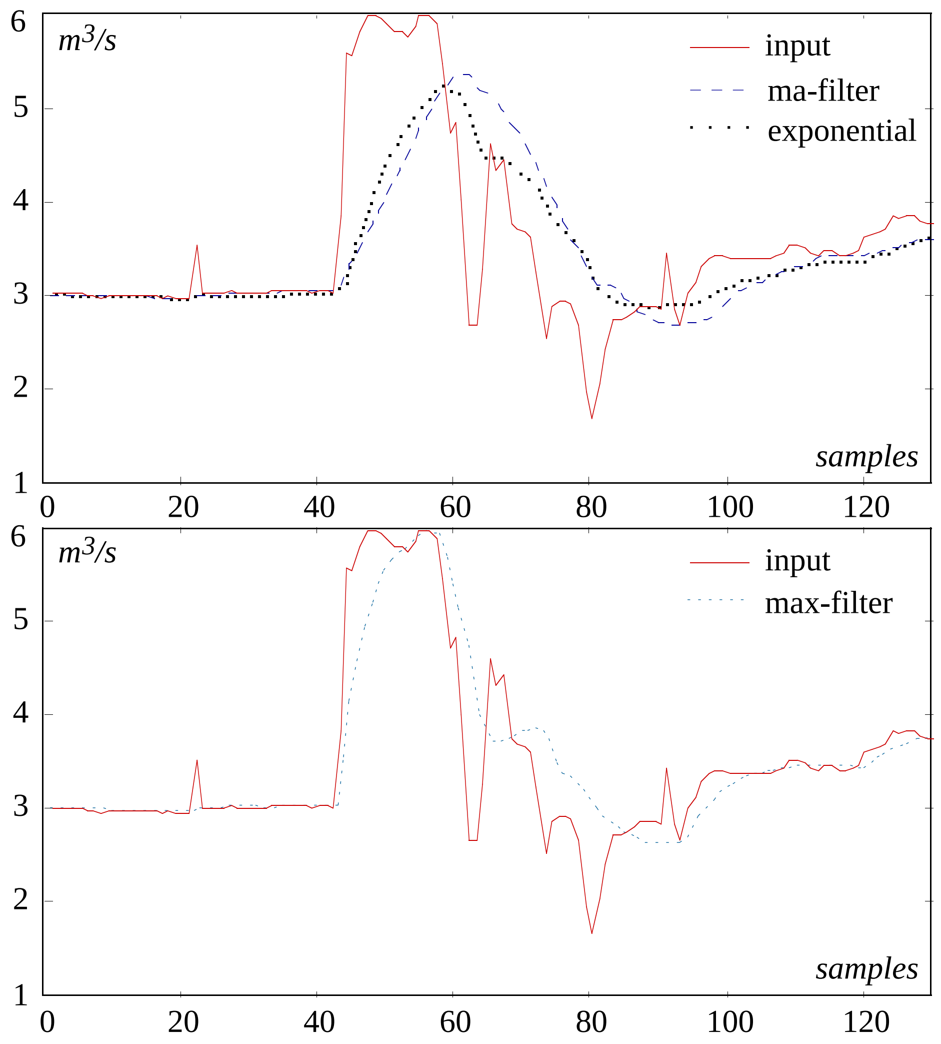


Figure 4.13 A comparison of some common causal filters and the max-filter performed on the measurement in Figure 4.11. The filters are calibrated to reduce the noise component equally.

The input in Figure 4.13 has no high frequency noise superimposed on the signal. However, the max-filter may also be used for more noisy measurements, such as the suspended solids concentration. A similar comparison an a sequence of suspended solids measurements is shown in Figure 4.14. The filters are calibrated to reduce the noise component in the measurements equally.

It is apparent that the ability to respond to rapid changes in the input really makes a difference and works to the max-filters advantage. The reason for this is the intermediate step of logic in the max-filter structure, described in Figure 4.12.

In the purpose of compatibility and testing the filtering strategy was implemented in Matlab™ (MathWorks, 1992) and Simulink™ (MathWorks, 1995). However, its structure allows implementation in conventional programming languages as well.

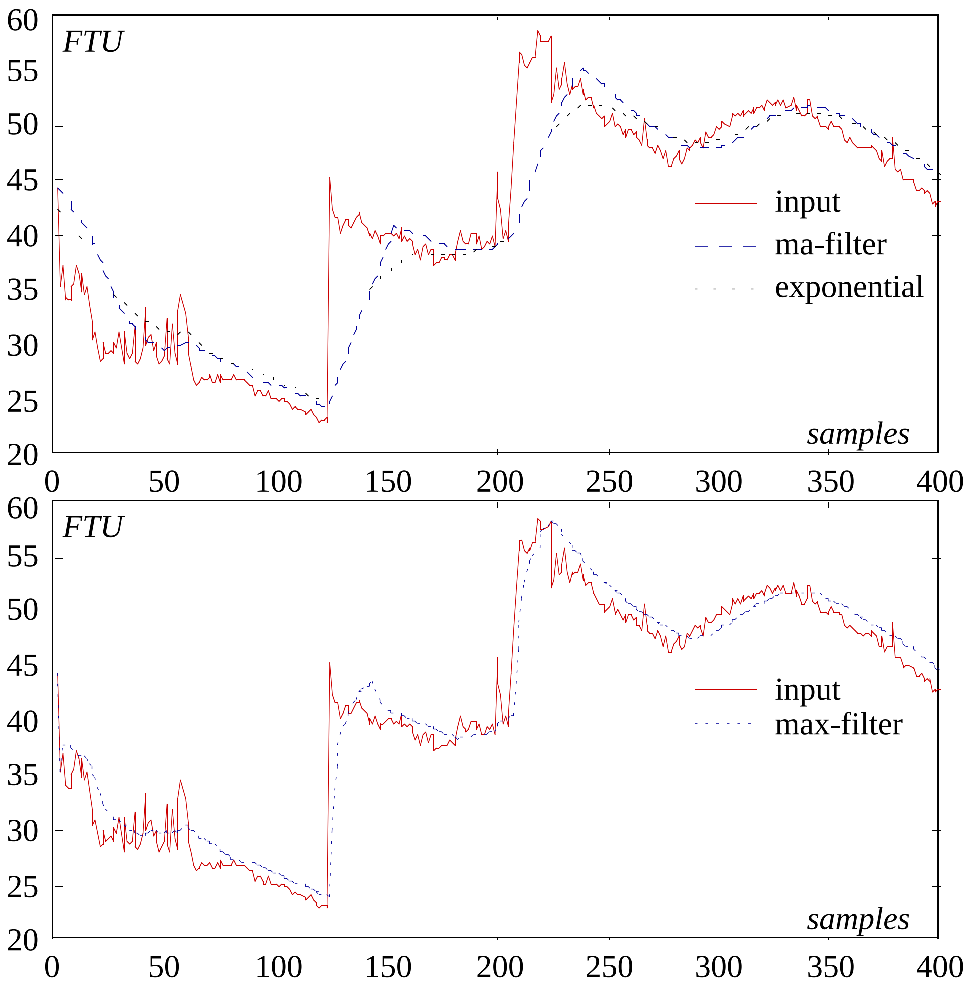


Figure 4.14 The same comparison as in Figure 4.13 is here shown for a suspended solids concentrations data sequence, which includes more high frequency noise.

5

Rule Based Diagnosis of Settler Data

In the previous chapter the problems using time series analysis for diagnosis were discussed. Most disadvantages are connected with the fluctuating quality of data acquired on-line. Since a time series model would require both adequate data and a proper input excitation the value of such analysis becomes limited in this application. Instead the efficiency of gathering information might increase if some rule based method is used (Bergh–Olsson, 1995). In order to use rule based methods the data set first of all has to be classified in accordance to its characteristics.

In this chapter the possibility of using rule based methods is investigated. First the advantages are considered and a method is developed and proposed. In the first section some different operating conditions are discussed and exemplified. It is also shown that if a data set does not appear normal it does not mean that it lacks information. In the second section principles for feature extraction are discussed. Instead of giving a quantitative interpretation of the data a qualitative one is used here. The third section deals with a simple tool, called an indicator matrix, that is used for a compact description of the different features in a data set. In the last section it is explained how the compact description in the indicator matrix can be used for diagnosis.

5.1 Various Operating Conditions

As mentioned in the previous chapter there are many conditions that are not suitable for parametric methods. At the end of section 4.2 it was mentioned that in order to overcome these problems some kind of intelligent shell has to be implemented. This shell should be able to evaluate whether a given situation is suitable for parameter estimation or not. Furthermore, it must have the ability of structuring and classifying a data set in order to choose the proper sub-model to be applied. Once a parametric sub-model has been chosen a proper interval has to be detected, where an adequate excitation takes place. The parametric method has to be surrounded and carefully nursed by this shell routine.

These concluding attributes of such a shell routine turns out to be more informative than the parametric method itself. The shell has to recognise any given situation and determine the most suitable action. The ability to properly identify any given situation is crucial in order to diagnose it.

Consequently, it could be worth keeping these recognising properties and investigate other possible methods for diagnosis. Once this is concluded and the parametric approach abandoned it is a natural continuation to analyse more qualitative methods, such as rule based reasoning.

Even though a parametric method does not produce a reliable result for a certain condition the situation may be recognised by the human eye. A trained operator is often able to extract the information given by the measurements and draw a likely conclusion. Consider the event shown in Figure 5.1. It is a trivial task for any operator to detect that this is a sequence with two bulking sludge events. The conclusion might appear basic. However, a parametric method without external intelligence support would have great difficulties to come up with it.

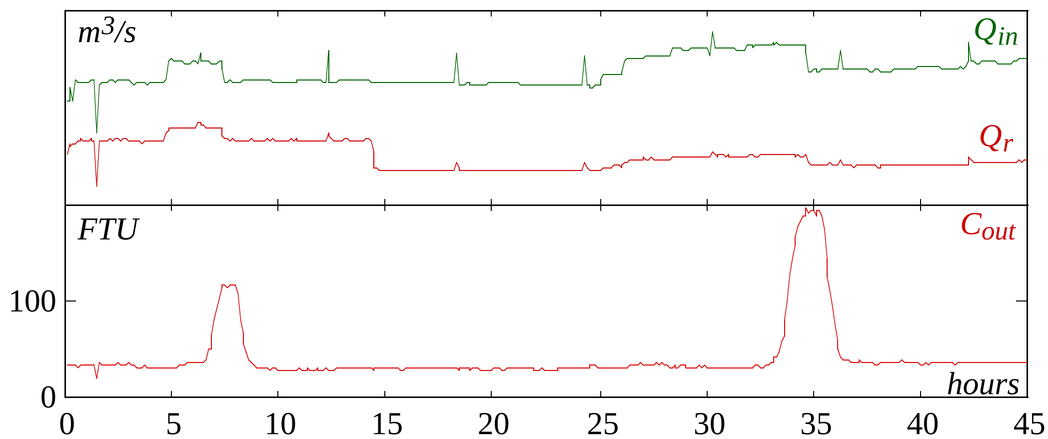


Figure 5.1 Illustration of bulking sludge events.

A similar situation is illustrated in Figure 5.2. A likely interpretation of this event is a washout, probably caused by a rain event. Note the principal difference between Figure 5.1 and 5.2. In the first case no obvious reason for the bulking is seen. In the latter case the bulking coincides with a large hydraulic load change. Consequently, a sensible conclusion is that the bulking is caused by the hydraulic impact. The statement that the hydraulic load comes from a rain event is also sensible, since that is a most common reason for this kind of massive hydraulic shocks.

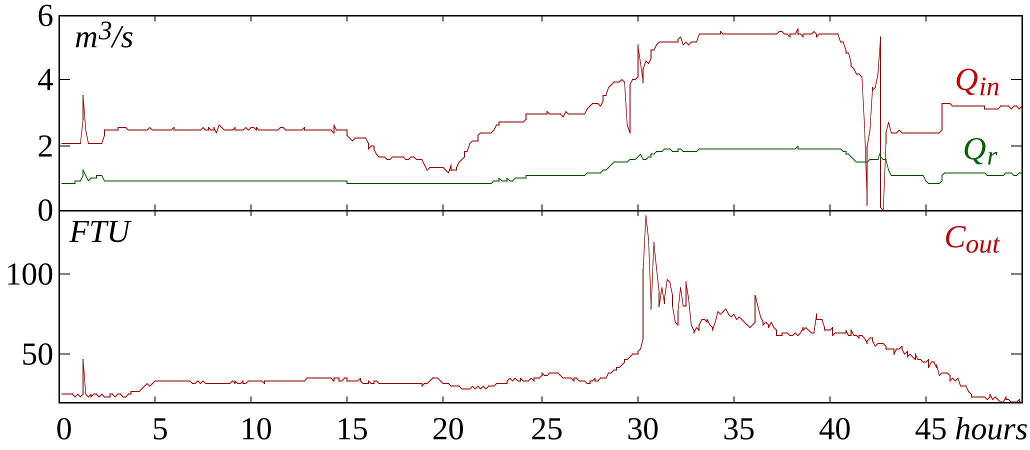


Figure 5.2 Display of a washout, probably caused by a rain event. A primary explanation to the bulking sludge can be found in the hydraulics. For some unknown reason the settler was not fit to deal with the sudden hydraulic load.

In Figure 5.2 a primary explanation to the sludge bulking was found. In the situation shown in Figure 5.1 no such obvious explanation is seen and it is likely that the explanation should be sought inside the process. A possible explanation is a rising sludge blanket level. If such measurements were at hand that hypothesis could easily have been confirmed or rejected. In the case of a rising sludge blanket there are many possible reasons. One is poor sludge control or management. Another is deteriorating microbial conditions affecting the flocculation properties of the sludge.

The attempt to explain an event, as shown in the paragraphs above, is a good example of a reasoning method. For every event a possible explanation is sought. Sometimes an explanation is found, sometimes not. Many steps in the chain of reasoning states a possible answer and raises a new question. One might say that it is a recursive *if…then…else…* procedure. In a way it reminds of a curious operator, that tries to come up with a possible explanation to every phenomenon seen.

Recall the settler transients shown in Figure 3.2 and discussed in Chapter 3. The discussion in the sections 3.3-3.5 explained how the transients were connected with the return sludge flow control. However, the transient phenomena of the settler do not always occur. Several drastic changes in the return sludge flow, without any effect on the effluent quality, have been detected. The current condition of the sludge seems to be the determining factor. During periods with good settleability the process is sufficiently robust to resist the hydraulic disturbances. Typically, the periods with very sensitive influence of the return sludge flow on the effluent turbidity have been observed during, or just before, periods with poor settling properties.

As a consequence they could be used for diagnostic purposes. If such a phenomenon appears, there is reason to believe that the settling process is about to fail. In order to discover them a diagnosis method has to detect the transient in the effluent suspended solids concentrations and examine whether a similar disturbance can be found in the return sludge flow. Even if the task looks simple, it requires some reasoning and knowledge about what to look for.

Once this possibility was recognised a small algorithm was implemented and batch tests were performed on data sets similar to those in Figure 3.2. The purpose was to see if the algorithm were able to detect the events and recognise them according to the given rules. Indeed it did, and it seemed to be a promising approach. The upper part of Figure 3.2 is repeated in Figure 5.3. Both the positive and the negative step in the suspended solids concentration in Figure 5.3 were detected and associated with the corresponding events in the return sludge flow.

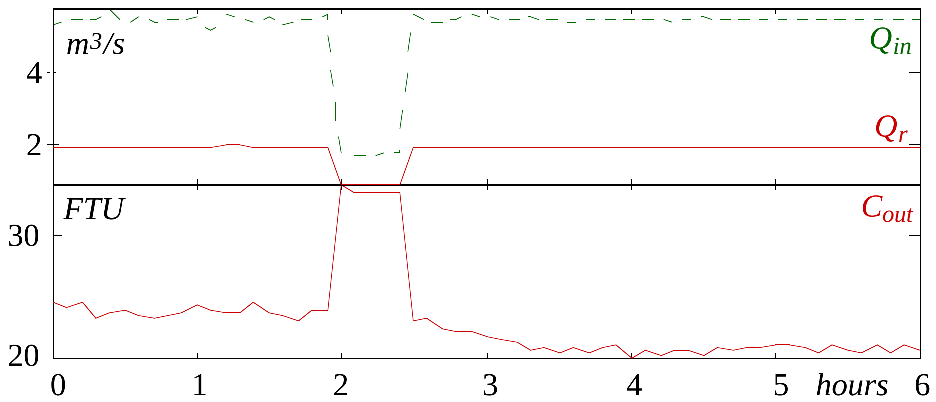


Figure 5.3 One of the events in Figure 3.2 is repeated. Together with other similar events this was used to test the performance of a simple algorithm.

It is quite an advancement when such a simple method could be used to recognise the situation in Figure 5.3. If this kind of phenomenon only appears during poor settleability conditions the ability to detect it is about enough to state a diagnose. The possibilities of detecting simultaneous deviations in the effluent quality and the return sludge flow are further discussed in section 5.4.

5.2 Feature Extraction

In order to implement a reasoning method, basic properties of the data have to be recognised. These are qualitative properties rather than exact numbers in a quantitative description. For example attributes like *normal*, *low* and *high* are used to describe every individual sample. Sometimes it might be useful to consider if a specific measurement is extremely high or low in order to get a rough feeling for *how* high or low it is.

It must be decided, what are to be considered as various high and low limits. The limits for one variable might differ between two plants.

Some other interesting features are missing data and drastic changes. In the latter case it is valuable to know if the measurement has observed a positive or negative step. The threshold for a sample to exceed in order to be classified as a step may be proportional to the standard deviation or a fixed value. Usually a mixture of the two is preferable.

Obviously it is quite simple to perform the tests required to classify a sample according to the discussion above. The features mentioned and how they could be implemented are summarised in Table 5.1.

There are several other attributes of a signal that might be considered. Sometimes it might be useful to look at a certain frequency range of the measurement. Since there are many coexisting processes in different time scales this could be a way to focus at individual processes, e.g. the hydraulic or microbial processes. In order to do this the signals have to be high- or lowpass filtered, or both. However, one might experience the timing phenomena discussed in section 4.3.

No.	*Feature*	*Implementation aspects*
0	Missing data	Easily recognised
1	Extremely low	Each sample is compared with a fixed predefined limit.
2	Low	-"-
3	High	-"-
4	Extremely high	-"-
5	Positive step	Compare the difference between each sample and its precursor to a certain threshold, that is determined by a percentage of the standard deviation and a fixed value.
6	Negative step	Analogous to above.

Table 5.1 Some basic features for classifying on-line samples.

Note that all of the attributes do not have to be mutually exclusive. As long as two features do not contradict each other they might coexist. For example a sample can be both high and performing a positive step at the same time, but it can not possibly be both high and low simultaneously.

Some of the features discussed here can be used directly in a simple warning system, e.g. extremely high or extremely low. However, most of the features call for some kind of cross reference treatment. The knowledge about the event in the suspended solids concentrations at about $t \approx 2$ hours in Figure 5.3 is useless, if the coupling to the simultaneous peak in the return sludge flow can not be found and interpreted. Consequently, it is often the combination of features of different parameters that can supply valuable pieces of information. In order to do this it is required to find the crucial combinations and likely explanations to what is happening inside the process.

5.3 The Indicator Matrix

The features of a signal are to be regarded as the smallest bricks of information. They often have to be put together in order to compose an image. Sometimes an individual feature gives sufficient information. Some other times it is rewarding to combine the information from two or more particular features of signals. In order to do this it is comfortable to obtain a compact representation of particular features of a signal.

The features of a signal will be described in terms of binary logic. For each sampling time several tests are performed. If nothing particular is observed at this sampling interval, it is represented by "0". This means that a certain test on the signal is represented with a binary vector. All the tests of the actual signal then are stored in a matrix format, where any element is 0 or 1. Having such a logical matrix facilitates the data handling. It is convenient to perform quick tests for diagnostic purposes.

In order to demonstrate the technique an example is used for illustration. The suspended solids concentrations in Figure 3.2c is repeated in Figure 5.4, where the period from about 8 to 11 hours has been highlighted.

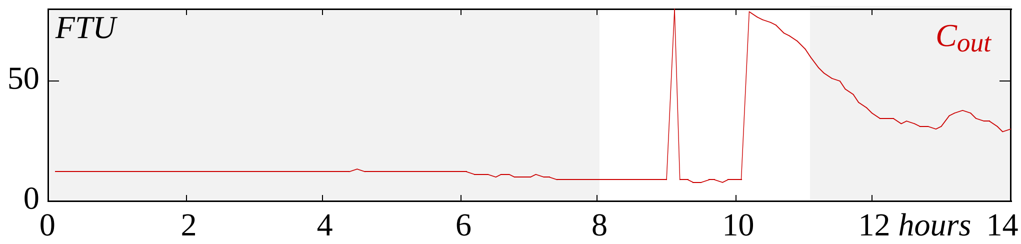


Figure 5.4 The effluent suspended solids measurement in Figure 3.2c is used to demonstrate the technique of feature extraction.

The highlighted period in Figure 5.4 contains 30 samples and is expanded into Figure 5.5a. The features from Table 5.1 have been automatically detected in the sequence of Figure 5.5a. These features are marked in an *incidence matrix*. Each sample of the data set is described by a column in the matrix. It is a binary matrix, that only consists of true (1) and false (0) values. If a feature has been detected then the corresponding element of the matrix is marked *1*. The incidence matrix for Figure 5.5a is shown in Figure 5.5b. At a specific time instant there may be more than one true element.

Since each column corresponds to a single measurement the whole matrix can be condensed into a single row using binary logic, i.e. the true elements in a column are given the weights 2^0, 2^1, 2^2, … according to the test numbers and summarised. The resulting indicator row is shown in Figure 5.5c.

This procedure is now repeated for each signal. Naturally, the test limits and conditions are different for each individual signal. All tests for each signal are condensed in a vector like in Figure 5.5c. The test information from all the signals can now be combined into one matrix, here called the *indicator matrix*.

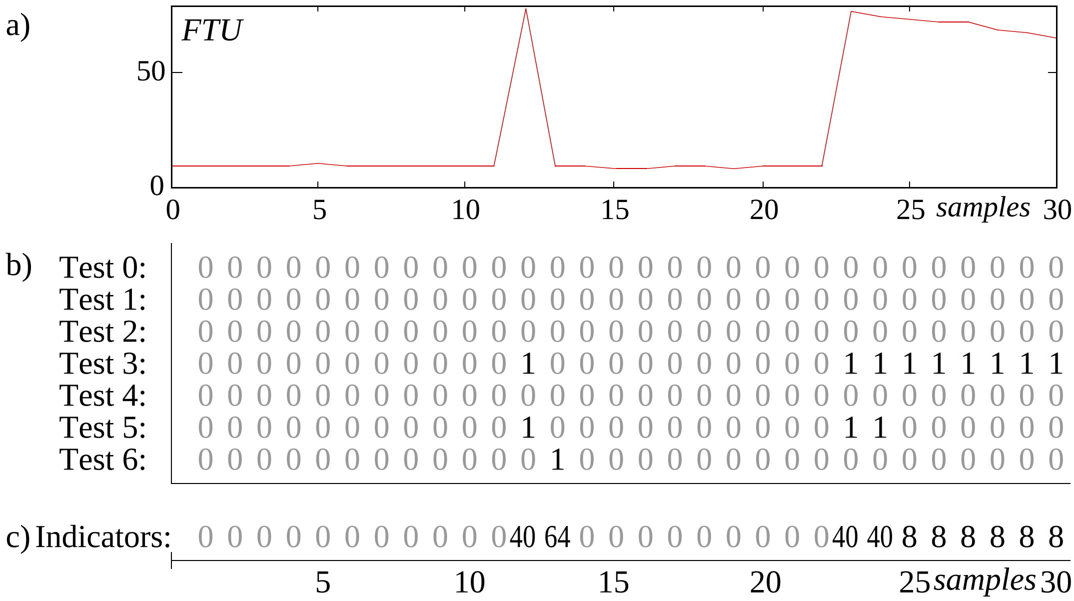


Figure 5.5 Illustration of how the incidence matrix is built and condensed into one indicator row.

a) A detail of the suspended solids concentration in Figure 5.4.

b) Incidence matrix for the time series in a). The rows correspond to the tests in Table 5.1: (0) missing data, (1) extremely low, (2) low, (3) high, (4) extremely high, (5) positive step, (6) negative step.

c) Each column in the incidence matrix, shown in b), is now condensed into an *indicator* value. Thus, the incidence matrix is condensed into a vector.

The indicator matrix makes it possible to perform many different qualitative tests of the relationships between the signals. For example, a pulse in one signal may cause some related phenomenon in another. Often the raw measurements are gathered in a matrix, since that is a convenient way to handle them. Note, that the dimensions of the indicator matrix will be the same as for the original measurement matrix. The index used for reference into the data matrix can also be used to refer to the corresponding test result in the indicator matrix.

In order to examine the attributes, described by a specific element in the indicator matrix, the following expression may be used.

$$D_x = \left(n \text{ div } 2^x\right) \text{ mod } 2 \tag{5.1}$$

where n is an indicator value and x denotes the test number. The value of D_x, either true or false, indicates the presence of the corresponding attribute.

5.4 Diagnosis Based on the Indicator Matrix

Diagnosis based on the indicator matrix has been tested with data from a full scale treatment plant. The time frame considered has been a period of about half a year during which the plant had considerable operational problems. All data were stored in 6 minute samples. The purpose has been to find out if a diagnosis system based on the indicator matrix could have given satisfactory early warnings.

It is obvious that visual inspection is a powerful tool to detect qualitative behaviour that deviates from normal. The human eye is well equipped to detect odd manners of signals. Certainly, many odd situations were detected during the manual inspection of the data. The challenge was to test if the method given above has a success rate similar to the human inspection.

The data set of more than half a year of 6 minute data of flow rate and effluent turbidity was inspected by the automatic method described. Although, the data sets had been inspected manually many times, several new interesting spots were detected. One illustrative example is just before the washout due to a rain event in Figure 5.2. During the manual scan the small peaks in the beginning of the sequence were neglected. Figure 5.2 is repeated in Figure 5.6 with the period of interest highlighted.

Each individual peak is not considered extraordinary. Using the indicator matrix, however, the simultaneous peaks were detected, even if they are small in amplitude. The interesting peaks are those in the return sludge flow and in the effluent suspended solids concentration. Note the small amplitude of the return sludge flow pulse. Still the effluent turbidity change is significant.

Each time that a peak disturbance has resulted in a turbidity pulse, some process operational problems has appeared a number of hours later. During normal conditions there may be flow peaks like the ones in Figures 5.3 or 5.6. However, when the settleability is more satisfactory, the turbidity does not display any noticeable response. In other words, it is empirically found that this type of peak disturbance sensitivity constitutes a clear indicator that the process is already in a troubled state. It ought to be emphasised that the peak disturbance itself is small enough not to cause any process operational problems.

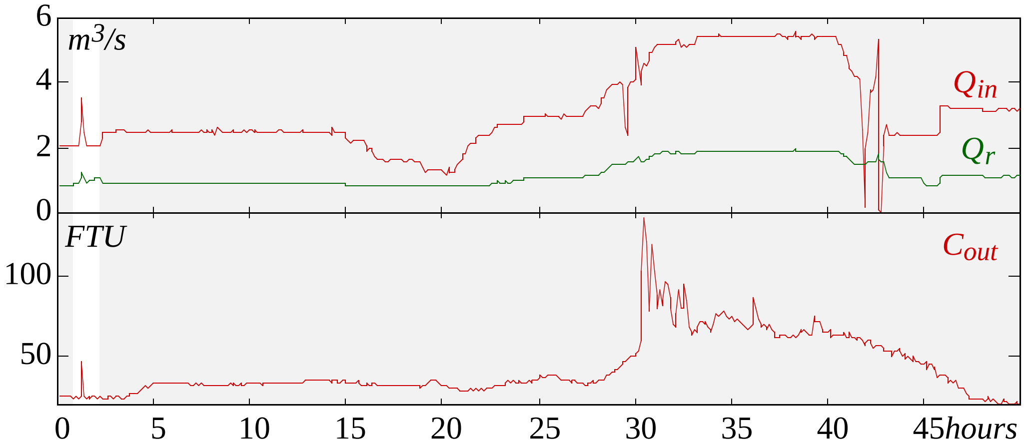


Figure 5.6 The event from Figure 5.2 is repeated, but now the phenomenon at about $t \approx 1$ hours is discussed. That is approximately 27 hours before the rain event and washout appears.

The reason for the poor settleability may have evolved gradually over a long time, depending on microbial changes. However, not until the flow increases at around $t \approx 27$ hours in Figure 5.6 the turbidity displays its sensitivity to hydraulic changes. It is this sensitivity that is first observed in the simultaneous peaks of the signals. Note, that the flow change is not at all extreme.

Given the warning signal there are several manual or laboratory tests that can be initiated. It is apparent that both the sludge blanket level and the sludge volume index can be monitored. Similarly, microscopic tests can complete the picture. The main result is, that an *early* warning gives better time margin for actions to improve the operation.

In Figure 5.6 there was an indication about 27 hours before the washout that the settling process was deteriorating. Such a time might be enough to turn poor settling into a better shape. A settler in poor condition is certainly not suited to meet a hydraulic impact like a rain event. If the warning in Figure 5.6 had been detected the washout might have been avoided.

Even if it is possible to gain several hours with this kind of diagnosis method, there is no way to quantify how bad a troubled situation may be. The condition may probably already be difficult, but it has not yet been revealed. Consequently, there is no way to estimate the time until a settler failure, like the washout in Figure 5.6. This heavily depends on the future hydraulic conditions. One important measure may thus be to try and soften the hydraulic influence as much as possible once a warning is stated. Often, though, there are strong limitations on what is achievable.

From the beginning the return sludge flow peaks were considered as undesired disturbances resulting from unsuitable return sludge control. These experiences show, that such a disturbance can be used purposefully to regularly and automatically indicate if the process is gradually deteriorating. Small peak disturbances of the return sludge flow could purposefully be injected into the system. As the settling properties deteriorate the consequences of a quick pulse disturbance become more and more noticeable.

Summary discussion

The indicator matrix can be used to supply building blocks for the test conditions that are required according to the current list of rules. Every rule tells to look out for one or several certain phenomena. If such a phenomenon is detected a conclusion may be drawn and other questions raised.

This hierarchy of possible tests have to be synchronised with the rule base. Some key tests will be performed first in order to apply a set of basic rules. The outcome of the rules will then determine the direction for further tests. Often no more tests will be needed, since well functioning conditions only call for the basic rules to confirm them. If some of the basic rules indicate a possible state of caution, the successive tests will be focused on that specific cause of concern.

In this iterative procedure of successively applying tests and rules the indicator matrix serves a basic task. It stores and handles the smallest indicators that are needed to perform the tests. If further tests should be needed, the indicators will be found in the matrix.

It should be emphasised that the structure of the rule base is crucial in order to minimise the tests needed for every conclusion. Since most disproportions will show up in the effluent suspended solids, it might be wise to start the procedure by looking for abnormalities there. Once an irregularity is detected in the effluent the search for the underlying justification may be initiated in terms of further tests.

Often a combination of several indicators will be of interest in the test conditions. Since all indicators are to be regarded as logical elements, the test conditions may easily be composed by using the logical operators `AND`, `OR` and `XOR`.

A suitable computational environment should be familiar in dealing with vectors and matrixes. The different logical operators could then be applied to entire binary vectors, e.g. the rows in Figure 5.5b. Otherwise the operators have to be repetitively applied to the individual elements for every single instant of time. The methodology presented with the indicator matrix is especially well suited for a routine of composing test conditions from logical vectors.

As an example, Matlab™ (MathWorks, 1992) is a well suited software to deal with the kind of binary calculations mentioned above. Primary calculations and simulations are easily implemented and tested in either Matlab™ or Simulink™ (MathWorks, 1995). Together they form a powerful toolbox for exploring new ideas.

6

Conclusions

This work demonstrates ways to use simple on-line measurements to give the operator a more elaborate picture of the process. This is done by means of qualitative methods for data handling and analysis. More quantitative methods, like parameter estimation, show weaknesses in handling untreated on-line data. Means to protect the parametric methods may be implemented by encapsulation into intelligent shells. However, this is just minor steps toward an knowledge based approach.

An essential result of this work is that qualitative and knowledge based signal testing is of great value in wastewater treatment systems. Often extreme sensor values are neglected when time series analysis is applied. Instead, periods of odd data can be constructively used for analysis.

A tool has to be able to test arbitrary time windows and combinations of signals. This makes an automatic tool superior to manual inspection. Here it is shown, that extreme values can contain important information, that will constitute early warnings and diagnosis for the operator. The warnings may be qualitative, but can initiate more elaborate manual or laboratory tests.

The traditional approach to on-line diagnosis is often passive, i.e. observing but not disturbing the process of interest. A more active approach is to allow the diagnosis system to introduce small excitations to the process. Possible correlated responses from the process may then be observed.

Ways of injecting excitations into the return sludge flow could be such an active approach. A good functioning settler will tolerate the disturbances without any significant deterioration of the effluent turbidity. However, hidden poor separation properties will be revealed in an early state if the settler dynamics is purposefully excited. How small, or big, excitations that should be used is mainly depending on the plant configuration.

Topics for Future Research

There are still many options to investigate about rule based methods. In this work some possibilities have been explored. The method discussed in Chapter 5 has shown interesting ability to deal with the kind of on-line data that appears in wastewater treatment facilities.

Similarities with fuzzy logic are easily recognised (Pedrycz, 1993). The basis for fuzzy logic, fuzzy sets, was first introduced by Zadeh (1965). The reception of fuzzy sets were sceptical initially, but the theory was gradually implemented. Mamdani (1974) gives an overview of an early application. The ability of handling possibility with fuzzy sets was later presented in Zadeh (1978). There have also been work done to combine fuzzy sets and neural networks (Kosko, 1992).

What is called features of a sample in this work may be compared to *sets* in fuzzy logic. The fact that a specified feature is recognised in a sample might as well be described as a degree of membership of a certain set. However, according to the method shown here the membership in a set is strict and not fuzzy. Various uncertainties of the signal properties may readily be formalised in fuzzy rules.

Fuzzy control have already been studied and successfully implemented for the activated sludge process, see e.g. Tong et al. (1980) and Tsai et al. (1994). The major difficulties is to estimate and handle the time delay between action and response. However, a fuzzy approach for diagnosis purpose would probably be slightly different.

Whatever rule based method used, it should be recognised that some dynamic phenomena that trig the detection will probably have a relatively quick time constant. The interaction caused by the return sludge flow typically has a response time of a couple of minutes, or even less. Other phenomena might be considered as static in this sense, although worth noticing. For example a high return sludge flow rate might not be of any immediate concern, but in the long run it is not a sustainable condition. Likewise for a low return sludge flow rate.

What was recognised during this work was the need for a hierarchical approach. Existing, as well as new, knowledge must be applied on the right process levels, in order for this kind of methods to be successful. In doing so the complexity of wastewater systems might be reduced.

There are many interesting approaches that should be investigated. Many disciplines use qualitative features rather than parametric values as a basis for their approach, even when quantitative measures are at hand or is easy to obtain. Fuzzy logic is already mentioned, but there are also knowledge based systems, rule based system or so called expert systems. Such approaches have already been made in the area of wastewater treatment showing promising results, see e.g. Chan et al. (1991) and Watanabe et al. (1993).

However, these disciplines often have their roots in manufacturing industries with a strong tradition of well structured systems. Some methodologies of interest, which applicability to wastewater systems should be studied, are data fusion (Bloch, 1996), hierarchical knowledge based systems (Zeigler et al., 1996) and maintenance of rule based systems (Gamage et al., 1996).

7

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A

List of Symbols

Symbol	Explanation	Unit
A	Generic notation for area.	m^2
A_c	Water jet area in vena contracta (the most narrow point of a jet).	m^2
A_w	Water jet area in weir.	m^2
A_{set}	Surface area of the settler.	m^2
a, b	Generic notation for parameters in time series models.	-
C_{bio}	Suspended solids concentration in the biological step, (sometimes called MLSS).	FTU[1], mg/l
C_{out}	Effluent suspended solids concentration.	FTU, mg/l
C_r	Return sludge suspended solids concentration.	FTU, mg/l
C_{set}	Influent suspended solids concentration to the settler unit. If the bioreactor is totally mixed this is the same as C_{bio}.	FTU, mg/l

[1] Most sensors for suspended solids concentration measure turbidity and use the unit FTU.

D_x	Logical indicator value, i.e. true or false.	-
d	Measure of a Sutro weir, see Figure 3.5c.	m, mm
e	White noise.	-
g	Acceleration due to gravity. In most places g = 9,81.	m/s^2
h	Water level in weir.	m, mm
k	Offset constant for Sutro weirs.	m^3/s, m^3/min
k_0, k_1, k_2	Constants used in settling models.	-
l	Generic notation for width (or length).	m, mm
m_{bio}	Total amount of sludge in the bioreactor.	kg
N	Number of weirs.	-
n	Generic notation for *number of* Often an arbitrary number.	-
p_0	Reference pressure just above the water surface (i.e. atmospheric pressure).	N/m^2
p_{bio}	Pressure at the bottom of the bioreactor.	N/m^2
p_{stat}	Static pressure in water jet after weir passage.	N/m^2
Δp	Difference in pressure.	N/m^2
Q_{bio}	Influent flow rate to the biological step.	m^3/s, m^3/min
Q_{comp}	Effluent flow of a weir, compensated for losses.	m^3/s
Q_{ideal}	Ideal effluent flow of a weir. No losses considered.	m^3/s

Q_{in}	Influent flow rate to the entire unit, WWT-plant or specified basin.	m^3/s, m^3/min
Q_{out}	Effluent flow rate from the unit, WWT-plant or specified basin.	m^3/s, m^3/min
Q_r	Return sludge flow rate.	m^3/s, m^3/min
Q_{set}	Influent flow rate to the settler unit.	m^3/s, m^3/min
Q_{set}^{net}	Settler net influent flow (Q_{set}-Q_r).	m^3/s, m^3/min
Q_w	Waste sludge flow rate.	m^3/s, m^3/min
q	Time shift operator. $q \cdot y(t) = y(t+\Delta t)$	-
r	Return sludge flow ratio (Q_r/Q_{in}).	-
T	Time constant.	-
t	Generic notation for time.	s, min, h, d
t_d	Time delay.	s, min
Δt	Sampling interval.	s, min
u	Generic notation for process (control) input.	-
V_{bio}	Volume of the bioreactor.	m^3
V_{set}	Volume of the settler.	m^3
ΔV	Difference in volume.	m^3
v	Velocity.	m/s
v_s	Relative settling velocity.	m/s, cm/s, mm/s
w	Waste sludge flow ratio (Q_w/Q_{in}).	-
X	Local concentration of suspended solids. Used in settler models.	mg/l, kg/m^3

X_0	Suspended solids concentration of non-settleable particles. Used in settler models.	mg/l, kg/m^3
x	Specifies the number for a certain test.	-
y	Generic notation for process output.	-
$\hat{y}$	Generic notation for estimated process output.	-
Z	Sludge blanket level.	m
z	Generic notation of depth.	m
α	Weir parameter. Mainly determined by weir measures.	-
ß	Weir parameter. Determined by the type of weir.	-
δ	Relation between the hydraulic retention time and the minimum sludge retention time.	-
ε	Clarifier effluent concentration ratio (C_{out}/C_{bio}).	-
ϕ	Flow efficiency coefficient of a weir. Accounts for flow losses in a weir.	-
Γ	Contraction coefficient of a weir. Accounts for the jet contraction after a weir.	-
γ	Thickening ratio (C_r/C_{set}).	-
λ	Exponential low pass filtering constant.	-
θ_h	Hydraulic retention time.	h
θ_χ	Sludge retention time.	d
$\theta_\chi^{\min}$	Minimum sludge retention time.	d

ρ	Density of water, ρ = 1,0.	kg/l
ψ	Velocity coefficient of a weir. Accounts for friction when a water jet passes a weir.	-

subscripts

bio	Bioreactor, i.e. aeration tank
ideal	An idealised value that does not account for any losses.
in	Influent flow
out	Effluent flow
r	Return sludge flow
set	Settler unit
stat	Static quantity

superscripts

(I), (II), (III)	Denotes test case
net	Net value
min	Minimum value
#	Denotes a polynomial, e.g. $A^{\#}(x)=a_0+a_1x+a_2x^2+\ldots$

Symbols

^	Denotes a predicted or an estimated value.

B

Data Acquisition

There have been two major parts in the process of data acquisition for this work. The first part is the on-line control system at the Rya wastewater treatment plant, *Cactus*. The second part is the database system called *Xwaste*, that runs on UNIX platforms.

All on-line sensors are connected to Cactus, the operators interface system. Cactus collects all measurements and communicates them to the Xwaste database. The sampling interval inside Cactus is typically 1 minute or shorter, while the shortest sampling interval that is communicated to Xwaste is 1 minute.

In order to be able to handle large amounts of data Xwaste stores them in a compressed format. The measurements are organised in several parallel databases. Due to the amount of data stored, the 1 minute samples are only kept for a limited period of time. Measurements that exceed this limit are stored with longer sampling intervals, such as 6 minutes or hours.

There is a support for remote terminal connections in Xwaste. This possibility was utilised during this work and a Xwaste client was installed at the Dept. for Industrial Automation at Lund Institute of Technology. The ability of selecting and transferring data from the Xwaste database at the Rya facility in Göteborg to Lund was indeed convenient. The sessions were run, and performed well, on an ordinary modem line. The reason for using a modem was that there is no stationary connection between Rya and the Department in Lund. The remote connections will be enhanced by a pure client-and-server concept in future versions of Xwaste.

Once data were transferred to Lund they were stored in new local databases. Then Xwaste was used to translate the data to ordinary text files. The format of the text files was not suited for import to Matlab™. However, this was a minor problem that was solved by a UNIX shell script that converted the text files into proper Matlab™ format. Once the data was accessible from Matlab™ all kinds of operations and calculations could be performed, and they were.

C

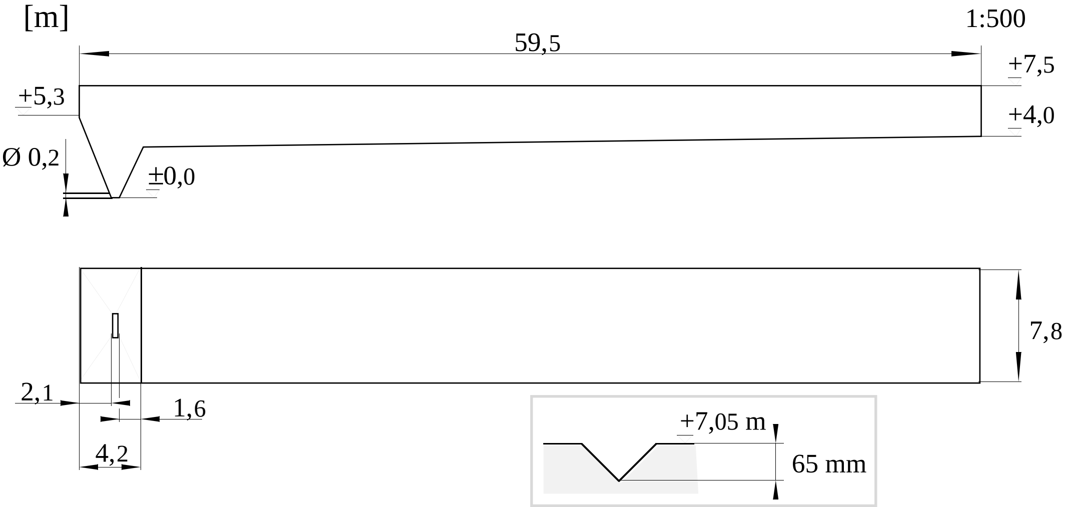
The Rya WWTP

The full scale data presented in this thesis originates from the Rya wastewater treatment plant in Göteborg, Sweden. The plant is operated by GRYAAB, (Göteborgsregionens Ryaverksaktiebolag) Göteborg Region Sewage Works.

Most data comes from the latter half of 1991, a troublesome period with frequent process upsets. Since the Rya plant is being extended the description below is not valid after 1995, but is for 1991. The description will focus on the overall dimensions and the secondary sedimentation, since those are of most relevance for this thesis. A more thorough description of the plant at this time is found in Lumley (1985). However, the work by Lumley resulted in the installation of new scrapers, 1986-87 and weir line, 1987-88.

The plant was built in 1970-71, taken into operation in 1972 and extended in 1982. The design flow was 3.8 m^3/s and a tunnel system with a total length of 120 km feeds the plant. In 1991 about 770 000 person equivalents were connected. About 20% of the total load comes from industrial facilities.

The total secondary settler volume is 31 200 m^3 with an area of 11 140 m^2. There are a total of 24 secondary settler units. The settlers measure 59,5 m by 7,8 m and an average depth of 2,75 m making them quite long and shallow. At the design flow the retention time is about 2 hours and 15 minutes. Each basin is equipped with a frequency regulated return sludge pump with a capacity of 0,13 m^3/s located at a water depth of 7,2 m. The outlet from each basin consists of six V-notch weir lines with a total length of 86 m. A rough outline of a settler basin is illustrated in Figure C.1, while some of the Rya plant dimensions in 1991 are summarised in Table C.1.



Basin		**Weirs**	
length:	59,5 m	type:	V-notch
width:	7,8 m	angle:	90˚
depth:	2,7 m	number:	324

Figure C.1 Outline of one settler basin. In total there were 24 identical basins in parallel in 1991.

Design flow	3,8	m^3/s
Total inlet lift pump capacity	18,0	m^3/s
Canal to primary settlers	2 800	m^3
Primary settler volume	22 800	m^3
area	5 750	m^2
Canal to aerator basins	3 500	m^3
Aerator volume	39 060	m^3
Aerator hydraulic retention time at design flow	2,9	h
Air blower capacity	200 000	m^3/h
Canal to secondary settlers	3 420	m^3
Secondary settler volume	31 200	m^3
area	11 140	m^2
hydraulic retention time at design flow	2,2	h
Return sludge pump capacity	3,0	m^3/s
Average flow during 1980's	3,2-4,3	m^3/s
Maximum flow under any one hour	14,3	m^3/s
Maximum flow under any one day	12,5	m^3/s
Minimum flow under any one day	1,4	m^3/s

Table C.1 A summary of dimensions and figures for the Rya wastewater treatment plant in 1991.

D

Clarity

Clarity is the name of a new clarifier hydraulics simulation software package that is to be released in a close future. It is a fully mass conservative modelling tool developed at Reid Crowther Consulting, Inc. in Seattle. A short description of the tool is presented below. For further information about Clarity please contact:

Reid Crowther Consulting, Inc.
155 NE 100th, suite #301
Seattle, WA 98125
USA
Phone: (206) 524-7330
Fax: (206) 526-8677

The model has several capabilities, such as: satisfying basic mass conservation requirements, predicting impacts of sludge density currents and supporting both circular and rectangular clarifiers. Although, rectangular basins was not incorporated in the version that was used in this work. It has been successfully applied to a number of full scale units.

The underlying equations have been described in several papers, see e.g. Zhou–McCorquodale (1992), Zhou et al. (1992), Samstag et al. (1992), Zhou et al. (1994) and McCorquodale–Zhou (1994).

Clarity has a Windows-compatible user interface that facilitates both the configuration of a simulation scenario as well as the analysis of its results. A scenario is composed by six main components that are graphically maintained: clarifier geometry, settling characteristics, influent hydraulics, return sludge geometry, return sludge flow and simulation parameters.

The graphical user interface makes it easy to configure and reconfigure different scenarios. The different components may be handled individually and are easily exchanged or replaced.