Universitat de Girona

DEVELOPMENT OF AN AIR-SCOUR CONTROL SYSTEM FOR MEMBRANE BIOREACTORS

Giuliana FERRERO

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Universitat de Girona

PhD Thesis

Development of an air-scour control system for membrane bioreactors

Giuliana Ferrero

2011

Directors: Prof. Ignasi Rodriguez-Roda Layret and Dr. Joaquim Comas Matas

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IGNASI RODRÍGUEZ-RODA LAYRET i JOAQUIM COMAS MATAS

Professors del Departament d'Enginyeria Química, Agrària i Tecnologia Agroalimentària de la Universitat de Girona i de l'Institut de Medi Ambient.

Certifiquen

Que la llicenciada en 'Ingegneria per l'Ambiente e il Territorio' Giuliana Ferrero ha realitzat, sota la seva direcció, el treball que amb el títol "**Development of an air-scour control system for membrane bioreactors**", es presenta en aquesta memòria la qual constitueix la seva Tesi per optar al Grau de Doctor per la Universitat de Girona.

I perquè en prengueu coneixement i tingui els efectes que corresponguin, presentem davant la Facultat de Ciències de la Universitat de Girona l'esmentada Tesi, signant aquesta certificació a

Girona, 3 de maig de 2011

Ignasi Rodriguez-Roda Layret

Joaquim Comas Matas

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ABSTRACT

The increasingly stringent legislation relating to freshwater preservation and pollution removal, affecting both domestic and industrial wastewater discharge, has been the main driver so far behind membrane bioreactor (MBR) installations. MBR technology usually results in high quality effluents with low concentrations of total suspended solids, and also makes for more efficient water reclamation. Other drivers are water scarcity, return on investment, environmental impact, and public and political acceptance. Technical innovations and significant membrane cost reduction have resulted in MBR becoming an established process option for wastewater treatment and caused an exponential increase in MBR plant installations since the mid 90s. The European market continues to be one of the most significant and accounts for a 21% share of the total MBR market.

The technology cannot yet be considered cost competitive as compared to conventional activated sludge systems, because of the high energy consumption required for membrane scouring. An intense research activity has aimed at minimising operational costs, mainly focusing on the design of energy-efficient membrane modules, and in some cases directed towards commercial solutions focused on air-scour reduction. Some of the most important publications can be found in the patent literature; however there is still a lack of robust control systems capable of reducing membrane aeration requirements while maintaining optimum filtration performances. Membrane air-scour, as a key factor in MBR operation cost, is central to this thesis.

The research presented here involves the development and implementation of a new and robust control system based on permeability trends but at the same time capable of reducing aeration proportionally to permeate flux. Permeability was made a key parameter for directly comparing temporary changes in membrane performance. Transmembrane pressure and flux were gathered every 10 seconds and permeability values were automatically calculated; different mathematical algorithms were applied for the signal filtering of on-line data. Short term and long term permeability trends were compared once a day, and a control action was applied proportionally to the short term/long term permeability ratio without exceeding the aeration flow recommended by the membrane suppliers.

The membrane-performance-based control system was developed and partially validated at pilot scale with different membrane configurations (flat sheet and hollow fibre), and achieved a maximum energy saving of about 20%. A semi-industrial pilot plant was operated for nearly two years in two different facilities in Catalonia, El Vendrell wastewater treatment plant (WWTP) and Granollers WWTP, both managed by OHL-Medio Ambiente INIMA S.A.U. at the time of this study. Various operational conditions, such as constant permeate flow and variable permeate flow, were tested while manually or automatically modifying the air-scour set point. The outcomes of the experiments were used to develop the concept of an innovative air-scour feedback control system, a fundamental part of a more ambitious and complex knowledge-based control system. Biological nutrient removal was monitored throughout study and it was demonstrated that the control system developed did not interfere with the process. Further investigation is being carried out, including full scale validation in La Bisbal d'Empordà MBR (Girona, Spain).

RESUM

La legislació, cada cop més restrictiva, referent a la conservació de les masses naturals d'aigua i a l'eliminació de contaminants, que afecta tant el tractament d'aigües residuals industrials com domèstiques, ha estat fins ara el principal motiu per a la instal·lació de bioreactors de membrana (MBR, per l'anglès *membrane bioreactor*). La tecnologia MBR permet obtenir efluents de gran qualitat amb concentracions molt baixes de sòlids en suspensió totals i, per tant, esdevé una font molt bona d'aigua regenerada. Altres raons que han permès el desenvolupament de la tecnologia MBR són l'escassetat d'aigua, la disminució dels costos d'instal·lació fins a valors propers a un tractament convencional amb terciari, el menor impacte ambiental i l'acceptació pública i política de la tecnologia. Diverses innovacions tecnològiques, així com la reducció significativa del cost de les membranes, ha causat que els MBR esdevinguin una opció tecnològica consolidada per al tractament d'aigües residuals i ha animat un creixement exponencial en la instal·lació de plantes MBR des de mitjans dels 90. El mercat europeu continua essent un dels més importants, ja que representa un 21% del negoci total del mercat dels MBR.

La tecnologia, però, encara no es pot considerar competitiva quan la comparem amb els sistemes de tractament convencionals de fangs actius, a causa del consum d'aire més elevat, necessari per a la neteja física de les membranes. Bona part de l'activitat actual de recerca s'està centrant a intentar minimitzar els costos d'operació, enfocant-se principalment en el disseny de mòduls de membrana energèticament més eficients i, en alguns casos, dirigida a solucions comercials que se centren en la reducció de l'aire per a neteja de membranes. Algunes de les publicacions més importants es troben a la bibliografia de patents; malgrat tot, encara hi ha una necessitat de sistemes robustos de control capaços de reduir els requeriments d'aeració de les membranes tot mantenint uns rendiments de filtració òptims. L'aeració de les membranes, com a factor clau en els costos d'operació dels MBR, és un aspecte fonamental d'aquesta tesi.

El treball presentat a la tesi inclou el desenvolupament i la implementació d'un nou sistema de control robust basat en les tendències de la permeabilitat i, al mateix temps, capaç de reduir l'aeració de forma proporcional al flux de permeat. S'ha seleccionat la permeabilitat com el paràmetre clau per comparar directament els canvis temporals en el funcionament de les membranes. La pressió transmembrana i el flux es mesuren cada 10 segons i llavors la permeabilitat es calcula automàticament. El senyal de les dades recollides en línia es filtra adequadament mitjançant diversos algoritmes matemàtics. L'algoritme de control compara diàriament una tendència a curt termini de la permeabilitat amb una tendència a llarg termini de la permeabilitat, i s'aplica una acció de control proporcional al quocient de les dues tendències, sense excedir mai el cabal d'aeració recomanat pels fabricants de membranes.

El sistema de control basat en el funcionament de les membranes s'ha desenvolupat i validat parcialment a escala pilot amb diferents configuracions de membrana (de fibra buida i planes) aconseguint estalvis d'energia propers al 20%. La planta pilot d'escala semi industrial s'ha operat durant gairebé 2 anys en dues plantes depuradores reals diferents a Catalunya, a l'estació depuradora d'aigües residuals (EDAR) de'El Vendrell i a l'EDAR Granollers, ambdues operades per l'empresa OHL-Medio Ambiente INIMA S.A.U. en el moment d'aquests estudis. Es van provar diverses condicions d'operació, com ara flux de permeat constant i variable, al mateix temps que manualment o

automàticament es va modificar la consigna d'aire per membranes. Els resultats de l'experimentació s'han utilitzat per desenvolupar el concepte d'un sistema innovador de control de l'aeració de membranes, el qual és una part fonamental d'un sistema de control basat en el coneixement més ambiciós i complex. L'eliminació biològica de nutrients s'ha monitoritzat durant tot l'estudi, i s'ha demostrat que el sistema de control desenvolupat no interfereix per res amb els rendiments de depuració. Els estudis que actualment s'estan portant a terme inclouen una validació a escala real del sistema de control desenvolupat, concretament a l'EDAR de la Bisbal d'Empordà (Girona, Catalunya).

CONTENTS

ACRONYMS

BOD	biochemical oxygen demand
C	carbon
CL	closed loop
COD	chemical oxygen demand
CPF	constant permeate flux
CS	carbon source
CSV	comma separated value
CT	capillary membrane
DO	dissolved oxygen
EPS	extra polymeric substance
FC	filter cartridge
F/M	food to microorganisms ratio
FS	flat sheet
HF	hollow fibre
IF	inflow
J	flux
Jc	critical flux
K	permeability
KB	knowledge-based
KBS	knowledge-based system
HRT	hydraulic retention time
MBR	membrane bioreactor
MF	microfiltration
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
MT	tubular membrane
N	nitrogen
NF	nanofiltration
OL	open loop
ORP	oxidoreduction potential
P	phosphorous
PAN	polyacrylonitrile
PAO	phosphate accumulating organism
PE	polyethylene
P.E.	population equivalent
PES	polyethylsulphone
PLC	programmable logic controller
PP	polypropylene
PS	polysulphone
PVDF	polyvinylidene difluoride
R	resistance
RO	reverse osmosis
SAD	specific aeration demand
SCADA	supervisory control and data acquisition
SMP	soluble microbial products

SR	slope ratio
SRT	solids retention time
SW	spiral wound
TMP	transmembrane pressure
TN	total nitrogen
TSS	total suspended solids
UCT	University of Cape Town
UF	ultrafiltration
V	volume
VPF	variable permeate flux
VSS	volatile suspended solids
WWTP	wastewater treatment plant
XML	extensible markup language

CHAPTER 1

PREFACE

1. Preface

1.1 Problem statement

Membrane bioreactors (MBR) are a relatively new technology which combines typical activated sludge and a tertiary treatment into a single treatment step. MBR have great potential in wide ranging applications including municipal and industrial wastewater treatment, solid waste digestion and odour control. Full-scale systems are operational worldwide and the list of installations continues to increase at a relatively rapid rate compared to conventional treatment solutions.

It is reported that, taking 2000 as a start-point, MBR technology will have grown by an average of 11.6 - 12.7% per annum by 2013. However growth rates and the extent of implementation vary according to a region's economic development and infrastructure (Judd, 2011). The economics of the technology rest on three main factors: 1) energy consumption, 2) membrane lifecycle costs, and 3) filtration rates.

Energy consumption in MBR plants is higher than in conventional activated sludge plants due to additional energy requirements during operation, mainly during the air scouring of membranes. The development and successful commercialisation of the technology has led to an appreciable decline in capital and operating costs, but the high energy costs due to membrane aeration remain a concern (Srinivasan, 2007).

1.2 Hypotheses

During the last ten years a large number of companies have devoted much effort to researching and developing cost efficient filtration technologies, but although recent studies illustrate that the energy consumption for membrane aeration can be drastically reduced, it is still not clear whether this operation causes a higher level of membrane fouling in the long term.

The main hypothesis of this thesis is that optimal results in terms of both energy optimisation and fouling mitigation are achievable through the implementation of automatic control systems. Air-scour can be reduced under specific circumstances such as low permeate fluxes, good sludge filterability, etc. Some of the most important publications can be found in the patent literature but in most cases there is no record of a validation of the controls systems proposed. Indeed, common practice in full scale MBR control often entails conservative operational strategies with unvarying aeration flow rates in different scenarios, based on manufacturers' recommendations, with no attention being paid to possible energy savings. Thus, there is still a need for robust control systems capable of reducing energy consumption in terms of membrane aeration requirements while maintaining optimum filtration performance.

The air-scour necessary to maintain membrane permeability and limit fouling phenomena can be dynamically adjusted depending on the tendency of the membrane to become fouled, and this can be done using data directly available from a standard MBR. No additional sensors are required. The control of the filtration process and the reduction in energy requirements can be integrated with the control of the biological processes, resulting in integrated control systems.

1.3 Contributions

The main contribution of this thesis is the development and implementation of an innovative feed-back air-scour control system based upon permeability trends. Permeability was chosen as the key parameter for directly comparing temporary changes in membrane performance. The air-scour control system was developed over two years of experimentation at pilot scale with different membrane configurations and under diverse conditions. It was validated at semi-industrial pilot scale and achieved a maximum energy saving of about 20%.

The encouraging results led to a patent application filed in Spain on the 12th of June 2009 and finally approved on the 22nd of October 2010. Since then the control system has been improved and multiple additional control rules have been added or modified. The intention for the future is to further develop the control system while operating under daily variable permeate fluxes.

The development and dissemination of many projects related to MBR technology for wastewater treatment (see the list of publications at the end of this chapter) has helped improve local acceptance of and confidence in this emerging and efficient technology.

1.4 Outline

The structure of this thesis is as follows:

In **Chapter 2** the objectives of the thesis are presented.

In **Chapter 3** there is an introduction to MBR technology, with a basic description followed by consideration of the current MBR market size and growth projections, the main drivers for MBR technology implementation, and some fundamental points about membrane processes, investment and operational costs. Finally, there is some general consideration of MBR process design and operation, which are then illustrated. In **Chapter 4** there is a review of the literature on the state-of-the-art of control systems for membrane bioreactors, and a comparative analysis of the different approaches, starting with the most common manipulated variables: strategies for air-scour, filtration cycles, permeate flux, chemical dosage control, chemical cleaning frequency and biological nutrient removal.

Materials and methods are described in **Chapter 5,** with a detailed explanation of the pilot plant used during the study and analytical protocols.

The results of the thesis are contained in **Chapters 6, 7 and 8**. In **Chapter 6,** the knowledge acquisition is presented with all the empirical data obtained from the biennial experimentation at pilot scale. **Chapter 7** provides a detailed description of the final product, the air-scour control system, with architecture comprising data acquisition and signal processing, control and supervision modules.

The implementation of the air-scour control system is presented in **Chapter 8,** focusing on codification and a web-based interface.

Chapter 9 presents the conclusions drawn from the results of the thesis. **Chapter 10** lists the references and finally an **Annex** is provided with the data of the filtration process during the pilot plant experimentation.

1.5 List of publications

1.5.1 Journal papers

Ferrero, G., Monclús, H., Buttiglieri, Gabarron, S., G. Comas, J., Rodriguez-Roda, I. (2011). Development of a control algorithm for air-scour reduction in membrane bioreactors for wastewater treatment. Journal of Chemical Technology and biotechnology. In press.

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1.5.3 Book chapters

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1.5.4 Patents

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CHAPTER 2

OBJECTIVES

2. Objectives

The main objective of this thesis is the development and implementation of an innovative and robust **control system that automatically regulates the air-scour flow rate and reduces energy requirements in membrane bioreactors for wastewater treatment,** while maintaining the efficiency of the filtration process and biological nutrient removal performance.

The achievement of this main objective is based on the following secondary objectives:

- Review of the state-of-the-art of control systems for membrane bioreactors focused on gaining a better understanding of MBR processes and operation (biological processes and filtration process);
- Experimentation at pilot scale with real wastewater and with different membrane configurations;
- Identification of key variables to be measured, controlled and manipulated;
- Development of data gathering and signal processing algorithms;
- Development of a feed-back control system;
- Development of supervision and/or safety rules to ensure robustness of the control system;
- Adaptation of the control system to different membrane configurations;
- Implementation and validation of the control system at semi-industrial pilot scale.

CHAPTER 3

INTRODUCTION

3. Introduction

3.1 Definition

Membrane bioreactor (MBR) technology is the combination of a membrane-based filtration process, such as a microfiltration (MF) or ultrafiltration (UF) system, with a suspended growth biological reactor. Essentially, the membrane system replaces the solids separation function of the secondary clarifiers in conventional activated sludge systems. It combines the unit operations of aeration, secondary clarification and filtration into a single process, producing a high quality effluent suitable for any discharge and most reuse or recycle applications, while greatly reducing space requirements, all under stringent norms (Figure 3.1).

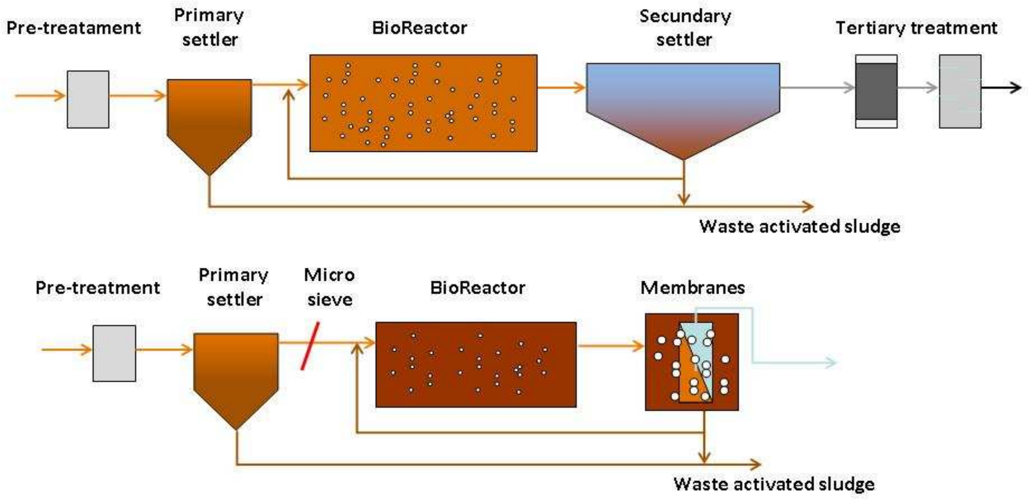


Figure 3.1. Simple scheme of a conventional activated sludge system with tertiary treatment (top) and a membrane bioreactor system (bottom).

3.2 Historical perspective

The MBR process was introduced in the late 1960s by Dorr-Olivier Inc. It combined the use of an activated sludge bioreactor with a crossflow membrane filtration loop, and was applied to ship-board sewage treatment. The first systems were based on polymeric flat-sheet membranes. Although the idea of replacing the settling tank of the conventional activated sludge process was attractive, it was difficult to justify the use of such a process because of the high cost of membranes, the low economic value of the product (tertiary effluent) and the potential rapid loss of performance due to membrane fouling. Because the focus was on the attainment of high fluxes, it was necessary to pump the mixed liquor suspended solids (MLSS) at a high crossflow velocity with a significant energy penalty (of the order 10 $kWh \cdot m^{-3}$ product) to reduce fouling. Due to the poor economics of first generation MBR, they only found applications in niche areas with special needs.

The breakthrough for the MBR came in 1989 with the idea of Yamamoto and co-workers to submerge the membranes in the bioreactor (Figure 3.2). Until then, MBR had been designed with their separation device located externally to the reactor. These sidestream MBR relied on high transmembrane pressure (TMP) to maintain filtration., For economic reasons, immersed MBR systems, with the membrane directly immersed in the bioreactor, are usually preferred for domestic wastewater treatment to a sidestream configuration, which is basically used in leachate treatment and industrial wastewater, 3-5 kWh·m^{-3}. The immersed configuration relies on coarse bubble aeration to produce mixing, scour the membrane surface (which limits fouling) and provide oxygen to the biomass. Investment and operating costs are significantly reduced due to energy savings and a reduction and simplification of the equipment and needed to pump the sludge in a sidestream MBR (0.8-1.2 kWh·m^{-3}).

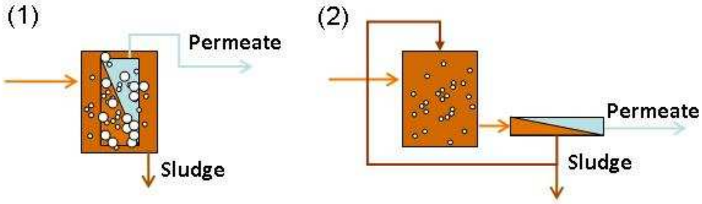


Figure 3.2. Immersed MBR (1) and sidestream MBR (2).

Initially, the membranes were placed in the same biological compartment where the influent was introduced, but nowadays the tendency is to locate them in a separate compartment to reduce fouling. The other key steps in recent MBR development have been the acceptance of modest fluxes (25% or less of those in the first generation), and using coarse bubble air flow to control fouling.

3.3 Current MBR market size and growth projections

Technical innovations (e.g. lowering operating costs with an immersed configuration) and significant membrane cost reduction have made MBR an established process option for wastewater treatment and encouraged an exponential increase in MBR plant installations since the mid 90s (Judd, 2006). As a result, the MBR process has become an attractive option for the treatment and reuse of industrial and municipal wastewaters, as evidenced by the constantly rising number and capacity of MBR installations.

MBR technology is experiencing faster growth than other advanced wastewater treatment systems. The global MBR market was estimated at around US$217 million in 2005 and to have risen to US$360 million by 2010 (Hanft, 2006). Frost & Sullivan put the figure at US$420.9 million in 2006 with a compound annual growth rate of 12.5% (Srinivasan, 2007). The European market continues to be significant and accounts for a 21% share of the total (Figure 3.3).

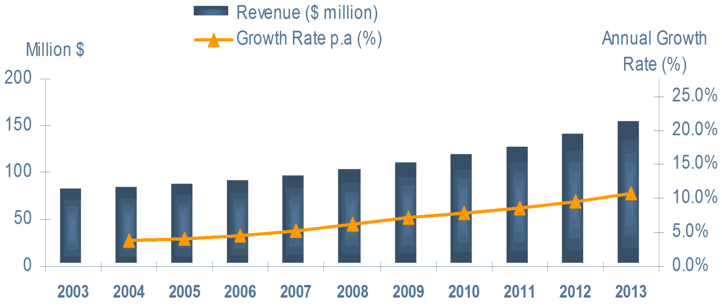


Figure 3.3. Revenue forecast for European MBR market (Srinivasan, 2007).

Figure 3.4 illustrates the percentage of MBR by wastewater type in the global market (Stephenson *et al.*, 2000).

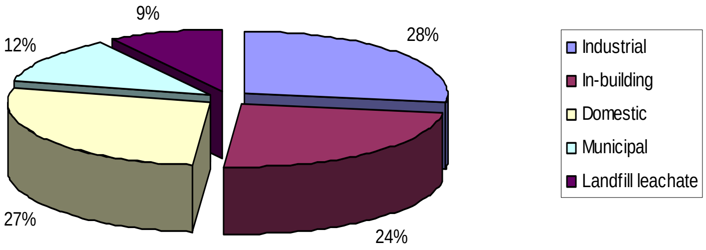


Figure 3.4. Approximate global distribution of MBR by wastewater type.

In terms of membrane configurations, hollow fibre and flat sheet membranes are the ones mainly used in MBR applications. Although the global market is dominated by Zenon, Kubota and Mitsubishi Rayon, which hold 85-90% of the municipal market, there is now a wide range of products available for both industrial and municipal applications. In Europe, Kubota technology is most often implemented in MBR from 5,000 to 20,000 $m^{3}\cdot d^{-1}$, while other larger plants are equipped with Zenon membranes, except for the Sabadell WWTP. Wehrle and Norit are the most important European suppliers.

Among European countries, Spain was the last to adopt MBR technology, with its first municipal plant installed in 2003. However, the Spanish market developed focusing on medium-sized municipal and small-sized industrial installations, with a few exceptions, such as two of the largest MBR in Europe (San Pedro del Pinatar and Sabadell: 48,000 $m^{3}\cdot d^{-1}$ and 35,000 $m^{3}\cdot d^{-1}$ respectively). The total number of MBR plants is reported to have grown from 47 at the end of 2005 to 111 in 2008 (Lesjean, 2009), but the impact of global recession brought an abrupt halt to this exponential growth.

3.4 Drivers for MBR technology implementation

While the most significant barrier to the more widespread installation of MBR remains their cost, there is a number of drivers which mitigate this factor. Probably the most important is the increasingly stringent legislation related to freshwater preservation and pollution removal, affecting both domestic and industrial wastewater discharge: the Urban Wastewater Treatment Directive (91/271/EEC) of 21 May 1991 and the European Union Water Framework Directive (2000/60/EC) of 23 October 2000. This, together with the introduction of state and regional incentives to encourage improvements in wastewater technology and recycling, has driven the development of more sophisticated technologies in the water sector.

Other drivers are water scarcity, return on investment, environmental impact, and public and political acceptance. Even without legislation, regional water resource problems can provide sufficient motivation for water reuse. Global change patterns are tending to aggravate water scarcity problems, in particular in those countries which are prone to drought conditions. For instance, nine European countries (Belgium, Bulgaria, Cyprus, Germany, Italy, Macedonia, Malta, Spain and the United Kingdom) are considered water stressed. Moreover, both investment (especially in membranes) and the operating costs of MBR systems have decreased dramatically over the past 20 years. New opportunities have emerged since retrofitting existing biological systems by adding membrane filtration became a viable option for increasing a WWTP's capacity and/or water quality without detriment to its environmental footprint. Finally, confidence in and acceptance of MBR technology is growing as reference sites increase in number and maturity.

3.5 Fundamentals of membrane processes

A number of membrane configurations are commercially available, including hollow fibre (both reinforced and non-reinforced), flat sheet and tubular. The differences between each of these types of membranes are significant. They include pore size, construction materials, chemical cleaning, air-scour requirements, hydraulic configuration and membrane tank volume.

3.5.1 Membrane separation process

Membrane filtration is defined as a pressure- or vacuum-driven separation process in which particulate matter is rejected by an engineered barrier, primarily through a size exclusion mechanism. The degree of selectivity depends on the pore size. This definition covers the following membrane processes commonly used in water treatment (Figure 3.5):

- Microfiltration (MF)
- Ultrafiltration (UF)
- Nanofiltration (NF)
- Reverse Osmosis (RO)

MF can deal with the removal of particulate or suspended material ranging in size from 0.1 to 10 µm, while UF is usually used to separate virus and colloids in the 0.01 to 0.1 µm range. Whereas NF can deal with the removal of small molecules and viruses with a pore size of 0.001 to 0.01 µm, RO membranes are capable of separating singly charged ions (< 0.001 µm). The permeate is the solution able to pass through the membrane, whilst the rejected fraction is commonly called the retentate.

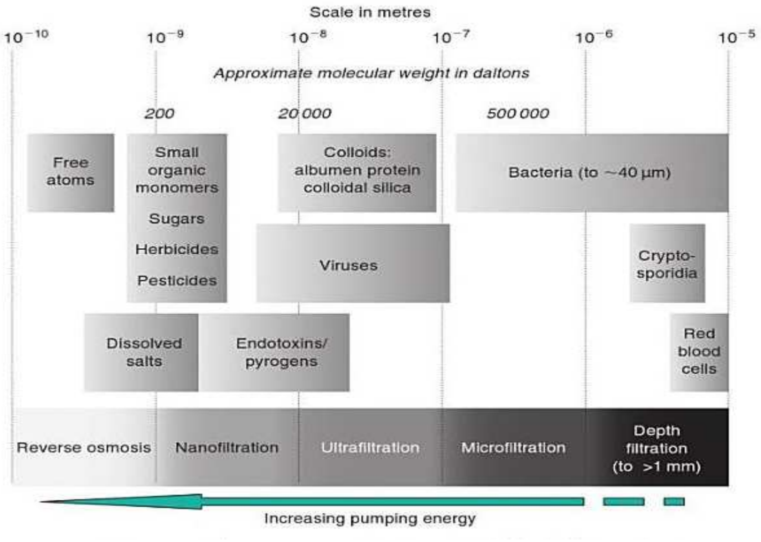


Figure 3.5. Membrane separation processes (Judd & Jefferson, 2003).

3.5.2 Membrane materials and their internal structure

Most membranes are made from polymeric or ceramic materials. The most widely used are celluloses, polyamides, polysulphone (PS), charged polysulphone and other polymeric materials such as polyacrylonitrile (PAN), polyvinylidene difluoride (PVDF), polyethylsulphone (PES), polyethylene (PE), and polypropylene (PP). All of these polymeric materials have the necessary chemical and physical resistance, but they are also hydrophobic, and it is known that hydrophobic membranes are more prone to fouling than hydrophilic ones due to the fact that most interactions between the membrane and the foulants are of a hydrophobic nature. The base material is treated to obtain a hydrophilic surface by chemical oxidation, organic chemical reaction, plasma treatment or grafting. This modification process, together with the method of fabrication of the membrane modules, is the proprietary information of most suppliers.

3.5.3 Membrane configurations

Conventional filtration can operate in one of two modes: if there is no retentate stream the operation is termed ‘dead-end’ or ‘full-flow’; if retentate flows continuously from the module outlet then the operation is called crossflow. Crossflow implies that for a single passage of feedwater across the membrane only a fraction is converted to permeate product; this parameter is termed ‘conversion’ or ‘recovery’. Suspended solids are captured on the filter surface, and can build up and eventually slow down the rate of filtration. This requires the process to be stopped for the filter to be cleaned or replaced. However, in crossflow filtration, the feed stream flows parallel or tangentially to the membrane surface. Flowing at a high velocity, the feed stream constantly sweeps the membrane surface clean of accumulated solids or solutes. The membrane separation mechanism is complex and ideally should be configured to have: a) a high membrane area to module bulk volume ratio, b) a high degree of turbulence, c) low energy expenditure per unit product water volume, d) low cost per unit membrane area, e) a design that facilitates cleaning, f) a design that permits modularisation.

The principal configurations used in membrane processes are based on the geometry of the membrane element (Figure 3.6): 1) flat sheet (FS), 2) hollow fibre (HF), 3) tubular (MT), 4) capillary (CT), 5) pleated filter cartridge (FC) (used only with low TSS waters), 6) spiral-wound (SW). Only the first three configurations are employed in MBR processes.

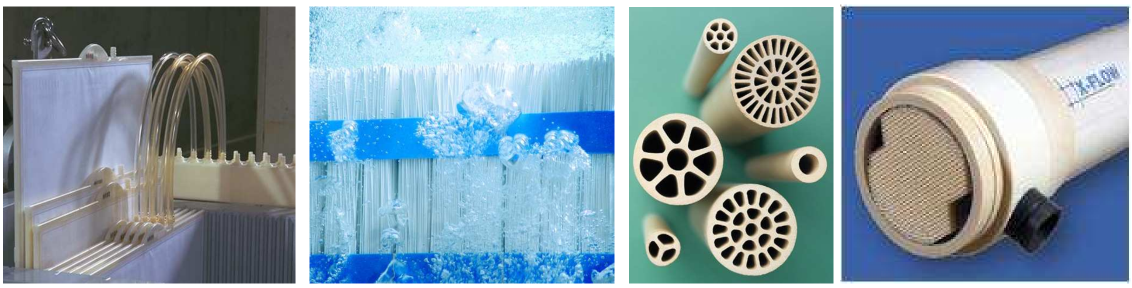


Figure 3.6. From the left: Kubota flat sheet, Puron hollow fibre, ceramic tubular and Norit capillary membranes.

3.5.4 MBR key parameters

The key elements in any membrane process are the following:

Flux (J): Quantity of material passing through a unit area of membrane per unit of time, in SI units $m^3 \cdot m^{-2} \cdot s^{-1}$, but more commonly expressed as $L \cdot m^{-2} \cdot h^{-1}$ (LMH).

Critical flux (J_c): Critical flux can be broadly defined as the flux, or the flux rate per unit membrane area, below which no deposition of foulants takes place (Field *et al.*, 1995).

Transmembrane Pressure (TMP): This is defined as the existing pressure drop (or difference) between the membrane pressure at the sludge side and the pressure at the permeate side, and is the driving force behind the biomass separation process (bar).

Permeability (K): This is calculated as permeate flux per unit of TMP and is usually given as $LMH \cdot bar^{-1}$.

Resistance (R): This is inversely related to permeability and fluid viscosity; it includes membrane resistance, the resistance of the cake layer or biofilm (reversible fouling) and resistance due to pore blocking or adsorption (irreversible fouling) ($bar \cdot LMH^{-1}$).

Specific aeration demand (SAD): This is the air flow necessary for the physical cleaning of membranes. It can be expressed as air flow per membrane unit area (SAD_m, $m^3 \cdot m^{-2} \cdot h^{-1}$) or per permeate volume unit (SAD_p, m^3 air$\cdot$ $m^{-3} \cdot h^{-1}$ permeate).

Normal values for flux range vary from 30 to 200 LMH for external membranes and 10 to 40 LMH for submerged membranes, which require more membrane area. Permeability is a very useful parameter for comparing membrane performance and monitoring the MBR operation, as well as for detecting fouling. Since submerged MBR require the use of air to scour solids from the membrane surface and hence limit fouling, the specific aeration demand is another key operational parameter. The SAD_m varies depending on the operational strategy and the recommendations of the membrane manufacturers, ranging from 0.28 to 0.75 $m^3 \cdot m^{-2} \cdot h^{-1}$. In most of the large scale MBR currently operating, SAD_p oscillates between 10 $m^3 \cdot m^{-3} \cdot h^{-1}$ and around 50 $m^3 \cdot m^{-3} \cdot h^{-1}$ or even higher. Aeration through fine bubble diffusers is used for suspending biomass and for biological reaction, as in conventional activated sludge systems, while a separate coarse bubble aeration system is typically applied for membrane scouring. Energy demand for submerged systems can be up to two orders of magnitude lower than that of side-stream systems.

Regarding operational parameters related to biological processes, while early MBR were operated with a solid retention time (SRT) as high as 100 days with mixed liquor suspended solids up to 30 $g \cdot L^{-1}$ and an F/M ratio around 0.05 kg COD$\cdot$ kg $MLSS^{-1} \cdot day^{-1}$, the recent trend has been to apply lower solid retention times (around 10–20 days with F/M ratios around 0.2 kg COD$\cdot$ kg $MLSS^{-1} \cdot day^{-1}$), resulting in more manageable mixed liquor suspended solids levels (10-15 $g \cdot L^{-1}$). Scientific studies indicate that SRT is a key parameter in determining fouling propensity through MLSS and extra polymeric substances (EPS) fraction concentrations. An optimum SRT can be envisaged where foulant concentrations (in particular in the soluble microbial product fraction) are minimised whilst oxygen transfer efficiency remains sufficiently high and membrane clogging and fouling is at controllable levels. Feedwater quality and fluctuations also have a big impact on fouling. Typical hydraulic retention times (HRT) range between three and 10 hours.

3.5.5 Membrane fouling

Membrane fouling can be defined as the undesirable deposition and accumulation of microorganisms, colloids, solutes and cell debris on membranes. It is a major obstacle to the faster commercialisation of MBR because it results in an increase in TMP or a reduction in permeate flux, depending on the mode of operation.

The factors affecting membrane fouling can be classified into four groups: membrane module characteristics, biomass characteristics, feedwater characteristics, and operating conditions (Figure 3.7). The complex interactions between these factors complicate understanding of the issue. For a given MBR process, fouling behaviour is directly determined by sludge characteristics and hydrodynamic conditions. However, operating conditions (i.e., SRT, HRT and F/M) and feedwater have an indirect effect on membrane fouling by modifying sludge characteristics (Meng *et al.*, 2009).

From the viewpoint of fouling components, fouling in an MBR can be classified into three major categories: biofouling, organic fouling, and inorganic fouling.

Biofouling refers to the deposition, growth and metabolism of bacteria cells or flocs on membranes. For a low pressure membrane such as microfiltration and ultrafiltration for treating wastewater, biofouling is a major problem because most foulants (microbial flocs) in an MBR are much larger than the membrane pore size. Biofouling may start with the deposition of individual cell or cell cluster on the membrane surface, after which the cells multiply and form a biocake. Many researchers suggest that SMP and EPS secreted by bacteria also play important roles in the formation of biological foulants and cake layer on membrane surfaces.

Organic fouling in an MBR refers to the deposition of biopolymers (i.e., proteins and polysaccharides) on the membranes. Due to their small size, biopolymers can be deposited onto membranes more readily as a result of permeate flow, but compared to large particles (e.g., colloids and sludge flocs) they have lower back transport velocity due to lift forces.

Inorganic fouling can form in two ways: through chemical precipitation and biological precipitation. A great number of cations and anions such as Ca^{2+}, Mg^{2+}, Al^{3+}, Fe^{3+}, CO_3^{2-}, SO_4^{2-}, PO_4^{3-}, OH^- and others are present in an MBR. Concentration polarisation will lead to higher concentration of retained salts on the membrane surface. Chemical precipitation occurs when the concentration of chemical species exceeds saturation concentration due to this polarisation. Biological precipitation is another contributory factor in inorganic fouling. The biopolymers contain ionisable groups such as COO^-, CO_3^{2-}, SO_4^{2-}, PO_4^{3-}, OH^-, and metal ions can be easily captured by these negative ions. In some cases, calcium and acid functional groups (R-COOH) can form complexes and build a dense bio-cake or gel layer that may exacerbate flux decline.

Despite the fact that inorganic fouling is troublesome in an MBR, it is possible to prevent or limit the phenomenon by pre-treatment of feedwater and/or chemical cleaning. But the presence of a small quantity of metal ions such as calcium can be beneficial for membrane permeation in an MBR due to their positive effect on sludge flocculation ability.

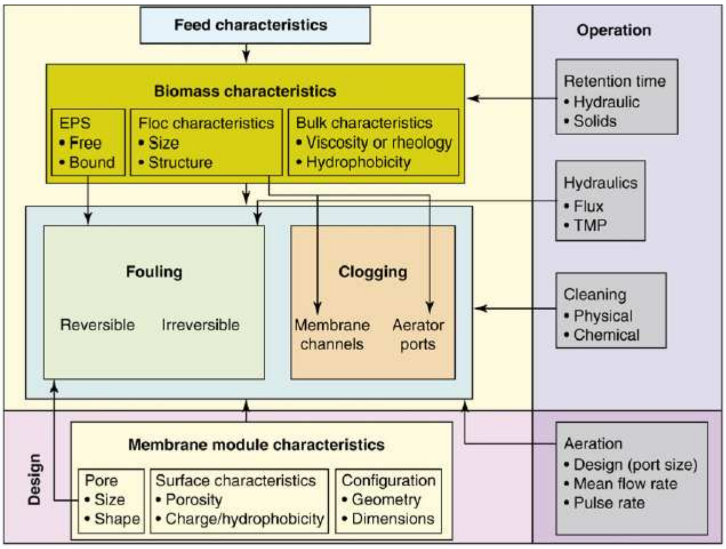


Figure 3.7. Main factors affecting membrane fouling (Judd, 2006).

3.5.6 Fouling control

There are three types of fouling: removable, irremovable and irreversible. Removable fouling can be easily eliminated by physical cleaning, such as aeration bubbles coupled with relaxation periods or backwashing, while chemical cleaning is needed to eliminate irremovable fouling. Both are caused by loosely attached foulants and are attributable to the formation of a cake layer. Irreversible fouling is permanent fouling which cannot be removed by any approach. It is attributable to pore blocking due to strongly attached foulants during filtration (Meng *et al.*, 2009). Clogging can arise both in the membrane channels and in the aerator ports, in both cases impacting detrimentally on flux distribution, and thus fouling rates.

Whilst an understanding of fouling phenomena and mechanisms may be enlightening, control of fouling and clogging is in practice generally limited to five main strategies viable for the full-scale operation of an MBR (Judd, 2006):

- Applying appropriate pre-treatment to the feedwater;
- Employing appropriate physical or chemical cleaning protocols;
- Reducing the flux;
- Increasing the aeration;
- Chemically or biochemically modifying the mixed liquor.

Since hollow fibre modules are more susceptible to clogging and the impact is rather more severe, for such modules screens normally rated at between 0.8 and 1.5 mm are usually employed. Flat sheet modules are slightly more tolerant of clogging, despite being non-backflushable, and screens of 2-3 mm rating are normally adequate for an MBR with this membrane configuration.

Physical cleaning is normally achieved in an MBR either by backwashing or relaxation, which simply means ceasing permeation whilst continuing to scour the membrane with air bubbles. The key general cleaning parameters are duration and frequency, since these determine process downtime. For backflushing, a further key parameter is the backflush flux, generally 1-3 times the operational flux and determined by the backflush TMP.

Chemical cleaning is carried out with mineral or organic acids, caustic soda or sodium hypochlorite, and can be performed either in situ or ex situ. Alternatively, a low concentration of chemical cleaning agent can be added to the backflush water to produce a chemically enhanced backflush. As inorganic fouling can result in severe irremovable fouling, chemical cleaning is more effective than physical cleaning in the removal of inorganic precipitation. Chemical cleaning agents such as citric acid and EDTA can efficiently remove inorganics on the membrane surface. EDTA can form a strong complex with Ca^{2+}, and biopolymers associated with Ca^{2+} ions are replaced by EDTA via ligand exchange reaction.

Reducing the flux always reduces fouling but it obviously impacts directly on capital cost through membrane area demand. A distinction must be made, however, between operating (or gross flux), and net flux, i.e. the flux based on throughput over a complete cleaning cycle, as well as between peak and average flux. Modern practice appears to favour operation at net fluxes of around 25 LMH for municipal wastewater, incorporating physical cleaning every 10-12 minutes, regardless of membrane configuration. The greatest impact on operating vs. net flux is therefore peak loading, normally from storm waters.

Whilst increasing the aeration rate invariably increases the critical flux to some threshold value, increasing membrane aeration intensity is normally prohibitively expensive. Much attention has focused on the commercial development of efficient and effective aeration systems to reduce aeration demand. Developing methods of ensuring homogeneity of air distribution would enhance both fouling and clogging control.

Finally, biomass quality can be controlled biochemically, through adjustment of the SRT, or chemically. In practice, SRT is rarely chosen on the basis of foulant concentration control; instead a target value is almost invariable based on membrane module clogging propensity and biomass aeration efficiency. However, studies have shown that a small degree of fouling control can be attained through the addition of chemicals such as coagulant-flocculants, adsorbent agents and membrane performance enhancers.

3.6 Investment and operational costs

The exponential growth in the MBR industry over the last decade has caused an increase in the number of manufacturers, which has gradually reduced the costs of MBR equipment and materials. As a result, the capital costs of an MBR plant have become very competitive compared with conventional activated sludge plants (Wallis-Lage and Levesque, 2009). Depending on the size and local conditions, investment costs could be between 200 and 400 €/P.E. Investment costs for comparable effluent quality from an

MBR and a conventional activated sludge system (including tertiary treatment) can be the same, or even lower for the MBR. Brepols *et al.* (2009) show that the investment costs for an MBR with a capacity of 10,000 P.E. and with effluent quality requirements for water reuse are lower than those for a conventional activated sludge system with tertiary treatment and disinfection (780 €/P.E. vs. 610 €/P.E.). These are mainly due to savings on civil works which compensate for the costs of membranes.

Operational and maintenance costs have also experienced a significant reduction in the last few years but they are still higher than in conventional activated sludge systems, mainly due to energy requirements. These requirements in an MBR represent approximately 30% of the total operational costs, of which the main part corresponds to membrane aeration (two thirds of the total energy requirement), while pumping energy represents 14% of the total energy demand. Historically, MBR energy requirements are about 1.5 to three times higher than for conventional activated sludge systems. According to 2008 data, the energy requirement for a modern, optimised MBR is around 0.6-1.1 kWh·m^{-3} (still high compared to 0.38-0.48 kWh·m^{-3} for conventional activated sludge systems, Günder and Krauth, 1999; Evans and Laughton, 1994). The energy requirement is also higher than that required by conventional activated sludge system with tertiary disinfection (sand filtration plus UV or tertiary filtration with micro- or ultra-filtration, Lesjean, 2009). Thus, in spite of the significant decrease in operational and maintenance costs, there is still a need for energy saving and optimisation. In fact, most of the present-day MBR research is focused on improving knowledge of the interactions between biological and filtration processes, in order to minimise fouling and thereby reduce operational costs, without losing water effluent quality (Yang *et al.*, 2006; Muñoz *et al.*, 2008; Rodríguez-Roda *et al.*, 2009a; Comas *et al.*, 2010). The aim is ensure a maximum life-time for the membranes and hence limit membrane replacement costs.

3.7 General considerations on MBR design and operation

A number of the practical aspects of MBR plant design and operation which have a big impact upon performance, investment and operational costs are analysed in the following sections.

3.7.1 Design

Water management within the facility is one of the most important aspects to be taken into account during the design of an MBR. In conventional systems, a peak flow of 1.5 to two times the average flow is assumed, but the overestimation of membrane surface to be able to treat these peaks is not recommended, due to the higher costs involved and non-optimal operation during dry periods. Flow equalisation making it possible to work with a constant (and reasonable) flux is recommended, either by the inclusion of an equalization tank or by modifying the level of the biological reactor (0.5 -1 mm) (Rodriguez-Roda *et al.*, 2009b). For high capacity facilities a hybrid or dual MBR configuration is currently the general trend (Kraume and Drews, 2010); the hybrid configuration might include secondary settlers to treat wastewater excess during peak flows, or integrated fixed film activated sludge technology to treat a portion of the influent wastewater and daily peak flows or wastewater excess, particularly during rain or storm events.

When MBR technology was introduced in municipal wastewater treatment in Europe in the mid 90's, problems caused by hair and fibrous material were observed and the inevitable need for microsieves as a form of mechanical pre-treatment was identified (Frechen *et al.*, 2008). The focus on rigorous pre-treatment has increased over the years and recent studies have reported that 19 European MBR plants use conservative screening systems of 0.5 to 1 mm (Judd, 2011). Gabarrón *et al.* (2011) state that in the last few years a decrease in pre-treatment screening size has been detected in Catalan MBR treatment plants, from 1 to 0.5 mm for HF and from 3 mm to 2 mm for FS. Furthermore, to protect the membrane and ensure clogging minimization, in some cases additional "by-pass sieving" has been installed. This allows further screening and the removal of unwanted material from the recycled activated sludge (Itowaka *et al.*, 2008).

Primary settling is recommended as a means of decreasing the organic loading on an MBR, reducing the volume of the biological compartment and aeration demand, and maximising biogas production in anaerobic digestion. Lowering organic and solids loading impacts only on aeration demand for an aerobic reactor, but this significantly adds to the environmental footprint. Primary settling also improves the performance of screens since settling solids are already removed. If primary settling is not present, at least grit removal is needed, and the upgrading and maintenance of screens and grit removal systems is essential (Wallis-Lage and Levesque, 2009).

Sludge treatment is another key point in MBR design, as many difference between MBR and CAS sludge can be identified. For example, flocs from CAS plants have a mean diameter of 200 - 500μm (although the size shows considerable seasonal variation), while in MBR sludge a decrease in floc size from 100μm during start-up to 40μm after almost 2 years of operation has been observed (Manser and Siegrist, 2006; Judd, 2011). Furthermore, MBR sludge has a higher MLSS concentration and higher viscosity, making dewatering a more difficult task.

It is well known that MBR technology reduces the plant's footprint compared to conventional activated sludge. However it is advisable to devote some extra space to extracting membrane modules and carrying out visual inspections. Some, more sophisticated, MBR facilities are provided with specific instrumentation for ex-situ testing of the correct functioning of modules/cassettes.

Retrofitting MBR plants places additional constraints on the design, since the tank size determines the HRT and the shape and placement of membranes. Sufficient installed capacity is required to deal with the total volume while the membrane tanks are being cleaned, which usually involves draining them.

Foaming control is particularly important since aeration is more intense than in CAS systems; for this reason, it is important to equip MBR facilities with devices to "break" (e.g. with a spray) and collect the scum layer on the surface (e.g. with a skimmer). However, once the scum is generated, it is really difficult to reduce it sufficiently.

The occurrence of air in the permeate pipe is another typical operational problem that can cause adverse effects like permeate flux reduction or permeate pump malfunctioning. The installation of evacuation pumps or valves should be carefully considered in MBR design (Itowaka *et al.*, 2008).

3.7.2 Operation

Aeration demand for membrane cleaning is still a hot topic in membrane research (Yang *et al.*, 2006), due to the large percentage of the operational costs that is involved (Verrecht *et al.*, 2010). Significant improvements include (i) intermittent aeration (e.g. 10'' aerated and 10'' non-aerated), (ii) configuration of modules (e.g. double deck) and (iii) a decreasing aeration rate when the treated flux is very low.

External recycling in an MBR is one of the main operational factors which can differ markedly from a CAS system, as the typical return activated sludge (RAS) flow from secondary clarifiers ranges from 0.5 to 1.5 of inflow (IF). For an MBR, the RAS flow is usually 3-6 times IF, which can represent up to 15% of the total energy requirements (Bagg, 2009). Recycling can also affect nitrogen removal, if recycling from the membrane compartment (DO levels of 2-6 $mg \cdot L^{-1}$) to the anoxic zone (DO levels <0.5 $mg \cdot L^{-1}$) causes slightly aerobic conditions at the sludge inlets and reduces denitrification efficiency. The problem can be solved by: (i) increasing anoxic HRT (ii) recycling from the membrane compartment to the aerobic and then to the anoxic tank, (iii) using a DO sensor in the recycle and diverting the flow to the anoxic or aerobic compartment depending on DO concentration or (iv) using a pre-anoxic compartment.

It is important to monitor the suspended solids gradient in the different reactor for an MBR system, especially if it has been designed for nutrient removal, in order to reduce energy for pumping, optimise nutrient removal and potentially increase the α factor.

The temperature effect on membrane permeability is not always taken into account in an MBR operation, but when the temperature of the mixed liquor decreases its viscosity increases, with a negative impact on membrane fouling (Judd, 2011). It is advisable to reduce permeate flux (or eventually use flux enhancers) during cold periods to ensure a low degree of membrane fouling.

As in other wastewater treatment systems, process control and alarm triggering relies on monitoring key parameters such as TMP (for indicating membrane fouling conditions and triggering a cleaning cycle), DO (for biological process control), MLSS (for SRT control, sludge wasting) and turbidity (for membrane integrity).

In terms of foaming control, many MBR are currently being designed allowing for the use of coagulants or adsorbent substances (flux enhancers) during operation to guarantee a wider range of flux able to be treated, during peak flows, without affecting significantly the membrane fouling rate. Finally, the maintenance schedule should include the periodic cleaning of aerators to avoid clogging.

CHAPTER 4

STATE-OF-THE-ART OF CONTROL SYSTEMS FOR MEMBRANE BIOREACTORS

4. State-of-the-art of control systems for membrane bioreactors

Membrane fouling control and energy saving are the key issues in MBR operation. Up to the present day few papers and innovations aimed at minimising costs end enhancing MBR efficiency have been published or patented. Due to the complex mechanisms of fouling it is not yet possible to describe clearly its development, or build a deterministic model, but it is known that these mechanisms are responsible for permeability loss. Air-scouring, together with relaxation (or backwash), is used to agitate and loosen the accumulated solids from the surfaces of the membranes. MBR systems are usually time-based operated with fixed filtration sequences (cycles) and constant aeration, generally proposed by the membrane suppliers or selected according to the operator's experience. Chemical cleaning is carried out on a time basis or depending on a TMP set point. This kind of operation frequently results in sub-optimal performance in dynamic conditions due to the use of fixed filtration strategies and set points. Current control approaches used for MBR processes are too simple and limited since they lack the flexibility to cope with changeable operational conditions and ignore the potential for optimisation and energy savings. In recent years, several membrane manufacturers have modified their operational strategies to reduce air-scour fouling control requirements, even though it is still not clear whether these strategies in the long term may cause a higher level of membrane fouling (Wallis-Lage and Levesque, 2009). As far as the biological process is concerned, the operational strategy is generally similar to the one adopted for activate sludge systems, but with higher sludge retention times.

The objective of this chapter is to explore the advances in automation and control for membrane bioreactors. Most of the publications can be found in the patent literature, since there are only few papers (published in journals included in the Science Citation Index list) that describe the development and implementation of advanced control systems for MBR optimisation, mostly focused on energy reduction. A review of the state-of-the-art will be carried by means of a comparative analysis of the different control systems, classifying the available knowledge as a function of the manipulated variables used, the type of automatic controller operational mode (open loop or closed loop), and the controlled variables used. The manipulated variables will be grouped in six categories: air-scour control, filtration cycle control, permeate flux control, additive dosage control, chemical cleaning frequency control and biological nutrient removal (BNR) control.

In an open loop (OL) controller the control action, i.e. a change in a manipulated variable, is not based on any feedback or measurement, but rather on disturbance or time (Olson *et al*., 2005). For example, in the case of aeration for biological oxidation in conventional activated sludge treatment, a blower providing air for an aeration tank can be turned on and off at certain times. No measurement of the dissolved oxygen is then made and there is no guarantee that the dissolved oxygen concentration will be correct. Such an open loop control is completely different from closed loop control, where the change of aeration is based on a true dissolved oxygen measurement.

In a closed loop (CL) control system, the input (or manipulated) variable is adjusted by the controller in order to minimise the error between the measured output (or controlled) variable and its set point.

4.1 Air-scour control

Air-scour is clearly a key factor in both fouling control and energy requirements. It can be modified in terms of the aeration flow and aeration frequency factor, or aeration cycles (Table 4.1).

Table 4.1. Air-scour control.

Manipulated variables	Type of control	Controlled variables	[1]Patents; [2]Articles
Aeration on/off cycles	OL	-	[1]Cote *et al.*, 2000 [Zenon - GE] [2]Mansell *et al.*, 2006
	CL	Resistance	[1]Ginzburg *et al.*, 2007 [Zenon - GE]
	OL	-	[1]Dimitriou *et al.*, 2006 [ITT] (SBR)
	OL	-	[2]Lorain *et al.*, 2010
Aeration flow	OL	-	[2]Lorain *et al.*, 2010
	OL	-	[1]Livingston, 2007 [Eimco]
	OL	-	[1]Zha *et al.*, 2007 [Siemens]
	CL	Resistance	[1]Ginzburg *et al.*, 2007 [Zenon - GE] [2]Ginzburg *et al.*, 2008
	CL	ΔTMP	[1]Ginzburg *et al.*, 2007 [Zenon - GE]
	CL	Permeate production	[1]Brauns *et al.*, 2008 [VITO] [2]Huyskens *et al.*, 2008, 2010
	CL	ΔTMP	[1]Hong *et al.*, 2008 [Kruger]
	CL	TMP	[2]Jeison and van Lier, 2006 (AnMBR)
	CL	Permeability trend	[2]Ferrero *et al.*, 2011a, 2011b, 2011c

Many patents and publications focus on open loop control systems that regulate aeration cycles, such as Zenon Environmental Inc.'s well known cyclic aeration (Cote *et al.*, 2000) which uses a valve set and a valve controller to connect an air supply to a number of distinct branches of an air delivery network. The air flow to each distinct branch alternates between a higher flow rate and a lower flow rate in repeated cycles (the so called aeration frequency factor), usually a cycle of 10 seconds on and 10 seconds off (a 10/10 aeration cycle) and more recently the 10/30 eco-aeration cycle, where the membrane is scoured for 10 seconds on and 30 seconds off during non-peak flow conditions. This is considered to reduce air-scouring requirements by up to 50%. Mansell *et al.* (2006) compared 10/30 and 10/10 aeration strategies at pilot-scale and concluded that the first led to sustainable fouling rates only if operating at lower fluxes. They estimated that the implementation of the 10/30 cycle in a full-scale facility would result in approximately a 20% reduction in the overall power costs for the system.

Dimitriou *et al.* (2006), from ITT Manufacturing Enterprises Inc., have developed another open loop control system for a sequenced batch reactor comprising a biological section and a membrane filtration section, where air is supplied only during backwash and not during filtration.

A French company, Polymem (Lorain *et al.* 2010), has developed an external membrane module and performed various trials with encouraging results. Different on/off aeration cycles, and a strategy of low aeration during filtration and high aeration during backwash, were tested at pilot scale.

Eimco Water Technologies Inc. (Livingston, 2007) have created a patent that includes three different concepts: a reduction in cycle lengths, proportional aeration and enhanced relaxation. With regard to proportional aeration, the air-scour flow rate increases and decreases in approximate proportion to the flow rate of the permeate; the enhanced relaxation is achieved with higher air-scour during relaxation, rather than during the filtration period.

With regard to closed loop control systems, the literature includes results of pilot and full scale tests for a membrane fouling control system applied to ZeeWeed membranes. The system, patented by Zenon (Ginzburg *et al.*, 2007), uses real time analysis of membrane filtration operating conditions to determine the fouling mechanisms present in an MBR system. The information obtained from the algorithm dictates the implementation of specific control actions that respond to the particular fouling mechanism. The control comprises three steps: a) calculating a membrane resistance value, b) comparing the calculated value to a pre-determined set point; and c) adjusting a system operating parameter or process to alter membrane resistance in order to provide a more desirable resistance value. The system acts under different operational modes, depending on the resistance of the membrane, and adjusts the aeration frequency factor, membrane aeration flow, permeate flux, permeation duration, relaxation duration and maintenance recovery chemical cleaning frequencies. The patented control system was validated at full scale, but only applied to frequency factor modification, at an 11.350 $m^3 \cdot day^{-1}$ plant in Pooler, Georgia (Ginzburg *et al.*, 2008). The fouling controller/algorithm provided the MBR's programmable logic controller (PLC) system with the information needed to select between the traditional 10/10 (air-scour on/off) protocol and a 10/30 eco-aeration energy saving protocol. Ginzburg and his co-workers concluded that additional research was required to further develop the on-line fouling controller to include additional control parameters such as membrane aeration flow rate, backwash flow rate and duration amongst others. Another method used to adjust aeration in Ginzburg *et al.* (2007), in search of optimised conditions, consists of an on-line filterability test, where aeration is stopped and permeation at a specified flux is maintained for a period of between 30 seconds and 20 minutes. A relationship between TMP and time is then extrapolated and the aeration is modified accordingly. There is no record of pilot or full scale validation of such a control methodology.

Siemens have engineered a method that alternates air-scour flow rate using a "normal" flow rate during one cycle and a lower or higher flow rate during the next; in practice, one membrane cell can be operated at the normal air-scour flow rate and the other one at a lower flow rate in repeated cycles. The frequency can be varied independently of the filtration cycle (Zha *et al.*, 2007). It is difficult to understand from the patent document whether or not this has been validated in a closed loop system using specific control variables.

The Flemish Institute for Technological Research (VITO) have developed a device that calculates the permeate production for a given TMP. The measurement is repeated in iterative steps with different membrane cleaning strategies, and the control action is calculated with fuzzy set logic. The amount of reversible and irreversible fouling is also calculated. The control actions are taken during back-wash, relaxation, aeration flow, floc-modification, chemical cleaning and coagulant addition (Brauns *et al.*, 2008; Huyskens *et al.*, 2008, 2010).

Kruger Inc. (Hong *et al.*, 2008) have patented a strategy to control membrane fouling dynamically by varying the air-scour flow rate, relaxation phase duration and permeation phase duration as a function of TMP variation over time. Hierarchal ordering of the process control variables means that the logic first looks to one process control variable. If its change is sufficient to meet certain process requirements, the control action is ordered and the control logic returns to the initial starting point; if not, the control logic continues to move to the control logic scheme.

Jeison and van Lier (2006) have introduced a new operational strategy based on continuous critical flux determination preventing excessive cake-layer accumulation. Since a full scale MBR must be able to handle highly dynamic conditions, such as changes in wastewater flow and concentration, an on-line identification of critical conditions is required for process optimisation. The control proposed uses a mathematical tool for steady-state assessment to identify pressure increases and optimise the air-flow, and consequently minimise energy consumption. The control system has shown promising results, although it was developed and tested only in anaerobic membrane bioreactors.

Finally, the control developed by the University of Girona (Ferrero *et al.*, 2011a, 2011b and 2011c), in collaboration with OHL-Medio Ambiente INIMA S.A.U., led to promising results during its partial validation at pilot scale and will be explained thoroughly in this thesis.

4.2 Filtration cycles control

Another relevant manipulated variable used in published or patented MBR control systems is the manipulation of filtration-relaxation-backwash cycles. Filtration process control is attempted through the regulation of backwash duration, backwash initiation, relaxation initiation, and permeation duration. For simplicity, the control systems will be presented here with the distinctive features suggested by the authors (Table 4.2), although it is clear that the manipulated variable is always the cycle length.

Table 4.2. Filtration/relaxation-backwash cycles control.

Manipulated variables	Type of control	Controlled variables	[1]Patents; [2]Articles
Backwash duration	CL	TMP	[2]Smith *et al.*, 2006a, 2006b
	CL	Permeate production	[1]Brauns *et al.*, 2008 [VITO] [2]Huyskens *et al.*, 2008, 2010
	CL	Resistance	[2]Busch *et al.*, 2007 [1]Ginzburg *et al.*, 2007 [Zenon - GE]
Backwash initiation	CL	TMP	[2]Smith *et al.*, 2006a
	CL	Permeate Flux	[2]Vargas *et al.*, 2008 (SBR)
	CL	Resistance	[1]Zha *et al.*, 2007 [Siemens]
Relaxation duration	CL	Resistance	[1]Zha *et al.*, 2007 [Siemens]
	CL	ΔTMP	[1]Hong *et al.*, 2008 [Kruger]
	CL	Permeate production	[1]Brauns *et al.*, 2008 [VITO]
	OL	-	[1]Linvingston *et al.*, 2007 [Eimco]
Permeation duration	CL	Resistance	[1]Ginzburg *et al.*, 2007 [Zenon - GE] [2]Busch *et al.*, 2007
	CL	TMP	[1]Hong *et al.*, 2008 [Kruger]
	OL	-	[1]Linvingston *et al.*, 2007 [Eimco]

Smith *et al.* (2006a, 2006b) have developed two simple control systems able to optimise backwash frequency and duration. The first system involves closed loop control of the backwash initiation based upon a pressure increase, leading to productivity improvements because the backwash is only activated when required, not at a fixed time. The second system involves closed loop control of the backwash duration, where the backwash finishes when the pressure reaches a steady state, which implies that reversible fouling has been removed.

The control systems patented by VITO (Brauns *et al.*, 2008), illustrated in section 4.1, also make it possible in a VITO filtration device to modify backwash or relaxation duration based on permeate production at a fixed TMP. There is no mention in the validation of this aspect of the control system (Huyskens *et al.*, 2010).

Busch *et al.* (2007) have proposed a model-based run-to-run control of membrane filtration processes, in which manipulated variables are optimised after each filtration cycle. A simple filtration model was developed based on Darcy's Law, with the aim of operating the filtration process at its economic optimum, so the objective function considers electrical energy as a means of providing transmembrane pressure. The manipulated variables are permeate and backwashing fluxes, filtration and backwash durations.

Backwash initiation is activated when the flux drops below a fraction of the maximum value reached, in membrane sequenced batch reactors operating at a constant TMP, developed by Vargas *et al.* (2008) for toxic wastewater treatment.

The method patented by Siemens (Zha *et al.*, 2007) includes a claim about the variation in cycle duration. The membrane resistance increase is used as the preferred indicator to determine the backwash or relaxation cycle requirements, although in the patent changes in the operational strategy based on a TMP increase or permeability decline are also mentioned; for example, if the filtration time is 12 minutes with normal flux, the filtration time can be reduced to 6 minutes or less with a flux twice the norm.

Kruger Inc. (Hong *et al.*, 2008) have developed a control that acts on relaxation phase duration and permeation phase duration as a function of TMP variation over time. Eimco Water Technologies Inc. (Livingston, 2007) have proposed a cycle length control that is considered more effective in terms of removal of accumulated solids from membrane surfaces - a more frequent relaxation of the membrane from filtration, while a roughly similar ratio between total filtration time and total relaxation time is retained. This is considered to prevent clogging proceeding as far as with typical relaxation cycling.

4.3 Permeate flux control

Patents and publications already mentioned often include permeate flux control (Table 4.3).

As previously described, Busch *et al.* (2007) and Ginzburg *et al.* (2007) have developed control systems based on resistance control which, additionally to many other features, manipulate permeate and backwashing fluxes.

Another part of the control patented by Kruger is a system based on the assumption that when permeate flux decreases, the fouling rate will decrease. TMP and its variations over a selected period of time (which can be between two single points in a permeation cycle or two points across two or more permeation cycles) are used as control variables. In addition, the water level in the membrane tank is monitored and compared with maximum and minimum set points, and based on the results of the comparison the permeate flux can be varied (Hong *et al.*, 2008).

Siemens (Zha *et al.*, 2007) include in their rather vague patent a modification to the permeate flux but the type of control applied is not clearly specified.

Finally, Jeison and van Lier (2006) use permeate flux modification as a control action for the optimal operation of an anaerobic membrane bioreactor around (but not exceeding) the critical flux.

Table 4.3. Permeate flux control.

Manipulated variables	Type of control	Controlled variables	[1]Patents; [2]Articles
Permeate flux	CL	Resistance	[2]Busch *et al.*, 2007 [1]Ginzburg *et al.*, 2007 [Zenon - GE]
	CL	ΔTMP	[1]Hong *et al.*, 2008 [Kruger]
	-	-	[1]Zha *et al.*, 2007 [Siemens]
	CL	TMP	[2]Jeison and van Lier, 2006

4.4 Additives dosage control

Flux enhancer dosage (Table 4.4) is another element mentioned in VITO's patent, but once again this seems not to have been validated at pilot or full scale.

Degremont (Langlais, 2008) have patented a method for the optimal management of a membrane filtration unit based on membrane micro-coagulation injection when membrane permeability (normalised at 20ºC) becomes lower than a threshold value.

Table 4.4. Additives dosage control.

Manipulated variables	Type of control	Controlled variables	[1]Patents; [2]Articles
Flux enhancers addition rate	CL	Permeate production	[1]Brauns *et al.*, 2008 [VITO]
Micro-coagulant addition	CL	Permeability (T)	[1]Langlais, 2008 [Degremont]

4.5 Chemical cleaning frequency control

Although most existing full scale facilities control the frequency of maintenance and recovery chemical cleaning (automatically or manually), no patent describing such a type of control was found. Usually, maintenance chemical cleaning is activated manually weekly or every few weeks, depending on the TMP achieved or the filtered water volume. In the case of recovery chemical cleaning, the most common procedure is for it to be initiated manually when a TMP alarm is recorded.

Only Zenon Inc.'s patent (Ginzburg *et al.*, 2007) proposes dynamically modifying maintenance and recovery chemical cleaning as a function of an on line calculated variable, i.e. resistance, which is constantly compared to selected reference values.

Table 4.5. Chemical cleaning control.

Manipulated variables	Type of control	Controlled variables	[1]Patents; [2]Articles
Maintenance chemical cleaning	CL	Resistance	[1]Ginzburg *et al.*, 2007 [Zenon]
Recovery chemical cleaning	CL	Resistance	[1]Ginzburg *et al.*, 2007 [Zenon]

4.6 Biological nutrient removal (BNR) control

As far as BNR in an MBR is concerned, very few papers or patents deal with advanced control systems for their optimal operation (Table 4.6).

Siemens (Zha and Liu, 2007) have developed another control algorithm that calculates the optimal solids retention time and guides system operators to increase or decrease sludge waste. Because the MLSS concentration is lower in warmer months, the factor α value (the ratio of the overall oxygen transfer coefficient in dirty water to the clean water transfer coefficient) will increase, and the airflow requirements of the biological process will decrease, resulting in a significant energy saving. Moreover, bearing in mind that such a control system will increase sludge waste (and decrease solids retention time) when the temperature is warm, it will have a favourable impact on biological phosphorous removal. Another function of the control system is the automatic modification of the membrane circulation ratio, calculated as the flow rate entering the membrane tank divided by daily average flow rate, when a maximum set point of MLSS concentration in the membrane tank is reached.

Fatone *et al.* (2008) have validated at pilot and full scale on-line control of intermittent biological aeration. By controlling the bending points in on-line profiles of dissolved oxygen (DO) and oxidation reduction potential (ORP), the system is able to optimise the removal of total nitrogen while minimising power requirements, with on/off periods for biological aeration.

Table 4.6. BNR control.

Manipulated variables	Type of control	Controlled variables	[1]Patents; [2]Articles
Sludge waste	CL	SRT	[1]Zha *et al.*, 2007 [Siemens]
Membrane circulation ratio	CL	MLSS	[1]Zha and Liu, 2007 [Siemens]
Biological aeration on/off	CL	DO and ORP	[2]Fatone *et al.*, 2008

4.7 Discussion

The number of patents and papers on the control of membrane bioreactors is very limited. The patents are usually very general, in an attempt to cover a wide spectrum of "know-how property", but what is stated is not always scientifically proven or validated. Very few research publications describe control systems validated at pilot scale, and none has been validated in a full scale facility so far.

The great majority of the control systems analysed can be implemented using the instrumentation and signals already existing in a conventional MBR, with no additional costs incurred, and only a few of the control system previously described use external devices to measure membrane performance. The advanced control system developed at the Flemish Institute for Technological Research (VITO) uses a sensor that calculates the permeate production for a given TMP, and the measurement is repeated in iterative steps with different membrane cleaning strategies. Fuzzy set logic is applied to select control actions. It is claimed that significant correlation was found between reversible fouling propensity measured by the on-line sensor and on-line permeability, which suggests that on-line permeability could be used instead of a sophisticated sensor.

One of the most complete control systems is the one patented by GE Zenon Inc., which can count on real time analysis of the membrane's filtration operating conditions. The patent is based on the resistance-in-series model for determining the fouling mechanism present in an MBR system. Different operational modes are applied by the system, depending on the resistance of the membrane and adjustment to the membrane aeration frequency factor, membrane aeration flow, permeate flux, permeation duration, relaxation duration, and maintenance and recovery chemical cleaning frequencies. However, the algorithm is based on very big assumptions (e.g. complete cake layer removal between different cycles due to backwashing or relaxation); it was validated at full scale but only applied to frequency factor modification, switching from the traditional 10/10 (air scour on/off) protocol and a 10/30 eco-aeration energy saving protocol. As noted in the literature, further research is required to further develop the on-line fouling controller to include additional control parameters such as membrane aeration flow rate, backwash flow rate and duration, amongst others.

Some of the patents, especially those from Siemens, are very unclear and it is often very difficult to distinguish the control strategy described and the variables involved.

Generally, there is no mention of integrated control systems, which can be counted on to optimise the filtration process and at the same time control biological nutrient removal.

It would be of great help if new indicators were developed in the future that could detect and distinguish between reversible and irreversible fouling and automatically take corrective actions. If big companies were to open up to the academic world and share their findings through scientific papers, this would speed up the development of accurate and efficient integrated control systems for MBR. The creation of new synergies between research institutes and company R&D departments could be the key to progress in the future.

CHAPTER 5

MATERIALS AND METHODS

5. Materials and methods

An industrial scale pilot plant was operated for nearly two years, during the first year in the El Vendrell WWTP and during the second in the Granollers WWTP. Both facilities at the time of the study were managed by OHL-Medio Ambiente INIMA S.A.U. All the technical details concerning the pilot plant are provided in this chapter.

5.1 General description of the industrial scale pilot plant

The pilot plant, with a University of Cape Town (UCT) configuration (Figure 5.1 and 5.2), was operated under different conditions and with different membrane configurations (Table 5.1).

Table 5.1. Pilot plant characteristics.

Type of membrane		Kubota FS-50	Zenon ZeeWeed500a
Total volume	m^3	14.7	12.5
Anaerobic/Anoxic/Aerobic/Membrane	%	17/17/42/24	20/20/49/11
Total filtration surface	m^2	40	46.45
Pore size	µm	0.4	0.04
Maximum flux	$L·m^{-2}·h^{-1}$	36	29
Recommended aeration	$m^3·h^{-1}$	38	20
	SAD_m $m·h^{-1}$	0.95	0.43
Filtration/Relaxation-Back pulse cycles		9’ filtration	10’ filtration
		1’ relaxation	40’’ back pulse

Figure 5.1. Pilot plant images.

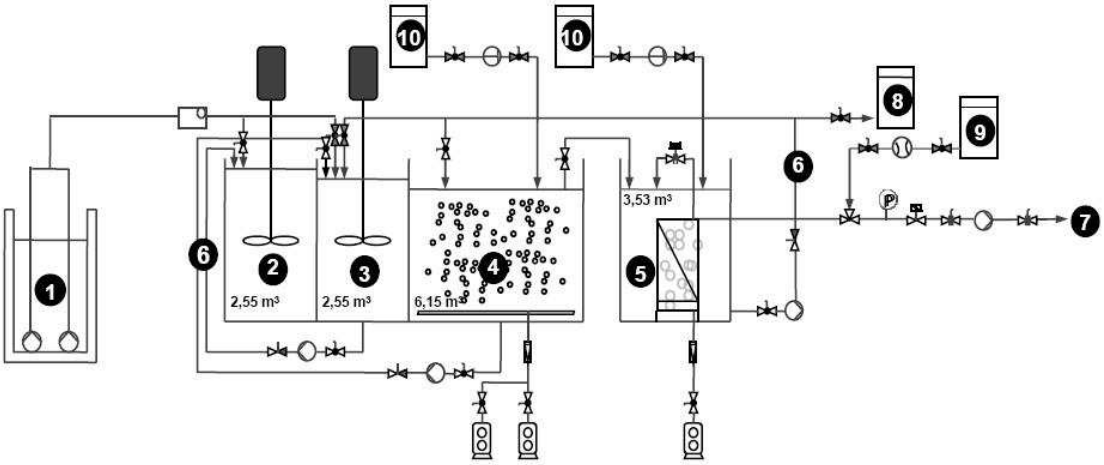


Figure 5.2. Pilot plant scheme: 1. Influent pumps; 2. Anaerobic tank; 3. Anoxic tank; 4. Aerobic tank; 5. Membrane tank (with Kubota membranes); 6. Recycles; 7. Permeate; 8. Waste sludge deposit; 9. Chemical cleaning solution tank; 10. Chemical additive tanks.

5.1.1 Bioreactor

The bioreactor (Figure 5.3) was a prefabricated polypropylene tank reinforced with carbon steel, partitioned into three chambers (anaerobic, anoxic and aerobic), in a rectangular layout and with a total volume of 11.25 m^3. The compartments were connected to each other through an overflow and by pipes between adjacent reactors. The bioreactor was designed for biological nutrient removal (C, N and P).

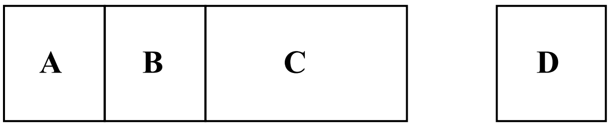


Figure 5.3. Bioreactor layout: (A) anaerobic reactor; (B) anoxic reactor; (C) aerobic reactor; (D) membrane tank.

5.1.1.1 Anaerobic reactor

The anaerobic reactor (A in figure 5.3), located on the left side of the bioreactor (Figure 5.3), would aim to provide the anaerobic conditions necessary for phosphorus removal (0 $mgO_2·L^{-1}$ and low nitrate concentration). This reactor had a maximum capacity of 2.55 m^3 and was equipped with an ORP probe and a mixer for the homogenization of the suspended biomass.

5.1.1.2 Anoxic reactor

The anoxic reactor (B in figure 5.3), situated right after the anaerobic reactor, would create conditions to enable denitrification processes, so it was necessary to maintain the dissolved oxygen (DO) concentration at less than 0.5 mg $O_2·L^{-1}$. This reactor had a maximum capacity 2.55 m^3 and was equipped with an ORP probe and a mixer for the homogenization of the suspended biomass.

5.1.1.3 Aerobic reactor

The aerobic reactor (C in figure 5.3) was located after the anoxic reactor. Its function was to provide aerobic conditions, necessary for the removal of organic matter, for the phosphorus uptake and nitrification process. It had a maximum capacity of 6.15 m^3 and was equipped with fine bubble air diffusers. A temperature and DO probe were also installed.

5.1.1.4 Membrane tank

While the biological reactor was the same during the whole experiment, the membrane tank (D in figure 5.3) was different because it had to be able to contain two different membrane configurations: flat sheet during the first year and hollow fibre during the second.

During the first year of experimentation with Kubota membranes, the membrane tank was a separate cylindrical PRFV tank of 3.53 m^3 net volume, while during the second year of experimentation with Zenon membranes it was a 1.31 m^3 rectangular steal tank. In both cases it was equipped with a level transmitter, a pressure transducer and a thermometer. During the experimentation with Zenon membranes a 115L PVC tank, suitable for storing the permeate water needed to periodically backwash the membranes, was installed and equipped with a level transmitter and maximum and minimum level switches.

5.1.2 Sludge waste accumulation tank

The biological sludge storage tank was made of PE and had a capacity of 2,000 L. Sludge was wasted through the external recirculation pump.

5.1.3 Chemical dosing tanks

Three chemical dosing tanks were provided: two for the dosing of ferric chloride to precipitate phosphorus (not used) and one for dispensing a chemical cleaning solution for the membranes.

5.1.4 Control booth

A 2.4 m x 2.2 m x 2.25 m galvanized steel container (Cimat) hosted the electrical panel, the PLC, a barebone computer for remote control and all the equipment (pumps, blowers, etc.).

5.2 Equipment

5.2.1 Pumps

The pilot plant was equipped with five different types of pumps: submersible, dosing, magnetic drive, self-priming centrifugal and centrifugal.

5.2.1.1 Submersible pumps

Two submersible pumps operated alternately with a switch time of 6 hours in order to raise wastewater from the influent channel to the primary settlers. The pumps initially installed were two submersible MF334Ds (ABS), but they were replaced by two Grundfus AP35.40.06.3V.

5.2.1.2 Dosing pumps

Two TEKNA AKL 800 (SEKO) dosing pumps were installed to dispense chemical reagents (e.g. ferric chloride to precipitate phosphorus) in the aerobic reactor and the membrane tank. The dosage was through mechanical membranes and manual adjustment from 0 to 100%.

5.2.1.3 Magnetic drive pump

An HCM-75LX Torres magnetic drive pump was installed to pump NaClO solution for the chemical cleaning of the Kubota membranes. Another magnetic drive pump was used to extract the permeate through the membranes

5.2.1.4 Centrifugal pumps

Three Bloch model SIL25K5 pumps were installed as anoxic-anaerobic, aerobic-anoxic and external recycle pumps. An ITUR model EZ 2/1 Monoblock centrifugal pump was installed to extract permeate through the Kubota membranes, substituted by a Lowara model BG5 while operating with Zenon membranes.

5.2.2 Compressors/blowers

Inside the control booth three compressors were installed. Two of them, DT 4.40K (H.P.E) models, oil-free and air-cooled, with a maximum air-flow of 40 $m^3 \cdot h^{-1}$, supplied the aeration to the aerobic reactor. They were regulated by frequency converters to maintain the required dissolved oxygen set point. The third compressor supplied air for the physical cleaning or air-scour of the membranes. During the experimentation with Kubota membranes, the third compressor initially installed was a l DT 4.40K (H.P.E) model, but due to a miscalculation of the required air-flow, this was exchanged for a bigger model with a maximum flow of 54 $m^3 \cdot h^{-1}$. During the experimentation with Zenon membranes a Becker DT 4.25K compressor was installed, with a maximum air-flow of 25 $m^3 \cdot h^{-1}$.

5.2.3 Membrane modules

Figure 5.4. Kubota FS-50

During the first year an FS-50 Kubota membrane module was used, which provided a membrane surface of 40 m^2, sufficient to treat the design flow (1 $m^3 \cdot h^{-1}$). The pore size of the membranes was 0.4 µm. On average, it is necessary to chemically clean Kubota membranes every three to six months. Usually they are cleaned in place by simply injecting, or pouring, a dilute solution of NaClO or oxalic acid (0.5% typical concentration) into the permeate suction line. The cleaning solution remains inside the cartridges and soaks the membranes for about an hour, and then normal operation is resumed. For fouling due to organic substrates, NaClO is recommended, and for inorganic fouling, oxalic acid should be used. For municipal applications, two to four annual clean-in-place (CIP) procedures are typically sufficient to maintain adequate permeability.

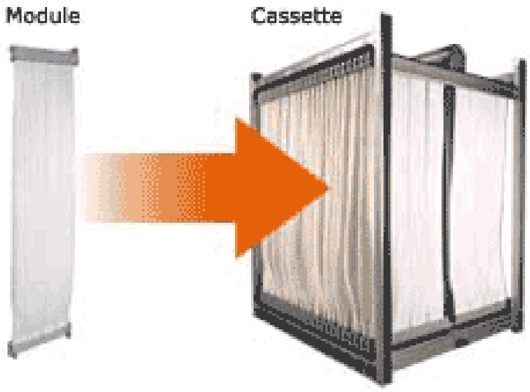


Figure 5.5. Zenon ZeeWeed 500a

During the second year a Zenon ZeeWeed 500a module was used. This provided a membrane surface of 45.46 m^2 with a pore size of 0.04 µm. Zenon recommends weekly maintenance cleaning based on backwashing with a 100 ppm NaClO solution. To prevent severe fouling, operators are required to perform recovery cleanings by draining the membrane tank and soaking the membranes in a cleaning solution for several minutes. The solution is then drained and chemical residues are flushed from the membranes before the system resumes normal operation.

5.3 Instrumentation

5.3.1 Sensors

Two ORP probes (Crison) were located in the anaerobic tank and in the anoxic tank; they had no control function, but values were saved every minute in the PLC memory. The DO and temperature sensor positioned in the aerobic tank was a model MM44 probe with optical electrode (Crison). Based on the readings of this sensor, the PLC regulated the airflow supplied to maintain the DO setpoint.

5.3.2 Flow meters

Two Badger electromagnetic flow meters, model DN15 (Iberfluid), provided instantaneous reading of flow in $L \cdot h^{-1}$ and totalized flow in L. During the second year these were replaced by two Promag 20 Model 99 (Endress + Hauser) flow meters.

Plastic tube rotameters were used to measure the airflow supplied to the aerobic and membrane tanks.

5.3.3 Pressure transducers

The, Cerabar M PMC41 (Endress + Hauser) pressure transducer used during the first year and the Cerabar S used during the second, measured the pressure applied by the permeate pump in the suction pipe. From this it was possible to calculate the transmembrane pressure.

5.3.4 Level meter

A hydrostatic level meter with a ceramic diaphragm sensor, model FMX 167 (Waterpilot), measured the water level in the membrane tank.

5.3.5 Mixers

A VGR-1041-S-200 (Dosapro) vertical mixer was set into the anaerobic tank and an SS-4 (Agitaser) agitator into the anoxic tank.

5.3.6 Valves

A solenoid valve, automated and controlled by the PLC, was installed for the daily cleaning of the diffuser.

During the experimentation with Zenon membranes, six pneumatic valves, series 301-302 (Sirca), connected to a compressor Atlas Copco, LXF06, were used.

5.4 Operational mode

5.4.1 Influent pumps

The influent pumps were controlled by the level in the membrane tank. If the tank filled to its maximum or if the security level was detected, the operation of the pumps was arrested. Deactivation of the high level switch and detection of the minimum level would restart the pumps.

Each pump was controlled by a variable frequency drive. An hourly set point could be introduced through the PLC menu as the pumps were controlled by a PID that adjusted their revolutions depending on the desired flow. In the event of failure of one of the two pumps, the second one was automatically activated. In manual mode the operating frequency of each pump (30-50 Hz) could be independently selected.

5.4.2 Rotating sieve

The operation of the rotating sieve (1 mm) was connected with the operation of the influent pump, with a disconnection time delay of 30 seconds. The disconnection of the rotating sieve would arrest the influent pump and generate an alarm.

5.4.3 Anaerobic reactor

The operation of the mixer was connected to the operation of the inlet and anoxic-anaerobic recirculation pumps.

5.4.4 Anoxic reactor

The operation of the mixer was connected to the operation of the inlet and anoxic-anaerobic recirculation pumps. The anoxic-anaerobic recycle pump followed the profile of the influent pumps; the flow could be modified by introducing into the PLC a set point factor (between 1 and 6) multiplied by the influent flow, which would represent the recycle flow. The anoxic-anaerobic recirculation pump was interlocked with the influent pump. If the influent pump was not working, the recycle pump would run according to on/off times. In manual mode the operating frequency of the anoxic-anaerobic recycle pump (30-50 Hz) could be selected.

5.4.5 Aerobic reactor

The aerobic-anoxic recycle pump did not follow the set points of the influent pump and always worked at a constant flow.

5.4.6 Membrane tank

The water was extracted by the suction produced by a self-priming centrifugal pump, connected to the output manifold of the membrane module. A pressure transducer allowed continuous monitoring of the TMP, measurement of which was performed by adding to the reading of the pressure transducer located in the permeate suction pump the height of the pressure transducer over the water level.

The permeate flux followed the profile of the influent pump and its speed was adjusted by a variable frequency drive. To ensure that the membranes always remained submerged in mixed liquor and that permeate extraction did not exceed the peak capacity of the pilot plant, a minimum level switch was installed in the membrane tank.

The blower supplied the air necessary for the physical cleaning of the membranes. Air bubbles scoured the membrane surface and removed the excess sludge that might have caused fouling and promoted a right degree of mixing and turbulence in the membrane tank.

The permeate pump worked in two different modes with Kubota membranes: ‘normal’ operation mode and ‘high TMP’ operation mode. When, operating in normal conditions, a TMP of -0.17 bar was reached, an alarm was automatically activated. While at $-0.17 < \text{TMP} < -0.220$ bar the high TMP mode was activated and the plant automatically decreased the permeate flux in order to prevent a further TMP decrease. The TMP value that would stop the installation was -0.220 bar.

5.5 Chemical analysis protocol

Total suspended solids (TSS; 2540B), volatile suspended solids (VSS; 2540C) and total chemical oxygen demand (COD; 5220B) were analysed according to *Standard Methods* (APHA, 2005). Total nitrogen was analysed with Hach Lange reagent kits. Ammonium concentration in the supernatant was determined by distilling a sample into a solution of boric acid (Büchi, *Postfach, Switzerland*; B324). The ammonia in the distillate was determined by a trimetric method (Tritino 719S Metrohm, *Herisau, Switzerland*) using H_2SO_4 and a pH meter and nitrites (NO_2^--N), nitrates (NO_3^--N) and phosphates (PO_4^{3-}-P) were analysed using ion chromatography (Metrohm 761-Compact; 4110B). Sludge filterability was measured according to the protocol suggested by KUBOTA: a 50 mL sample of mixed liquor is filtered through filtering paper Type C (specified in JIS P 3801); if the filtered volume after 5 min is ≥ 10 mL, then sludge filterability is considered “good”, while if the filtered volume is ≤ 5 mL, sludge filterability is considered “bad”. The off line analyses described above were performed twice a week. There were also other offline analyses carried out during this study: EPS analysis (weekly) and PAO/DPAO assay (twice during the experimental run).

Extracted extracellular polymeric substances (eEPS) and soluble microbial products (SMP) were separated by centrifugation at 12,000 g a 100 mL sample for 20 min at 4°C. eEPS were extracted using a cation-exchange resin (Frolund *et al.*, 1996). Polysaccharides were determined by the fenol/H_2SO_4 colorimetric method (Dubois *et al.*, 1956) and proteins by the Lowry colorimetric method (Frolund *et al.*, 1995).

Activated sludge samples were incubated in two different batch tests in order to observe PAO and DPAO phosphate uptake and release potential. The sludge was inoculated and kept anaerobic in the presence of sodium acetate for 3.5 hours. Subsequently, one of the incubations was exposed to aerobic conditions and the other was exposed to anoxic conditions by the addition of nitrate to a final concentration of 20 mg. NO_3^--N·L^{-1}. The phosphate uptake rate (PUR) was estimated from the linear regression of phosphate concentrations. The ratio of anoxic PUR to aerobic PUR (the anoxic/aerobic PUR ratio) was used as an index to reflect the fraction of DPAOs (Wachtmeister *et al.*, 1997).

Laboratory analyses were carried out in two different laboratories: the laboratory of the University of Girona (LEQUiA) and the laboratory of El Vendrell WWTP (Table 2.4 and 2.5). In the first, all analyses were developed according to the Standard Methods protocol while in the second a HACH LANGE DR2800eco spectrophotometer and corresponding kits were used. Some of the analyses were repeated in both laboratories to validate the results.

Composite samples of the influent and effluent were collected two days a week (Tuesdays and Thursdays) and were taken manually from the influent right after the rotative sieve. The sample volume was 1L every two hours, and at the end of 24 hours the same amount from each sample, typically between 100mL and 200mL, was integrated to obtain a 2L composite sample. The permeate sample was drawn by an electric timer placed in the permeate pipe (after the flow meter). The valve opened for 10 seconds every hour and the sample was stored in a tank outside the control booth.

Parallel to this, the evolution of MLSS in the different reactors was monitored by collecting samples three times a week (Mondays, Wednesdays and Fridays). Nitrate, nitrite and phosphate concentration in the different reaction chambers was monitored three days a week.

Table 5.2. Influent and permeate laboratory analyses.

Parameter	Frequency	Volume of sample (mL)	Type of sample	LEQUiA Laboratory	WWTP Laboratory
COD(T+S)	2/week	20	Soluble - filtered with 1.2 μm filters		X
BOD_5	1/month	100		X	
TOC	2/week	25	filtered with 0.45 μm filters	X	
N_T	2/week	2			X
TKN	2/week	50		X	
NH_4^+	2/week	25	filtered with 1.2 μm filters	X	X
$N\text{-}NO_x^-$	2/week	2	filtered with 1.2 μm filters		X
$P\text{-}PO_4^{3-}$	2/week	2	filtered with 1.2 μm filters		X
$N\text{-}NO_x^-$ $P\text{-}PO_4^{3-}$	2/week	10	filtered with 0.2 μm filters	X	
TSS - VSS	2/week	25(influent) 300 (permeate)			X

Table 5.3. Activated sludge laboratory analyses.

Parameter	Frequency	Volume of sample (mL)	Type of sample	LEQUiA Laboratory	WWTP Laboratory
$N\text{-}NO_x^-$	3/week	2	Soluble - filtered with 1.2 μm filters		X
$N\text{-}NO_x^-$ $P\text{-}PO_4^{3-}$	3/week	10	filtered with 0.2 μm filters	X	
MLSS MLVSS	3/week	5			X
Filterability	3/week	50	filtered with 1 μm filters		X
EPS	1/week	100		X	

CHAPTER 6
KNOWLEDGE ACQUISITION

6. Knowledge acquisition

A wide range of operational conditions were experimented with in order to design a control system able to adapt to multiple scenarios and different membrane configurations. In this chapter the experiments carried out in both flat-sheet and hollow fibre pilot plants are described. For each facility, a brief description of the wastewater characteristics is given, followed by a detailed description of operational conditions and biological nutrient removal process results. The final focus is on the filtration process, with a description of the main experiments and results obtained.

6.1 Experimentation with flat sheet membranes

6.1.1 Urban wastewater characteristics

The industrial scale pilot plant was located at the El Vendrell WWTP, Catalonia, North-East Spain. At the time of the study this plant was managed by OHL-Medio Ambiente INIMA S.A.U. The pilot plant treated municipal wastewater with a C:N:P ratio of 100:13.1:1.1, collected after WWTP pre-treatment and before the primary settlers. All the raw wastewater characteristics during the experimental run are shown in Table 6.1.

Table 6.1. Characteristics of the pilot plant's influent wastewater.

Parameter	Units	Mean (S_D)	Max	Min
COD	mg COD·L^{-1}	481 (186)	833	176
TN	mg TN·L^{-1}	63 (15)	114	27
NH_4^+	mg N-NH_4^+ ·L^{-1}	44 (11)	76	20
PO_4^{3-}	mg P -PO_4^{3-} ·L^{-1}	5.2 (3.5)	13.5	1
C /N /P ratio		100/13.1/1.1		

The influent and permeate flows, when working under variable fluxes, followed a flow pattern similar to the typical daily flow observed in the full scale municipal WWTP where the pilot MBR plant was located (see Figure 6.1), with a permeate flux varying from 20 to 36.5 LMH.

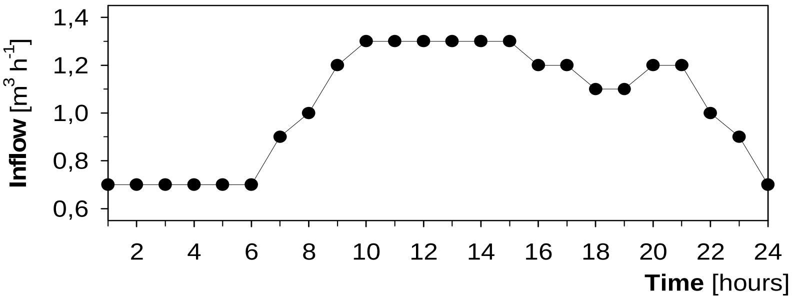


Figure 6.1. Daily flow pattern of variable flux entering the MBR pilot plant and treated during the project.

6.1.2 Operational conditions and phases

Operational conditions for optimal BNR were determined via simulations performed using BIOWIN software from OHL-Medio Ambiente INIMA S.A.U. (Table 6.2).

Table 6.2. Results of the BIOWIN simulation.

Parameter	Units	Set point
External recycle	% of the inflow	400
Internal recycle	% of the inflow	400
Anaerobic recycle	% of the inflow	200
Sludge waste	$L{\cdot}day^{-1}$	200
DO aerobic set point	$mg\ O_2{\cdot}L^{-1}$	1

Table 6.3 summarises the operational conditions throughout the experimental run.

Table 6.3. Operational conditions of the MBR pilot plant during the experimental period.

Parameter	Units	Experimental period
Operational days	days	245
HRT	hours	12-21
LMH	$L{\cdot}m^{-2}{\cdot}h^{-1}$	17-36.5*
Anaerobic recycle	% of the inflow	200
Internal recycle	% of the inflow	340-400
External recycle	% of the inflow	400-470
DO aerobic set point	$mg\ O_2{\cdot}L^{-1}$	0.5-1

** The peak flow was maintained for a maximum of 6 hours.*

The experimental period lasted 245 days, of which the first 77 can be considered as the start-up, in which time the MLSS concentration was increased by limiting the sludge wastage until MLSS values recommended by the membrane supplier were reached. The influent flow rate and the permeate flow rate were increased gradually from a daily average of 17 LMH to a maximum peak of 28.8 LMH, which corresponds to a decrease in the HRT from 21 to 12 hours.

Four different phases can be distinguished (Table 6.4):

- Phase 1 (day 1 to day 57): variable inflow and permeate flux throughout the day.
- Phase 2 (day 58 to day 79): constant inflow and permeate flux.
- Phase 3 (day 80 to day 157): constant inflow and permeate flux; new blower for membrane aeration: variable inflow and permeate flux starting from day 120.
- Phase 4 (day 158 to day 245): variable inflow and permeate flux; variable membranes aeration throughout the day: constant inflow and permeate flux starting from day 229.

Throughout the experimental period, fixed values were applied for external and internal recycles and sludge waste flow rates. The external recirculation ratio, from the membrane compartment to the aerobic compartment, was set at four times the inflow (IF). The anoxic recirculation ratio, from the aerobic to the anoxic compartment, was set at four times the IF and the recirculation from the anoxic to anaerobic reactor was set at two times the IF until Phase 4, when the internal recycle was raised to 4.78IF and the external recycle lowered to 3IF.

Table 6.4. Operational conditions of the MBR pilot plant.

	Day	**Membrane air flow**	**Permeate flux**	
Phase 1 *day 1-57*	1	33 m^3·h^{-1} Constant	17 LMH (daily average) (peak of 22 LMH during 6h·day^{-1}) (average inflow 600L·h^{-1})	**VPF**
	15	33 m^3·h^{-1} Constant	19 LMH (daily average) (peak of 25 LMH during 6h·day^{-1}) (average inflow 700L·h^{-1})	
	21	33 m^3·h^{-1} Constant	22 LMH (daily average) (peak of 29 LMH during 6h·day^{-1}) (average inflow 800L·h^{-1})	
	30	33 m^3·h^{-1} Constant	28 LMH (daily average) (peak of 36 LMH during 6h·day^{-1}) (average inflow 1000L·h^{-1})	
	39	33 m^3·h^{-1} Constant	22 LMH (daily average) (peak of 29 LMH during 6h·day^{-1}) (average inflow 800L·h^{-1})	
	44	Pilot plant out of order due to faulty influent pump		
Phase 2 *day 58-79*	58	33 m^3·h^{-1} Constant	25 LMH (average inflow 865 L·h^{-1})*	**CPF**
	71	33 m^3·h^{-1} Constant	20 LMH (average inflow 691 L·h^{-1})*	
	77	33 m^3·h^{-1} Constant	20 LMH (average inflow 720 L·h^{-1})	
Phase 3 *day 80-157*	80	54 m^3·h^{-1} Constant	20 LMH (average inflow 720L·h^{-1})	
	98	54 m^3·h^{-1} Constant	25 LMH (average inflow 900L·h^{-1})	
	106	49.5 m^3·h^{-1} Constant	25 LMH (average inflow 900L·h^{-1})	
	112	49.5 m^3·h^{-1} Constant	30 LMH (average inflow 1080L·h^{-1})	
	120	49.5 m^3·h^{-1} Constant	28 LMH peak of 36.5 LMH during 6 hours (average inflow 1008L·h^{-1})	**VPF**
	127	45 m^3·h^{-1} Constant	28 LMH peak of 36.5 LMH during 6 hours (average inflow 1008L·h^{-1})	
	134	47.5 m^3·h^{-1} Constant 143 49,5 m^3·h^{-1} 144 9.00 a 16.00 146 45 m^3·h^1 16:00 a 9:00	28 LMH peak of 36.5 LMH during 6 hours (average inflow 1008L·h^{-1})	
	148	45 m^3·h^{-1} Constant	28.8 LMH peak of 36.5 LMH during 6 hours (average inflow 1037L·h^{-1})	
Phase 4 *day 158-245*	158	37.8 m^3·h^{-1} Constant	28.8 LMH peak of 36.5 LMH during 6 hours (average inflow 1037L·h^{-1})	
	196	37.8 m^3·h^{-1} Variable	28.8 LMH peak of 36.5 LMH during 6 hours (average inflow 1037L·h^{-1})	
	202	35.3 m^3·h^{-1} Variable	28.8 LMH peak of 36.5 LMH during 6 hours (average inflow 1037L·h^{-1})	
	218	Pilot plant out of order due to rotative sieve fault		
	226	35.3 m^3·h^{-1} Variable	28.8 LMH peak of 36.5 LMH during 6 hours (average inflow 1037L·h^{-1})	
	229	38.5 m^3·h^{-1} Constant	25 LMH (average inflow 900L·h^{-1})	**CPF**

* Membrane surface of 38.4 m^2 (two damaged membrane plates were being replaced).
VPF = variable permeate flux; CPF = constant permeate flux.

6.1.3 Biological nutrient removal efficiencies throughout the experimental run

BNR was monitored throughout the entire experimental run in order to observe if the variations in operational conditions were interfering with nutrient removal performance.

During the start up period the SRT was not controlled or increased as sludge wastage was very limited (50 L·day^{-1}) to achieve high values of MLSS concentration. The MLSS in the membrane compartment increased from 3 g·L^{-1} to approximately 8 g·L^{-1} at day 77, when the wastage was finally fixed to obtain an SRT of around 50 days. It was finally set at day 150 in order to obtain an SRT of 31 days. Figure 6.2 (top) shows TSS removal was optimal throughout the study.

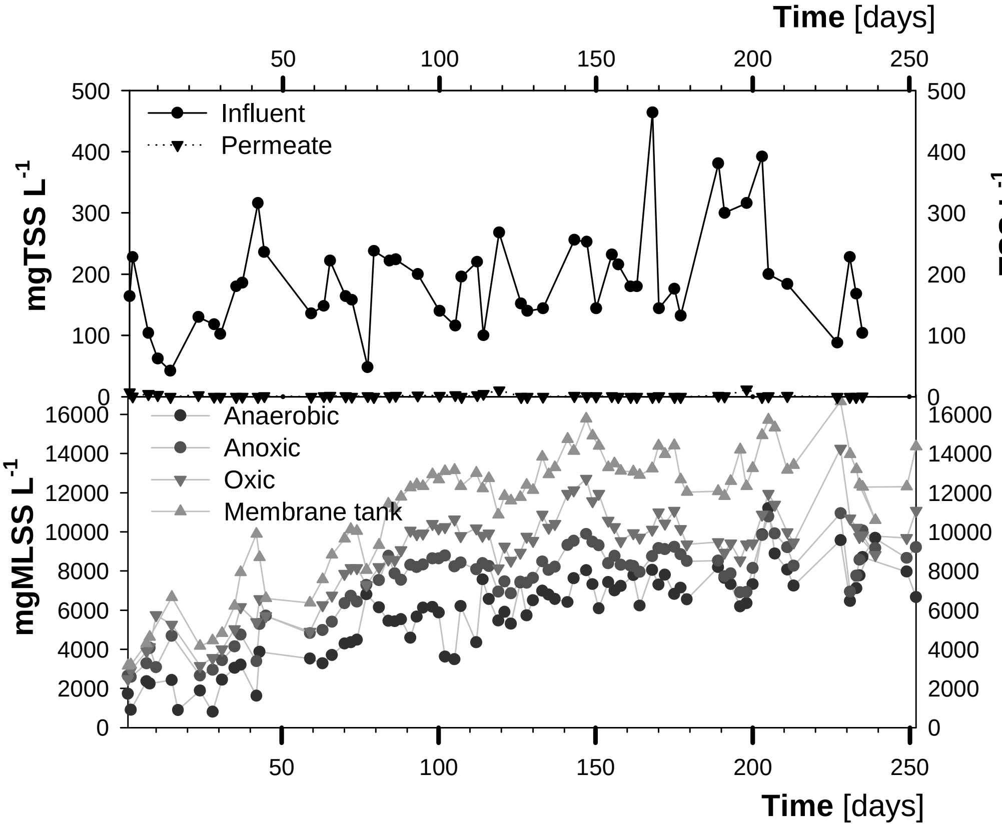


Figure 6.2. MLSS and TSS evolution during the experimental study.

COD removal efficiencies were very high throughout the experimental period (97±2%), even during the start-up phase. Although the influent COD concentration variability was very high all through the study, with an average applied load of 0.08 kg COD·kg SSV^{-1}·day^{-1}, the effluent COD concentrations that were achieved of 17.5±6.2 mg COD·L^{-1} fulfilled the discharge limits imposed by European legislation (91/271/CEE).

N removal efficiency during the whole of the experimental period amounted to 70±12%. The average concentration of total nitrogen in the influent was 63.2 mg·L^{-1}, of which 69% was in the form of ammonium, and showed high variability (Table 6.1). N removal was mainly affected by the size of the anoxic zone. Complete nitrification was obtained throughout the study, with values below 0.1 mg N-NH$_4^+$ ·L^{-1} in the effluent being achieved from the first days of operation (Figure 6.3). With regard to denitrification, specific analysis showed partial denitrification in the anoxic reactor due to a lack of organic matter and high oxygen concentrations in the recycle (see section 6.1.3.1). Improved oxygen control in the aerobic reactor to prevent high DO concentrations when influent flows were low, splitting the influent between the anaerobic and anoxic reactor to guarantee sufficient organic matter for denitrification, and increasing the anoxic reactor volume, were suggested as ways of improving N removal. However, in this experimental run, these modifications could not be performed. Even so, average effluent nitrate concentrations were 14.7±5.3 $mg{\cdot}L^{-1}$.

With respect to biological phosphorous removal, there was no activity between day 55 and 150, but the MBR achieved an average P removal efficiency of 77% during the final period, with effluent concentrations of 0.9 mg $P\text{-}PO_4^{3-}$. It can be observed that P removal was directly influenced by weak N removal until day 150. Batch tests showed that the population of polyphosphate-accumulating organisms increased throughout the experimental period and that the proportion of denitrifying phosphorus-accumulating organisms in the total increased as well, but with values considerably lower than in a pilot plant working with a constant flow (Monclús *et al.*, 2010). At day 150 the P_{uptake} rate under aerobic conditions was 3.1 mg $P{\cdot}g^{-1}VSS{\cdot}h^{-1}$, and the P_{uptake} rate under anoxic conditions was 0.7 mg $P{\cdot}g^{-1}VSS{\cdot}h^{-1}$, which is comparable to rates in an inoculum sludge with low biological phosphorous removal. From day 150 the $P\text{-}PO_4^{3-}$ influent concentration decreased considerably and the $P\text{-}PO_4^{3}$ concentration was < 2 $mg{\cdot}L^{-1}$.

Figure 6.3 shows the BNR's performance throughout the entire experimental run.

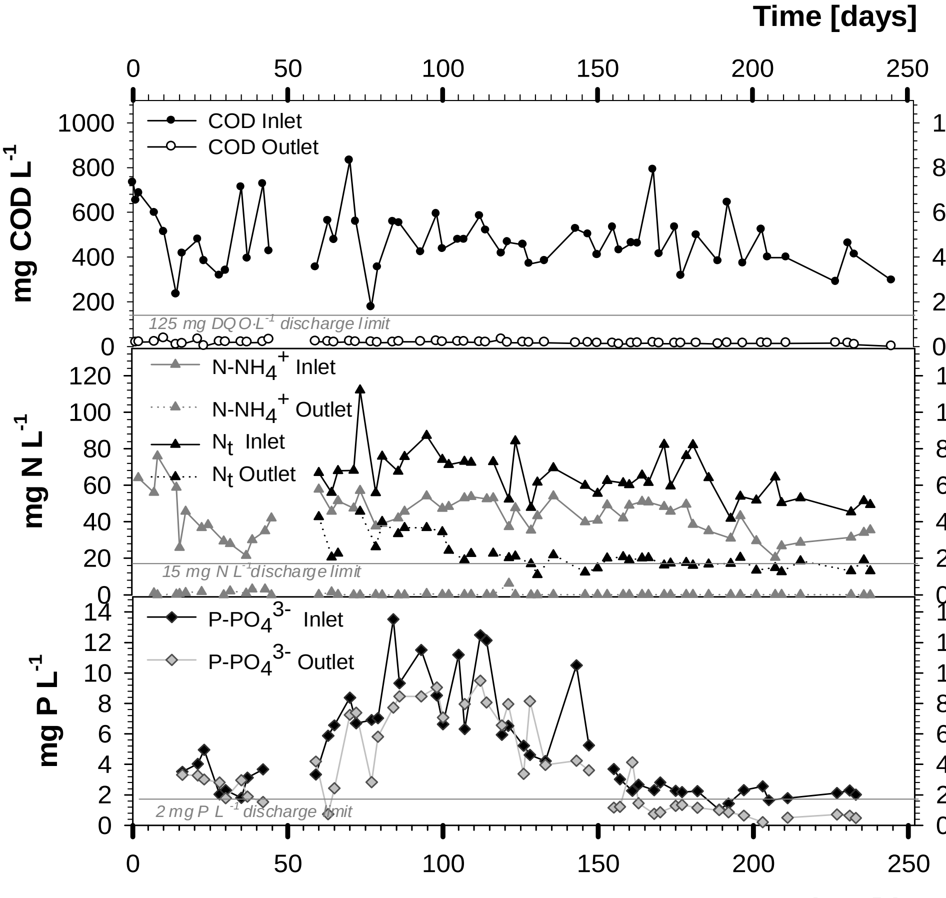


Figure 6.3. Biological nutrient (COD, N and P) removal evolution throughout the entire experimental run.

6.1.3.1 BNR limitations

The partial denitrification was investigated in order to find its causes. Usually, poor denitrification is caused by: a) the presence of dissolved oxygen in the anoxic chamber, b) lack of organic matter, c) errors in the design of compartments, i.e. volumes and hydraulic residence times. Option a) was initially excluded because DO concentration in the anoxic tank was measured daily (around 12.00 noon) and ranged between 0 and 0.03 ppm. A calculation to assess hypothesis b) was then carried out based on the assumption that the $N\text{-}NO_3$ to be denitrified = 50ppm.

$$\frac{COD_{rb}}{N\text{-}NO_{3\,to\,be\,denitrified}} = 2.86 \qquad \text{(Metcalf and Eddy, 2003)}$$

where the concentration of readily biodegradable COD, COD_{rb}= 2.86 · 50 = 143 ppm

Given that COD_{rb} can approximate to the difference between soluble COD in the influent and soluble COD in the effluent, then

$COD_{rb} = COD_{s\ in} - COD_{s\ out}$

where $COD_{s\ out}$= 20 ppm. Hence,

$COD_{s\ in}$ = 143 + 20 = 163 ppm

The concentration of soluble COD in the influent in the anoxic chamber was measured at 88.9 ppm and it was possible to obtain the soluble COD that would be additionally necessary to carry out complete denitrification in the anoxic chamber, i.e. 74.1 ppm. Given that the soluble COD in the influent was 236 ppm, it follows that 31.4% of the influent flow would have to be diverted directly to the anoxic chamber.

An alternative solution would be the addition of a carbon source (i.e. methanol, acetate, or ethanol) (Table 6.5).

$$5CH_3OH + 6NO_3^- \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^- \qquad \text{(Metcalf and Eddy, 2003)}$$

The theoretical calculation of the methanol necessary for complete denitrification is the following:

$$1\frac{mgN-NO_3^-}{L}.\frac{1mmolNO_3^-}{14mgN-NO_3^-}.\frac{5mmolsCH_3OH}{6mmolsNO_3^-}.\frac{32mgCH_3OH}{1mmolCH_3OH}.\frac{1mL}{792mg} = 0.0024\,{}^{mLCH_3OH}\!\big/_{mgN-NO_3^-}$$

For the acetate the calculation is:

$$1\frac{mgN-NO_3^-}{L}.\frac{1mmolNO_3^-}{14mgN-NO_3^-}.\frac{5mmolsCH_3COOH}{8mmolsNO_3^-}.\frac{60mgCH_3COOH}{1mmolCH_3COOH}.\frac{1mL}{1050mg} = 0.00255\,{}^{mLCH_3COOH}\!\big/_{mgN-NO_3^-}$$

Table 6.5. Calculation of carbon source addition to improve BNR.

Carbon source (CS)	mL CS · (mg NO^{3-})$^{-1}$	CS density mg · mL^{-1}	Nitrogen to be removed mg · L^{-1}	Treated volume L · day^{-1}	Volume to be added L · day^{-1}
Methanol	0.00240	792	50 (TKN)	24,000	2.880
Ethanol	0.00203	810			2.436
Acetate	0.00255	1,050			3.060
Methanol	0.00240	792	20 (NO^{3-})		1.152
Ethanol	0.00203	810			0.974
Acetate	0.00255	1,050			1.224

Finally, the control action taken was the partial diversion of the influent in the inflow to the anoxic chamber (Table 6.6).

Table 6.6. Operational conditions.

Inflow (IF)	% IF entering the anaerobic chamber	% IF entering the anoxic chamber
<900	100%	0%
900	80%	20%
1000	76%	24%
1300	63%	37%

An improvement in denitrification was achieved with the partial diversion of the influent but it was not possible to reach complete denitrification at this point. The causes identified were the variability of the DO concentration in the aerobic chamber (Figure 6.4) and the fixed internal recirculation flow.

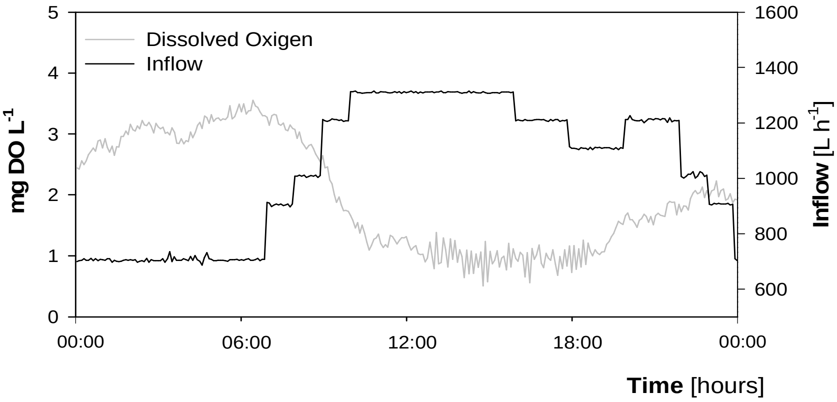


Figure 6.4. Dissolved oxygen profile in the aerobic chamber and inflow profile.

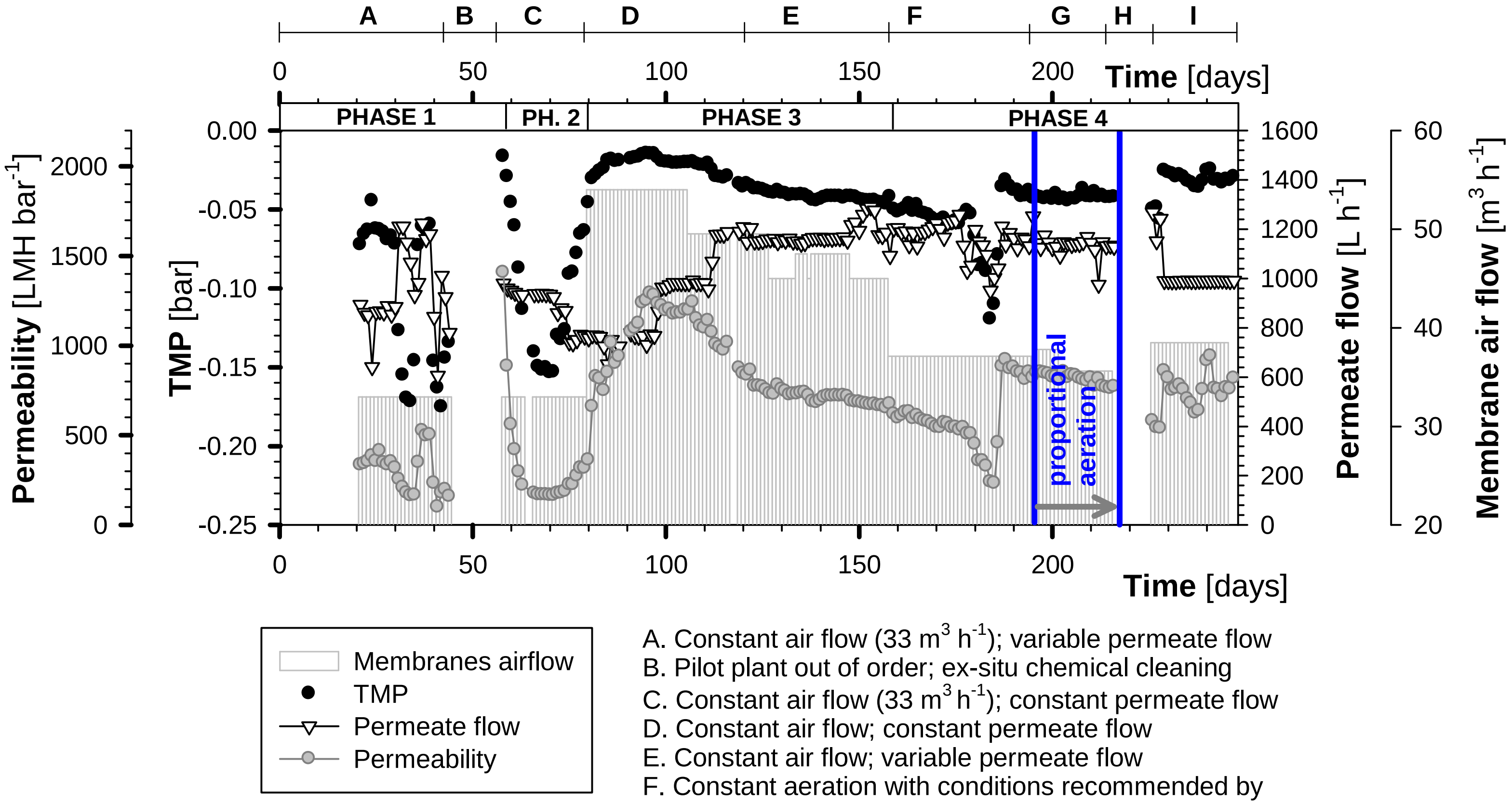
While working with a variable influent flow pattern, DO concentration in the aerobic chamber varied considerably during the day, but especially during the night, when IF was at a minimum and DO concentration was at > 4 mg·L^{-1} despite the DO set point of 1 mg DO·L^{-1}. The blower was oversized and even when working at the minimum frequency (30Hz) the aeration proportion exceeded the required flow. To this problem had to be added the absence of a frequency inverter to regulate the internal recirculation flow, which was set at 4IF. When IF was at a minimum the internal recycle was up to 7IF, and the concentration of DO in the aerobic chamber (and therefore in the aerobic-anoxic recycle) was very high. As a result, denitrification was very unlikely to occur during this time. To mitigate the problem, the DO set point in the aerobic chamber was lowered to 0.5 mg DO·L^{-1}.

6.1.4 Filtration process performance

The focus of the experimentation was on applying different air-scour flow rate set points and observing the evolution of permeability under such conditions. While Kubota flat sheet membranes were in operation the aim was to develop a control strategy when dealing with an MBR operated under variable fluxes. Although more complex strategies can be developed to optimise energy consumption, it was proven that the air-scour for the physical cleaning of membranes while treating a variable permeate flux could be lowered to below the minimum value recommended by the membrane suppliers. Figure 6.6 shows the evolution of flux and permeability.

During the experimental period, permeability and TMP were monitored as indicators of membrane fouling evolution. The flux was gradually increased from a daily average of 17 LMH to 28.8 LMH. The pilot plant operation started with variable permeate flux (phase 1), followed by a period of constant flux operation (phases 2 and 3) and ended with a variable flux phase (phase 4). The first phase was characterised by low values of permeability (300 $\mathrm{LMH{\cdot}bar^{-1}}$ on average), which were deemed to be due to lack of aeration. Until day 81 the pilot plant was operated with a specific aeration demand (SAD_m) of 0.83 $\mathrm{m{\cdot}h^{-1}}$ (air flow: 33 $\mathrm{m^3{\cdot}h^{-1}}$), while the minimum recommended for a Kubota FS50 module is 0.95 $\mathrm{m{\cdot}h^{-1}}$ (air flow: 38 $\mathrm{m^3{\cdot}h^{-1}}$). During the first two phases of operation the air-scour flow rate was kept constant throughout the day despite influent/permeate flow fluctuations. The low MLSS concentration during the start-up phase and the lack of aeration resulted in a rapid fouling of the membranes and the existing blower had to be replaced by another capable of delivering a maximum SAD_m of 1.35 $\mathrm{m{\cdot}h^{-1}}$ (air flow: 54 $\mathrm{m^3{\cdot}h^{-1}}$). Three chemical cleanings with different NaClO concentrations (0.25%, 0.5% and 0.75%) were carried out with unsatisfactory results on days 38, 42 and 43 and it was necessary to carry out an ex-situ cleaning (Figure 6.5). The plant then operated with optimal performance with respect to permeability values due to the excess of aeration until day 106. Subsequently, SAD_m was manually reduced to 1.24 $\mathrm{m{\cdot}h^{-1}}$ (air flow: 49.5 $\mathrm{m^3{\cdot}h^{-1}}$) until day 127. Starting from day 196, variable air-scour proportional to the treated flux was applied. At day 202 the air scour was reduced while operating at peak flow, resulting in a daily average of 0.89 $\mathrm{m{\cdot}h^{-1}}$ (air flow: 35.3 $\mathrm{m^3{\cdot}h^{-1}}$) without any observable short term impact on the permeability trend.

Figure 6.5. Images of cake formation on the membranes due to insufficient aeration.



A. Constant air flow (33 m^3 h^{-1}); variable permeate flow
B. Pilot plant out of order; ex-situ chemical cleaning
C. Constant air flow (33 m^3 h^{-1}); constant permeate flow
D. Constant air flow; constant permeate flow
E. Constant air flow; variable permeate flow
F. Constant aeration with conditions recommended by membranes suppliers (37,8 m^3 h^{-1}); variable permeate flow
G. Variable air flow; variable permeate flow
H. Pilot plant out of order
I. Constant air flow; constant permeate flow

Figure 6.6. Evolution of permeability and permeate flow during the experimental period in the flat sheet pilot plant.

The experiments carried out up to phase 4 were marked by a lack of flexibility in the pilot plant. Thanks to a miscalculation with regard to the air blower, the importance of adequate aeration especially during start-up became clear. When a suitable blower was installed, the lack of a frequency inverter made it impossible to modify aeration automatically, so all the changes were applied manually for a short period of time (i.e. days 143, 144 and 146). When on day 158 a frequency inverter was installed, the experiments were designed to test the viability of the proportional aeration concept being applied to flat sheet membranes. The pilot plant was operated under variable fluxes and the air flow was kept constant, at 37.8 $m^3 \cdot h^{-1}$, in conditions very close to the ones recommended by the membrane suppliers (38 $m^3 \cdot h^{-1}$). The exact value was not achieved because the only way to regulate aeration was by modifying the set point of the frequency inverter (in Hz). On day 196 the air flow was modified to follow a flow pattern similar to that of the permeate flow, and on day 202 to achieve variable aeration proportional to the permeate flow but not exceeding the minimum air-scour recommended by the suppliers (Figure 6.7). The results were positive and no significant increase in TMP (or decrease in permeability) was detected; neither was there observed any negative effect on the BNR.

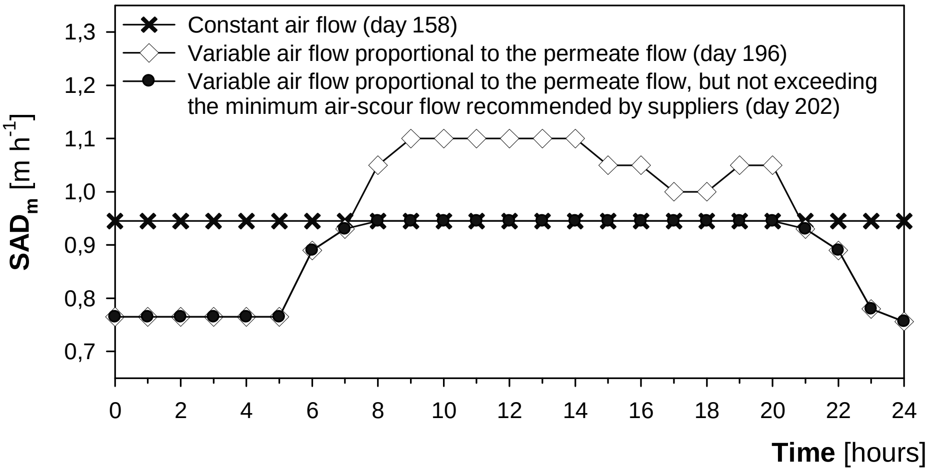


Figure 6.7. Different air flow patterns in operation during the study.

As can be observed in Figure 6.6, permeability decreased dramatically around day 180 due to the malfunctioning of a blower, and an ex-situ cleaning was carried out on day 186. The pilot plant was out of order from day 218 to day 226 because of a breakdown in the rotative sieve. When the sieve was finally repaired and reinstalled, a fault in the level transducer reading interfered with the results obtained, so the decision was taken to suspend experimentation with proportional aeration and to work with constant air flow (38.5 $m^3 \cdot h^{-1}$) and constant permeate flow.

As can be seen in Figure 6.8, EPS concentration showed low variability over the entire experimental run, at 27.6±7.9 mg EPS·g $MLVSS^{-1}$, although this increased slightly together with an increase in MLSS concentration. The absence of significant EPS concentration increase or decrease was further corroborated by good sludge filterability, which exceeded 10 mL·5 min^{-1} for almost the entire experimental period.

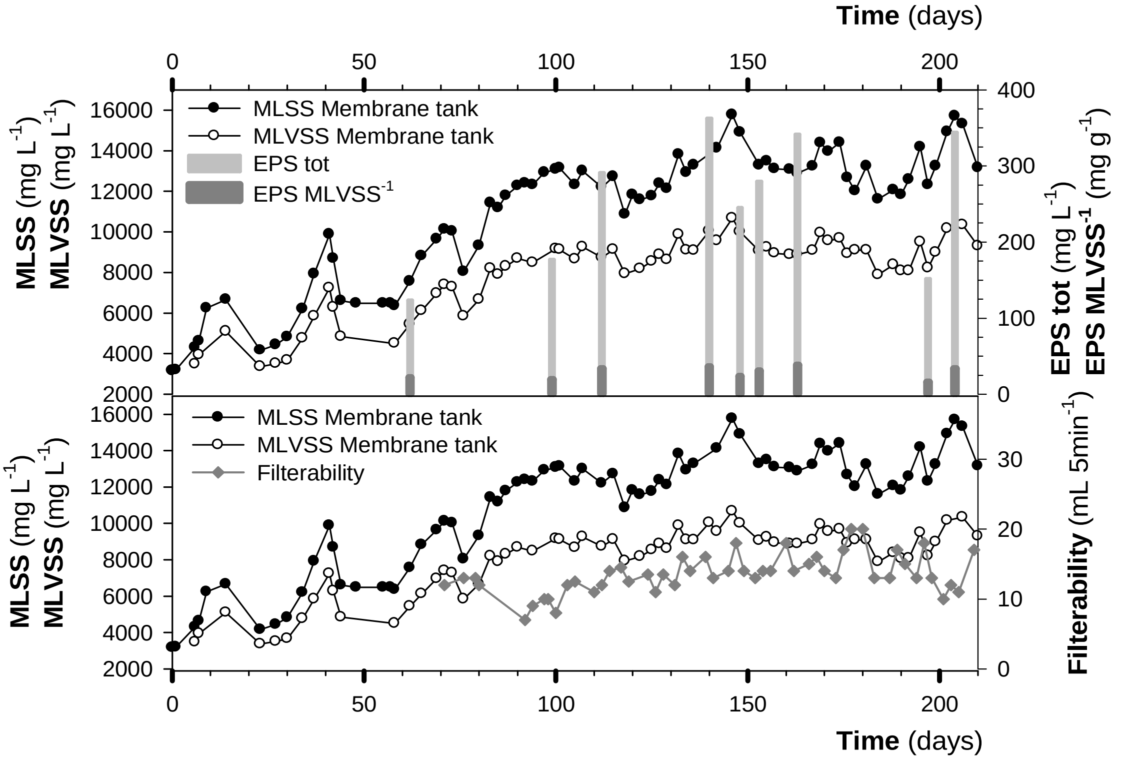


Figure 6.8. MLSS, filterability and EPS evolution.

6.2 Experimentation with hollow fibre membranes

6.2.1 Urban wastewater characteristics

The pilot plant was located at the Granollers WWTP in Catalonia, North-East Spain. It treated municipal wastewater collected after the WWTP pre-treatment and before the primary settlers, with a C:N:P ratio of 100:9.1:1.5. The complete set of raw wastewater characteristics during the experimental run are shown in Table 6.7.

Table 6.7. Characteristics of the influent wastewater in the pilot plant.

Parameter	Units	Mean (S_D)	Max	Min
COD	mg COD·L^{-1}	986 (453)	2999	395
TN	mg TN·L^{-1}	90 (28)	184	45
NH_4^+	mg N-NH_4^+ L^{-1}	56 (14)	99	23
PO_4^{3-}	mg P-PO_4^{3-} L^{-1}	15 (6)	30	5
C /N /P ratio		100/9.1/1.5		

The influent and permeate flows, when working under variable fluxes, followed the same flow pattern used during the experimentation with flat sheet membranes (see Figure 6.1), which resulted in a permeate flux varying from 21.5 to 28 LMH.

6.2.2 Operational conditions and phases

The operational conditions for optimal biological nutrient removal were determined via simulations performed using BIOWIN software as previously explained. Table 6.8 summarises the operational conditions throughout the experimental run.

Table 6.8. Operational conditions of the MBR pilot plant during the experimental period.

Parameter	Units	Experimental period
Operational days	Days	242
HRT	Hours	12.6
LMH	$L{\cdot}m^{-2}{\cdot}h^{-1}$	21.5-28*
Anaerobic recycle	% of the inflow	0-200
Internal recycle	% of the inflow	250-300
External recycle	% of the inflow	300-400
DO aerobic set point	$mg\ O_2{\cdot}L^{-1}$	1

** The peak flow was maintained for a maximum of 6 hours.*

The experimental period lasted 242 days, of which only the first six days can be considered as start-up. The influent flow rate and the permeate flow rate were increased gradually from 17 $L{\cdot}m^{-2}{\cdot}h^{-1}$ (LMH) to a maximum of 23.7 LMH (daily average). Throughout the experimental period, fixed values were applied for external and internal recycles and sludge waste flow rates, but they were not always respected due to multiple mechanical problems with the pumps. The external recirculation ratio, from the membrane compartment to the aerobic compartment, was set at four times the inflow (IF). The anoxic recirculation ratio, from the aerobic to anoxic reactor compartment, was also set at four times the IF and the recirculation from the anoxic to anaerobic reactor was set at twice the IF.

Table 6.9. Operational phases during the experimental period of the pilot plant.

	Day	Membrane air flow	Permeate flux	
Phase 1 *day 1-35*	1	$19.6\ m^3{\cdot}h^{-1}$ Constant	21.5 LMH (average inflow $1000L{\cdot}h^{-1}$)	**CPF**
	7	$19.6\ m^3{\cdot}h^{-1}$ Constant	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
	23	$17.9\ m^3{\cdot}h^{-1}$ Constant	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
	31	$16.4\ m^3{\cdot}h^{-1}$ Constant	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
Phase 2 *day 36-107*	36	Control system calibration	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
	53	Automatic control	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
Phase 3 *day 108-193*	108	$22.2\ m^3{\cdot}h^{-1}$ 45 Hz	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
	110	$20.18\ m^3{\cdot}h^{-1}$ 40 Hz	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
	117	$20.18\ m^3{\cdot}h^{-1}$ 40 Hz	23.7 LMH (average inflow $1000L{\cdot}h^{-1}$)	
	136	$20.18\ m^3{\cdot}h^{-1}$ 40 Hz	23 LMH daily average (average inflow $1000L{\cdot}h^{-1}$)	**VPF**
Phase 4 *day 194-218*	194	Automatic control	23 LMH daily average (average inflow $1000L{\cdot}h^{-1}$)	
Phase 5 *day 219-242*	219	Automatic control	21.5 LMH daily average (average inflow $1000L{\cdot}h^{-1}$)	**CPF**

* VPF = variable permeate flux; CPF = constant permeate flux.

6.2.3 Biological nutrient removal efficiencies throughout the experimental run

MLSS concentration in the membrane compartment was very high from the beginning of the experimentation and reached an average of 12 g·L^{-1}. The SRT was on average 19 days, with a sludge wastage factor that ranged from to 0.4 to 1 m^3·day^{-1}. Wide variability in the TSS in the influent to the pilot plant (519±282 mg·L^{-1}) and complete TSS removal in the permeate was observed (Figure 6.9). The MLSS concentration in the membrane tank reached values higher than 20 g·L^{-1} from day 130 to 140 because of the malfunctioning of the external recycle pump. The process was greatly affected by these MLSS concentrations, and therefore the experimental data from days 130 to 180 cannot be considered representative.

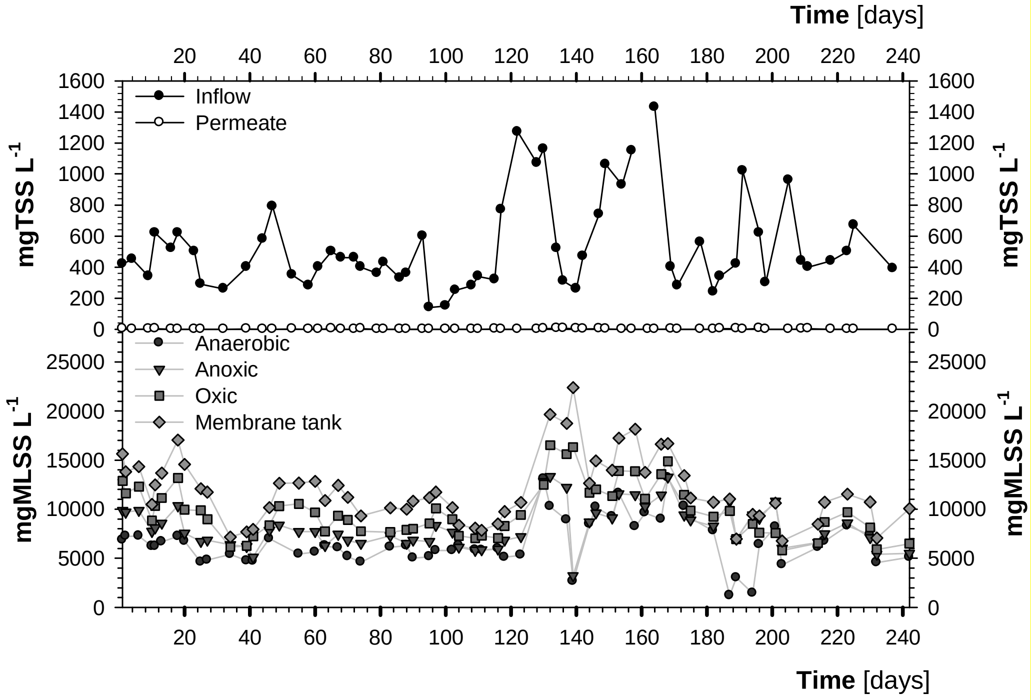


Figure 6.9. MLSS and TSS evolution during the experimental study.

COD removal efficiencies were very high throughout the experimental period (97±1%). Although the influent COD concentration variability was very high during the study, with an average applied load of 0.12 kg COD·kg SSV^{-1}·day^{-1}, the effluent COD concentrations achieved, at 25.3±3.6 mg COD·L^{-1}, fulfilled the discharge limits imposed by European legislation (91/271/CEE).

N removal efficiency throughout the experimental period amounted to 81.1±8.7%. The average concentration of total nitrogen in the influent was 92.8 mg·L^{-1}, of which 62% was in the form of ammonium, and showed high variability (Figure 6.10). Complete nitrification was obtained throughout the entire study, with values below 0.36 mg N-NH_4^+·L^{-1} in the effluent being achieved from the first days of operation. With regard to denitrification, the average nitrate concentration in the effluent was 9.5 mg N-NO_3^-·L^{-1}.

Biological phosphorous removal activity was affected by the malfunctioning of the recycle pumps, which led to the plant being operated without the anoxic-anaerobic recycle between days 79-86, 100-114, 135-151 and from day 164 until the end of the experimentation. Nonetheless, an average P removal efficiency of 65% was achieved. Figure 6.10 shows BNR performance during the entire experimental run.

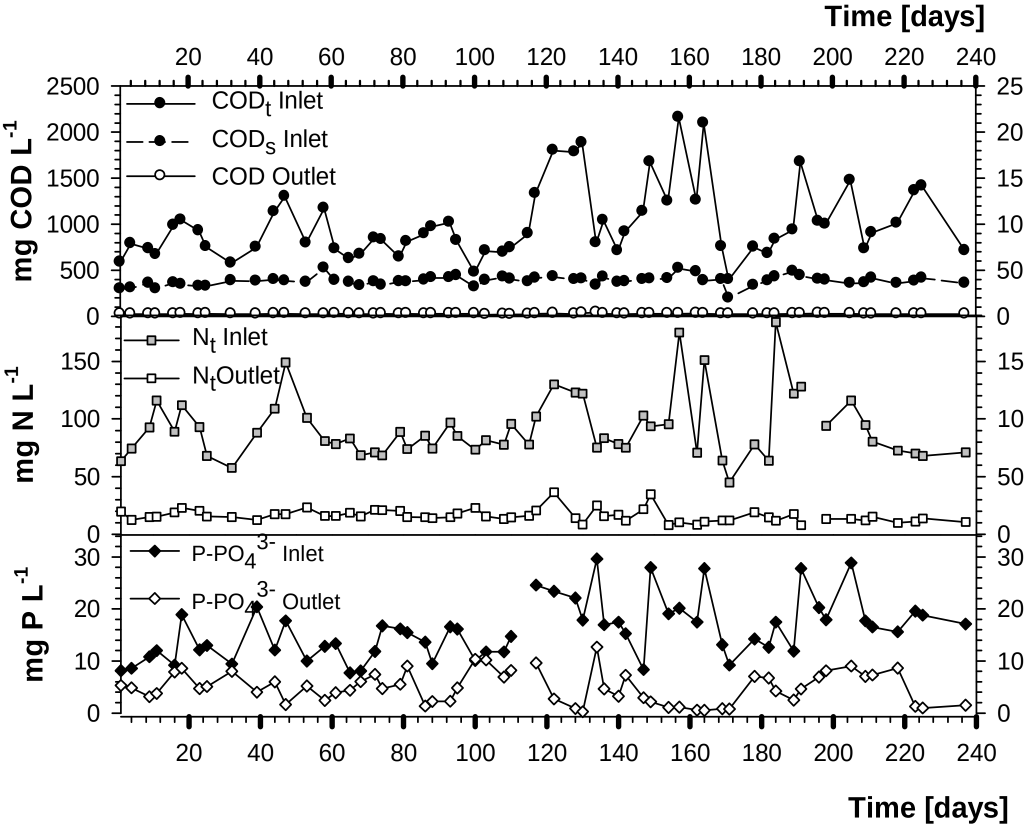


Figure 6.10. Biological nutrient (COD, N and P) removal evolution during the experimental study.

6.2.4 Filtration process performance

During the experimental period the pilot plant operated with a module of 46.45 m^2 and, in comparison to the experimentation with flat-sheet membranes, under lower fluxes, with an average flow of 1000 L·h^{-1} being maintained throughout the entire study. The flux was gradually increased from 21.5 LMH to 23.7 LMH with peaks of 28 LMH while working with variable fluxes. The operation started with constant membrane air flow and regular manual changes being carried out (phase 1 in Table 6.9), and was followed by a period with air-scour regulated by automatic control (phase 2 in Table 6.9). This was followed by two periods of operation with the aeration requirements recommended by the suppliers with constant permeate flux and variable permeate flux (phase 3 in Table 6.9), and ended with the automatic control of aeration both with variable and constant flux (phases 4 and 5 in Table 6.9). During the first phase, the plant was operated with a permeate flow of 1100 L·h^{-1}, corresponding to 23.7 LMH (period A in Figure 6.11). The blower initially installed was changed for a smaller size one (Becker DT 4.25 K) that permitted a reduction in membrane aeration. Manual changes were carried out to test membrane response to air-scour reduction, with air-scour firstly being reduced by approximately 9% with respect to the minimum aeration flow recommended by the manufacturer, and then 16% (period B in Figure 6.11). The second phase was characterised by numerous tests aimed at validating the reliability of the programming rules from a computational point of view (period C in Figure 6.11), and was followed by the first control system validation (period D in Figure 6.11). Period D represents the automatic control with the first control strategy, where the permeability slope of the final four days (a current or short term permeability slope $\left(\frac{dK}{dt}\right)_4$) was compared to a fixed long term (or reference) slope of 14 days $\left(\frac{dK}{dt}\right)_{14}$ calculated immediately after the start-up, which was considered to have ended when an MLSS concentration of 5 $g\cdot L^{-1}$ and sludge filterability higher than 5 $mL\cdot 5min^{-1}$ were achieved; the fixed long term slope was equal to -18.73. To each slope ratio ($\frac{\text{short term permeability slope}}{\text{long term permeability slope}}$) there was a control action in terms of air-scour reduction or increase, as shown in Table 6.10.

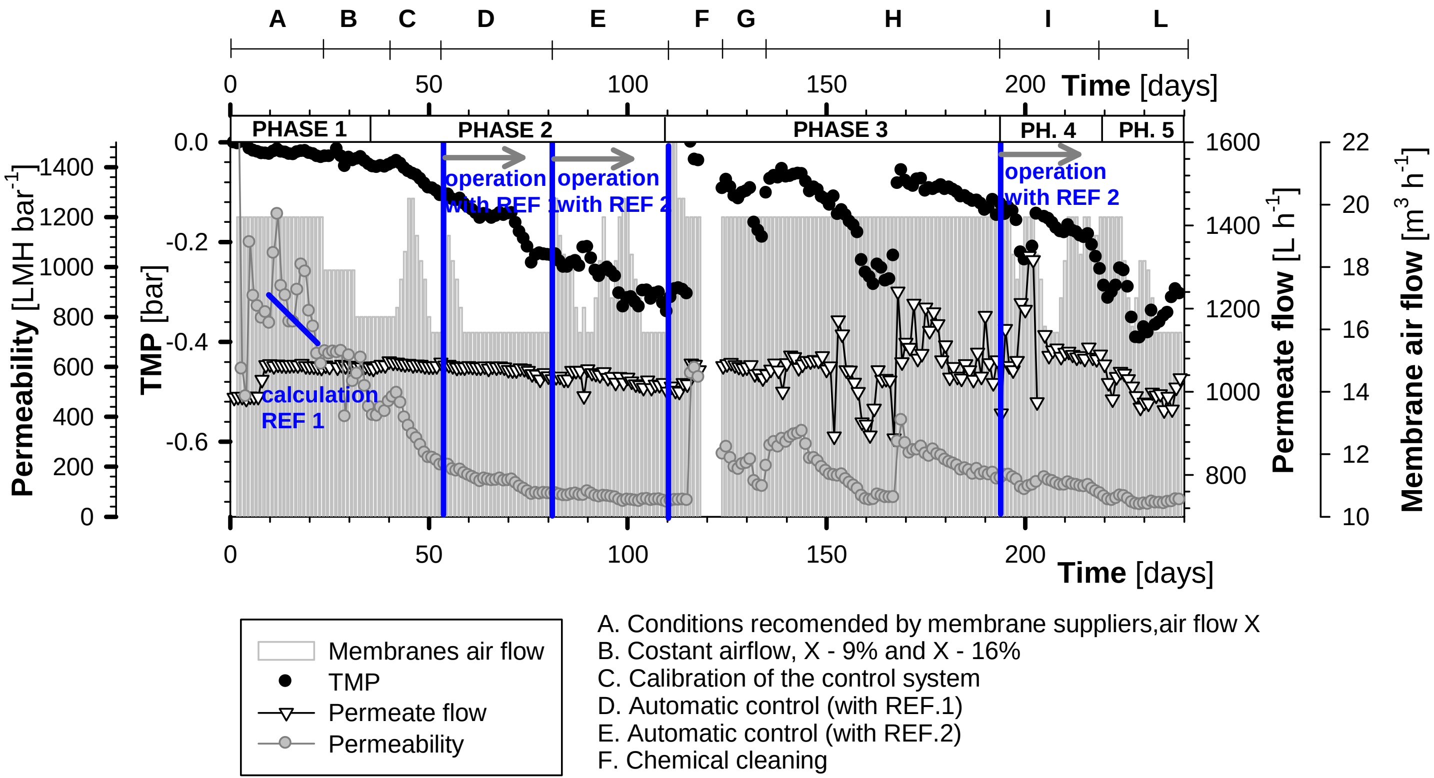
Table 6.10. Slope ratio and control actions.

Slope ratio	Control action	
	Δ Blower frequency (Hz)	**Δ Air-scour flow ($m^3\cdot h^{-1}$)**
<0	-3	-1.2
0 – 0.3	-2	-0.8
0.3 – 0.6	-1	-0.4
0.6 – 0.9	-0.5	-0.2
0.9 – 1.1	0	0
1.1 – 1.4	0.5	0.2
1.4 – 1.7	1	0.4
1.7 – 2.0	2	0.8
>2	3	1.2

The control strategy adopted with a fixed reference slope was shown to be inappropriate as the reference slope was always greater (in absolute terms) than the current slope, which resulted in daily control actions that diminished the air-scour flow set point until a minimum set during the calibration of the control system was reached. This can be justified considering that a clean membrane has a much higher propensity to foul, and is therefore subject to a faster permeability decrease and cannot be considered a reference for the whole experimentation period. The new control strategy adopted the mobile permeability slope of the last 14 days as a reference (period E). The comparison that led to the selection of the new control strategy is shown in Table 6.11. The results in Table 6.11 clearly illustrate that the use of the long term mobile permeability slope provides reasonable control actions while the use of a fixed long term slope always leads to a decrease in aeration.

Table 6.11. Comparison of different control strategies.

			Experiment with fixed reference			**Theoretical behaviour with mobile reference**		
Day	**K**	$\left(\frac{dK}{dt}\right)_4$	$\left(\frac{dK}{dt}\right)_{14}$	**(SR)** $_{4/14}$	**Control action (Hz)**	$\left(\frac{dK}{dt}\right)_{14}$	**(SR)** $_{4/14}$	**Control action (Hz)**
70	172.0	-4.2	-18.3	0.2	-1	-11.1	0.4	-1
71	164.4	-6.5	-18.3	0.4	-1	-9.7	0.7	-0.5
72	156.7	-9.6	-18.3	0.5	-1	-8.4	1.1	0.5
73	148.7	-7.7	-18.3	0.4	-1	-7.5	1.0	0
74	139.1	-8.4	-18.3	0.5	-1	-7.3	1.2	0.5
75	150.0	-3.0	-18.3	0.2	-2	-6.9	0.4	-1



A. Conditions recomended by membrane suppliers,air flow X
B. Costant airflow, X - 9% and X - 16%
C. Calibration of the control system
D. Automatic control (with REF.1)
E. Automatic control (with REF.2)
F. Chemical cleaning
G. Conditions recomended by membrane suppliers,air flow X
H. Conditions recomended by membrane suppliers,air flow X
variable permeate flow
I. Automatic control (with REF.2), variable permeate flow
L. Automatic control (with REF.2)

Figure 6.11. Evolution of permeability and permeate flow during the experimental period in the hollow fibre pilot plant.

Figure 6.12 and Table 6.12 show the results of the validation period of the automatic control system based on permeability trends with constant permeate flow (period E in Figure 6.11). Maximum and minimum aeration were selected (min 15.9 $m^3·h^{-1}$, max 20 $m^3·h^{-1}$), which allowed a reduction in the aeration of up to 20%. Due to the lack of a digital air flow meter, the control actions were taken in terms of an increase or reduction in blower frequency A maximum control action of a 3 Hz increase or reduction was set as the maximum daily control action permitted, corresponding to 1.2 $m^3·h^{-1}$, or 6%, of the aeration recommended by the membrane supplier (20 $Nm^3·h^{-1}$, SAD_m of 0.43 $m^3·m^{-2}·h^{-1}$, SAD_p of 20 $m^3·m^{-3}$).

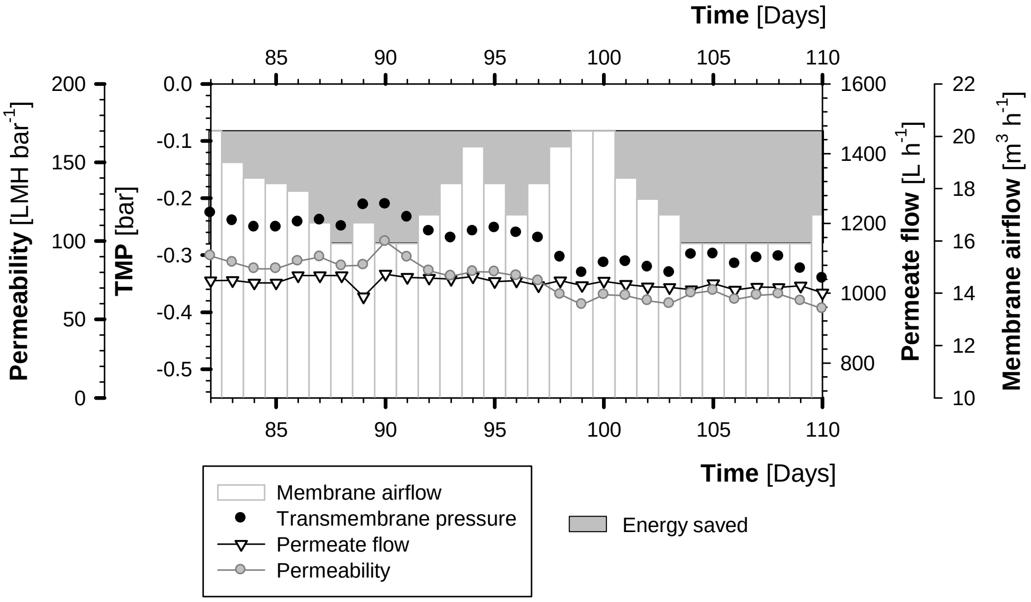


Figure 6.12. Results of control system validation (constant permeate flow); membrane air flow is automatically regulated by means of permeability monitoring.

Table 6.12. Results of control system validation.

Day	K	$\left(\frac{dK}{dt}\right)_4$	$\left(\frac{dK}{dt}\right)_{14}$	$(SR)_{4/14}$	Control action (Hz)	Air flow ($m^3·h^{-1}$)
91	89.6	3.1	-0.1	-37.2	-3	15.9
92	80.9	-2.1	-0.2	10.3	3	15.9
93	77.5	-7.5	-0.5	14.8	3	17.1
94	80.3	-3.1	-0.5	5.8	3	18.3
95	80.2	0.1	-0.6	-0.1	-3	19.5
96	77.7	0.1	-0.7	-0.1	-3	18.3
97	74.5	-2.0	-0.8	2.4	3	17.1
98	65.9	-4.6	-1.3	3.6	3	18.3
99	59.5	-6.3	-1.9	3.3	3	19.5
100	65.7	-3.3	-2.2	1.5	0.5	20
101	65.0	0.4	-2.2	-0.2	-3	20
102	61.8	0.6	-2.5	-0.3	-3	18.8
103	60.0	-2.0	-2.6	0.8	-0.5	18.3
104	66.6	0.3	-2.0	-0.1	-3	17.1
105	68.3	2.6	-1.5	-1.7	-3	15.9
106	62.6	0.9	-1.4	-0.7	-3	15.9
107	65.3	-1.0	-1.2	0.8	-0.5	15.9
108	66.1	-0.4	-0.9	0.5	-1	15.9
109	61.7	-0.2	-0.6	0.3	-2	15.9
110	56.8	-3.0	-0.4	6.7	3	15.9
111	60.7	-2.1	-0.2	9.8	3	17.1

In Figure 6.13 the results of the experimentation with variable permeate flow rate can be observed (period I in Figure 6.11). It can be seen, for example, that the decrease in permeability from day 215 to day 218 is translated automatically into an increase in aeration the following day (219). It should be noted, however, that the operational conditions were different and influenced the results: the experimentation with constant flow rate was carried out in summer with a lower average normalised flux as compared with the variable permeate flow rate experimentation, which was carried out in winter. Moreover, the daily peak flow can be taken as being responsible for a worse result in terms of energy saved. Nonetheless, in these tests, the energy saving was on average 7% and up to as much as 20%.

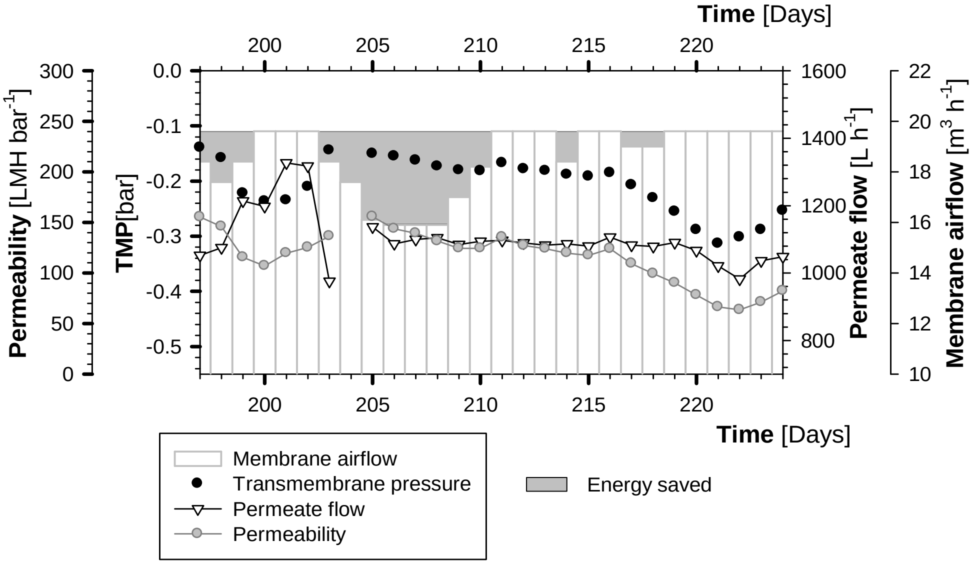


Figure 6.13. Results of the control system validation (variable permeate flow).

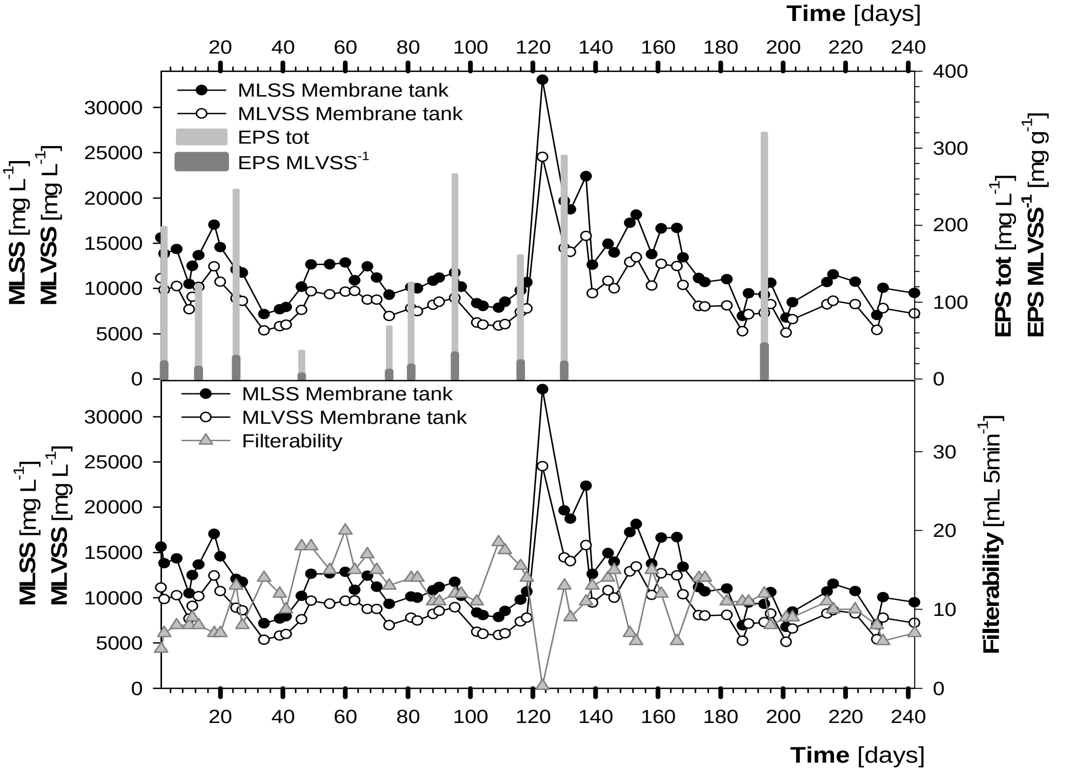


Figure 6.14: MLSS, filterability and EPS evolution.

Figure 6.14 shows the trend of extracellular polymeric substances (EPS) and mixed liquor filterability with total solids (MLSS) and volatile solids (MLVSS) in the membrane tank.

6.3 Discussion

A pilot plant was operated for two years with different membrane configurations with the aim of developing a control system to minimise air-scour. Initially, the viability of the ‘proportional aeration’ concept was tested by regulating the air-scour to follow the permeate flow pattern, and then a control algorithm based on on-line monitoring of the permeability evolution trends was developed and tested. Permeability was chosen as the key indicator for directly comparing temporary changes in membrane performance. Permeability trend was estimated as the slope of several daily averaged values.

Flat sheet membranes were operated under variable fluxes and different step tests were carried out. The pilot plant was initially operated with constant aeration, then variable aeration proportional to the permeate flux and finally proportional to the permeate flux without exceeding the minimum aeration recommended by the membrane suppliers. The results were positive and no significant increase in TMP (or decrease in permeability) was detected. A maximum daily energy saving of 6%, with respect to the constant aeration flow recommended by the membrane suppliers, was obtained. However, these good and promising results were achieved only at the end of the experimental run, due to numerous problems with the installation, mainly relating to a miscalculation of the aeration flow necessary for membrane air-scouring and the consequent choice of a blower that was too small. From this it was concluded that air-scour can be reduced below the recommended threshold but only and exclusively in a controlled way and with the possibility of re-establishing standard conditions if necessary. As far as BNR is concerned, general conclusions cannot be drawn as any effect is maximised in a small pilot plant, which has limitations that are not often found in full-scale installations. However, appropriate calculation of the anoxic zone volume based on the wastewater’s characteristics is certainly needed, and is strongly recommended.

Secondly, throughout the day various experiments with hollow fibre membranes with constant permeate flow rate were carried out. Instantaneous values for permeability were calculated automatically by dividing instantaneous values for permeate flow by membrane area and TMP. All the data were automatically filtered and hourly and daily average values were calculated every day at 00:01 by the system. The current evolution of permeability (slope of the daily values of the previous few days) was compared to a reference value (the mobile slope of a longer period). If the current value was below the reference value a favourable condition was detected and a reduction in the aeration flow was applied. The reduction was made proportional to the ratio of the current value divided by the reference value. A maximum energy saving of about 20% (which corresponds to minimum aeration) was established during the calibration phase of the control system. In Figure 6.12 the aeration saved by the automatic control can be appreciated and compared with the aeration requirements recommended by the membrane suppliers. It should be noted that a greater tendency to a decrease in permeability in the short term is associated with an increase in membrane aeration (days 93, 94, 95 and day 98, 99, 100) and that even in favourable conditions, aeration cannot be under the minimum aeration established (day 105 to 110). Around day 110 (phase 3) the pilot plant suffered a series of accidents related to the recycle pumps that led to an abrupt increase in MLSS concentration in the membrane tank and the consequent arrest of the filtration process for high TMP. An exact reconstruction of the facts behind this proved difficult due to a server fault. In period H the plant was operated under variable permeate fluxes and constant air-scour. Phase 4 is considered to begin on day 194 with the validation of the control system first working under variable permeate fluxes and then constant permeate flux. As previously mentioned, it has to be stressed that the operational conditions were different in phase 2 and phase 4 and influenced the results: the experimentation with constant flow rate was carried out in summer with a lower average normalised flux when compared with the variable permeate flow rate experimentation, which was carried out in winter.

Finally, it should also be pointed out that although the system developed was validated with satisfactory results at pilot scale with constant permeate flux, some faults were detected, such as a slow response to permeability changes. For example, from day 99 to day 111, permeability remained very stable, but aeration reached its minimum value on day 104 only. Therefore, further research needs to be carried out in order to achieve optimum performance. In particular, there is a need to identify short and long term optimal lengths and, ultimately, the best frequency with which to apply control actions (in this study daily, but perhaps more frequent control actions could be applied for variable permeate fluxes).

CHAPTER 7

DEVELOPMENT OF THE AIR-SCOUR CONTROL SYSTEM

7. Development of the air-scour control system

Based on the hypothesis of this thesis and knowledge acquisition, a system for air-scour control was developed as a fundamental part of a more ambitious and complex knowledge-based (KB) control system, which is explained in this chapter.

7.1 Architecture of the control system

The KB control system controls and supervises remotely the membrane filtration process. Figure 7.1 illustrates the multi-level architecture of the KB control system and the flow of information between the different levels: a lower level responsible for data acquisition and processing, a mid level in which the optimising control system is located and a higher level that supervises the control module on a knowledge basis.

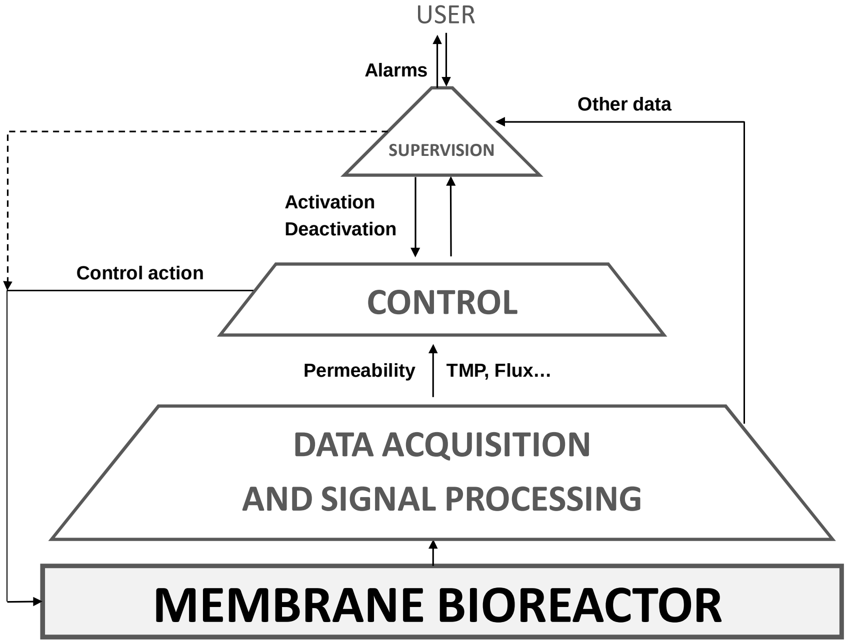


Figure 7.1. Multilevel structure of the control system.

The control system is accessible remotely via the web and allows the visualisation of all existing information, such as alarms, real-time data and stored databases. Moreover, it is also possible to change set points and modify parameters remotely.

7.2 Data acquisition and signal processing level

Signal filtering is essential for correctly identifying trends in control parameters by calculating median and average values. The presence of outliers could affect the reliability of the system and the comparison between different periods might be an issue. Hence, the user is warned when the permeate flow is zero for more than one filtration/relaxation (or backwash) cycle, and such values are excluded when calculating hourly and daily average values. The following signal processing approach is applied:

1) the values when the MBR is not permeating are eliminated (zeros and negative values)

2) a median for each cycle is calculated
3) the values that are a fixed percentage (i.e. 50%) above or below the median are excluded
4) an average for each cycle is calculated using the filtered values
5) hourly and daily average values are calculated using the average values per cycle

In Figure 7.2 an example of data filtering is shown; the filtered signal (blue dots) is the average per permeability cycle.

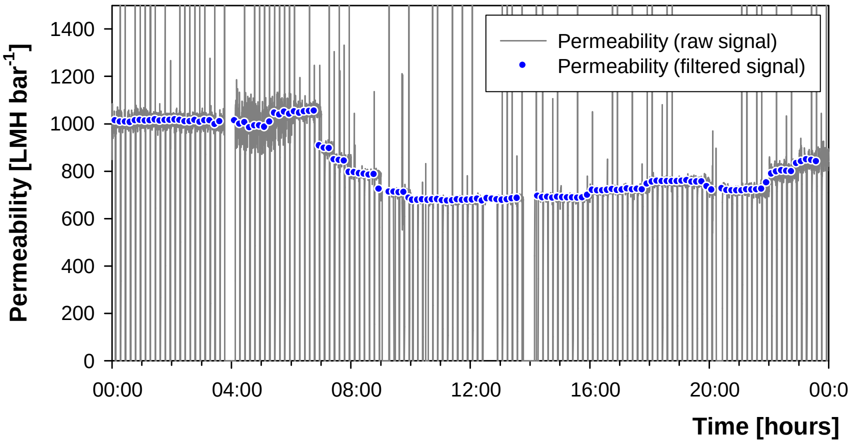


Figure 7.2. Raw and filtered data for on line permeability over 24 hours for a variable-flux MBR.

Automatic calculation of slopes has been chosen as the best solution to represent decreasing (or increasing) trends in the key parameters: permeability (K), flux (J) and TMP. Trends (slopes) are calculated daily using permeability average values.

7.3 Control level

The air-scour control algorithm (Figure 7.3) is one of the modules of a more complex multi-level control system (Ferrero *et al.*, 2011a, 2011b and 2011c) that includes, but is not limited to, start up, BNR, and operational problems. The aeration control system regulates the air-scour necessary for the physical cleaning of membranes using permeability trends as a control parameter.

$$K = \frac{J}{TMP} \qquad (1)$$

K = permeability [L m^{-2} h^{-1} bar^{-1}]

J = permeate flux [L m^{-2} h^{-1}]

TMP = transmembrane pressure [bar].

On-line raw signals and calculated values (K, J) are processed in real time and daily average values of permeability are calculated.

The algorithm is based on a comparison between a short term (or current) permeability slope $\left(\frac{dK}{dt}\right)_{ST}$ and a long term permeability slope $\left(\frac{dK}{dt}\right)_{LT}$.

A slope ratio (SR) is defined as the ratio of short term and long term permeability slopes:

$$SR = \frac{\left(\frac{dK}{dt}\right)_{ST}}{\left(\frac{dK}{dt}\right)_{LT}} \qquad (2)$$

when $\left(\frac{dK}{dt}\right)_{LT} < 0$, SR is compared to a set of reference values specified during the calibration phase, depending on different membrane characteristics and users' needs (i.e. users can define maximum and minimum aeration values and reduction). The aeration is regulated according to the current propensity of the membranes to fouling, and hence different control actions (in terms of aeration increase or reduction) are associated with each range of values (Table 7.1).

Table 7.1. Control actions corresponding to different slope ratios.

Slope ratio	Control action	Δ Blower frequency (Hz) Δ Air-scour flow ($m^3 \cdot h^{-1}$)
<0	↓	To be defined
0 – 0.3	↓	To be defined
0.3 – 0.6	↓	To be defined
0.6 – 0.9	↓	To be defined
0.9 – 1.1	↔	To be defined
1.1 – 1.4	↑	To be defined
1.4 – 1.7	↑	To be defined
1.7 – 2.0	↑	To be defined
>2	↑	To be defined

When $\left(\frac{dK}{dt}\right)_{LT} > 0$, which means that in the long term membrane permeability is improving, minor changes in aeration will depend only on a short term permeability slope:

- $\left(\frac{dK}{dt}\right)_{ST} > 0$ and $\left(\frac{dK}{dt}\right)_{LT} \leq \left(\frac{dK}{dt}\right)_{ST}$, maximum air-scour reduction can be applied;
- $\left(\frac{dK}{dt}\right)_{ST} > 0$ and $\left(\frac{dK}{dt}\right)_{LT} > \left(\frac{dK}{dt}\right)_{ST}$, moderate air-scour reduction can be applied (i.e. 50% of the maximum);
- $\left(\frac{dK}{dt}\right)_{ST} < 0$, a moderate aeration increase is applied.

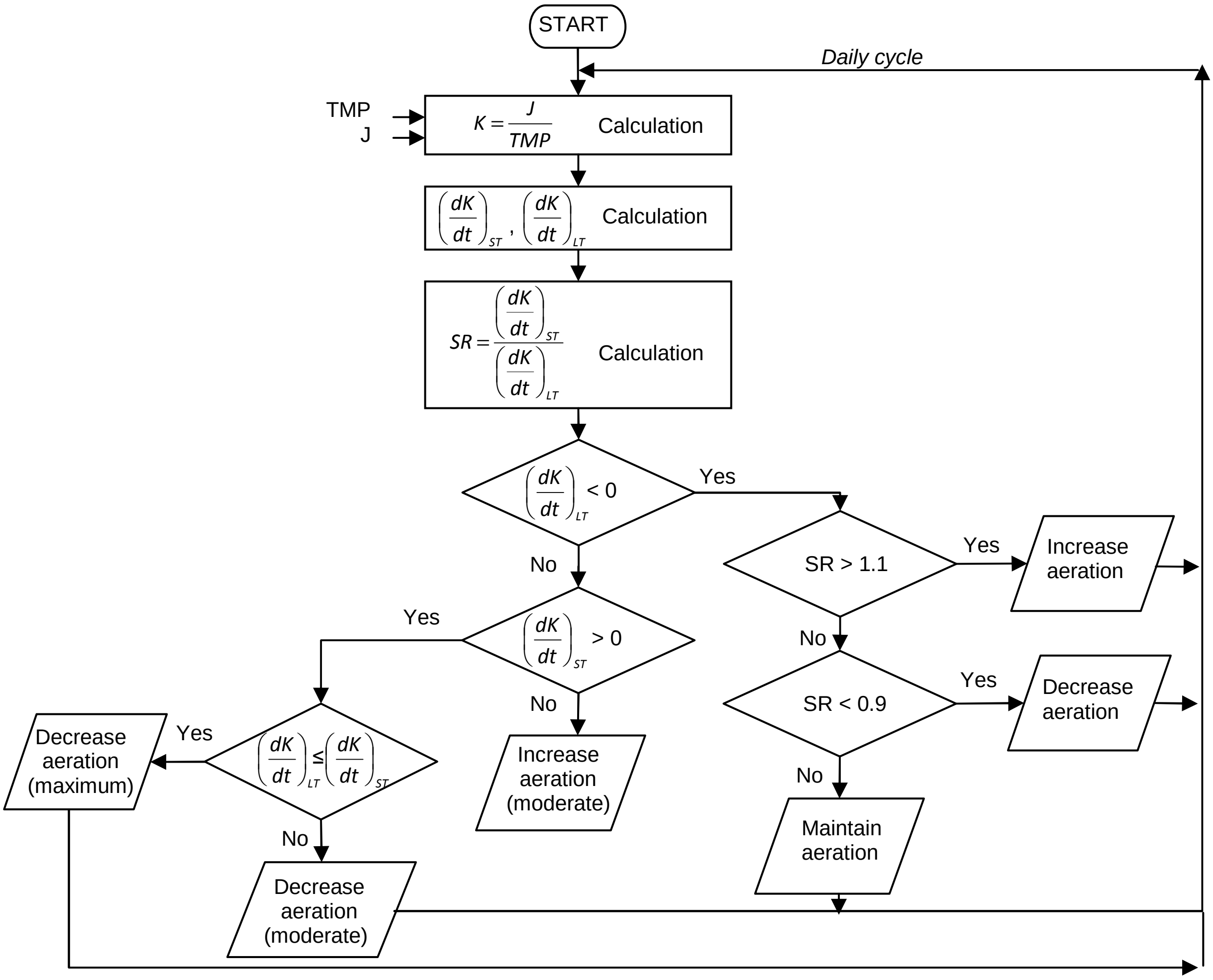


Figure 7.3. Decision tree for the aeration control algorithm.

7.4 Expert supervision level

The upper level automatically activates and deactivates the automatic control loop of the control level by means of several knowledge-based rules if abrupt changes in the key parameters of the biological system are detected (e.g. the concentration of mixed liquor suspended solids) or in case of failures or alarms related to sensors, equipment and control loops that can affect the current operation mode. These knowledge-based rules have been codified as a set of rule-based expert modules. A security rule is also established in order to prevent control actions being applied when the membrane is undergoing serious fouling. Therefore, when the daily permeability decrease is greater than 20% (the value can be modified by the user), the control action planned is not applied and an alarm is automatically sent to the user. To summarise, then, the aeration control is deactivated in cases of:

- Excessively low/high MLSS concentration
- Daily permeability decrease of >20%
- Mechanical failure

- On-line fouling rate $\left(\frac{dTMP}{dt}\right)$ per cycle >0.1 mbar·min^{-1} (Le-Clech *et al.*, 2003)

7.5 Discussion and future developments

Long term permeability trends are automatically compared to a short term (or reference) value, which varies daily, and control actions are automatically performed in order to reduce air-scour requirements and keep the filtration process performing well. The maximum and minimum air-scour flow can be set by the user, with the activation or deactivation of the air-scour control depending on the constant verification of a series of constraints, such as MLSS concentration, fouling rate and daily permeability loss.

The control algorithm was initially studied with membrane bioreactors operating with constant flux in mind, but the further development of a control system adapted to operation with daily variable fluxes is foreseen for the future. The control algorithm described here will be integrated with the proportional aeration concept (air-scour proportional to permeate flux) and air-scour will be increased during peak flows.

Currently being investigated is the addition of control rules based on different fouling characteristics (e.g. pore blocking, organic fouling, etc.) to regulate backwash flow and duration or acid/basic chemical cleanings.

In the case of MLSS concentration, on-line data were not available due to the absence of an MLSS probe. The data were integrated off-line with those proceeding from laboratory analysis in order that the energy optimisation control system could be automatically activated or deactivated. The influence of other parameters measured off-line, such as particle size distribution, EPS, SMP, etc., is also under study. If any significant correlation with membrane permeability is detected, such parameters will be integrated and new supervisory control rules added.

A full scale validation of the air-scour control system is currently being carried out at a full scale MBR in La Bisbal d'Empordà (Girona, Spain). The control system is undergoing open loop calibration and safety rules are under development which will complement the air-scour control algorithm. A closed loop validation will be implemented after iteratively increasing the set points of the maximum aeration reduction permitted. During the full scale validation, one of the two existing MBR trains in the facility will operate with 'standard conditions' and will be used as reference, while the other will be regulated by the proposed control system.

CHAPTER 8

IMPLEMENTATION OF THE AIR-SCOUR CONTROL SYSTEM

8. Implementation of the air-scour control system

The aim of this chapter is to describe the control system that was implemented from a programming point of view. The codification of the system is comprehensively explained and an overview of the web-based interface given.

8.1 Programming and codification

The knowledge-based control system described in section 7.1 is located hierarchically on top of the conventional supervisory control and data acquisition (SCADA) systems usually existing in WWTP. An Ole for process control (OPC) server was installed to enable communication with the PLC and SCADA (Figure 8.1). The language chosen for implementing the program was Java. The application was accessible on-line with a web application using an apache Tomcat web server and a database (MySQL). The PLC memory location was sent to the Java application through the OPC server and the Java application was responsible for data collection. All variables were saved in MySQL every ten seconds; at the same time, variables that were not directly available from the PLC (sensors or equipments) were calculated in real time and saved every ten seconds. Daily calculations were scheduled every 24 hours (usually at 00.05 A.M.), when 1) permeability and TMP daily average values were calculated, and 2) short and long term permeability slopes were calculated. Finally, the control system automatically checked if the control rules were activated and had executed the control rules described in Chapter 7.

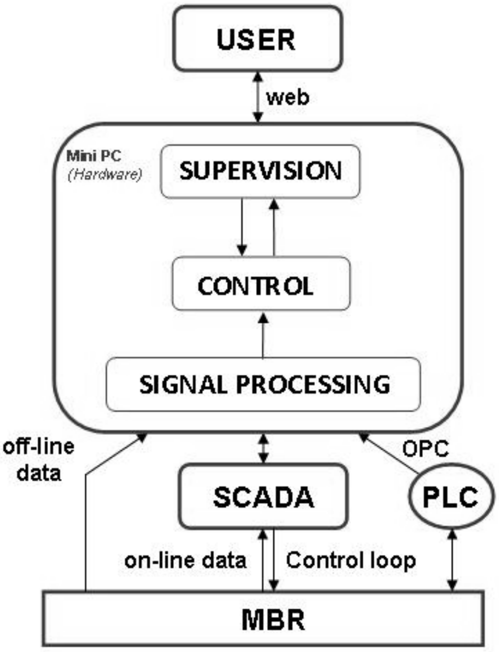
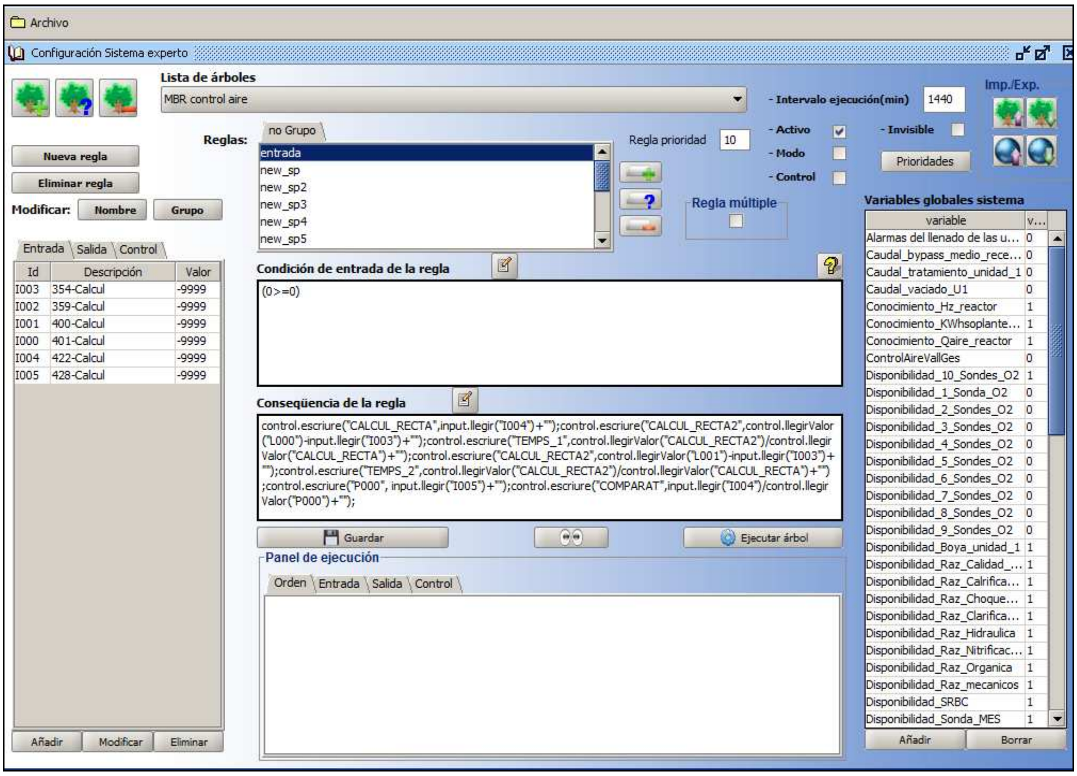


Figure 8.1. Control system architecture.

This chapter will only give details of the programming and codification of the control level (medium level of the Figure 7.1). The entry variables of the control system implemented were permeability, air blower frequency, short term and long term permeability slopes and short term and long term TMP slopes (Table 8.1 and Figure 8.2). The latter were not used for the control actions programmed, as permeability was selected as the key control parameter.

Table 8.1. Entry variables of the control system (Granollers pilot plant).

Id	Description/Type	Variable	Units
I003	354-Calcul	Permeability (K)	L m^{-2} $h^{-1}$$bar^{-1}$
I002	359-Calcul	Air blowers frequency	Hz
I001	400-Calcul	$\left(\frac{dTMP}{dt}\right)_4$	-
I000	401-Calcul	$\left(\frac{dTMP}{dt}\right)_{14}$	-
I004	422-Calcul	$\left(\frac{dK}{dt}\right)_4$	-
I005	428-Calcul	$\left(\frac{dK}{dt}\right)_{14}$	-



Lista de árboles: MBR control aire

- Intervalo ejecución(min): 1440

Regla prioridad: 10

- Activo ☑
- Modo ☐
- Control ☐
- Invisible ☐

Regla múltiple ☐

Reglas: no Grupo
- entrada
- new_sp
- new_sp2
- new_sp3
- new_sp4
- new_sp5

Entrada | Salida | Control

Id	Descripción	Valor
I003	354-Calcul	-9999
I002	359-Calcul	-9999
I001	400-Calcul	-9999
I000	401-Calcul	-9999
I004	422-Calcul	-9999
I005	428-Calcul	-9999

Condición de entrada de la regla

```
(0>=0)
```

Conseqüencia de la regla

```
control.escriure("CALCUL_RECTA",input.llegir("I004")+"");control.escriure("CALCUL_RECTA2",control.llegirValor
("L000")-input.llegir("I003")+"");control.escriure("TEMPS_1",control.llegirValor("CALCUL_RECTA2")/control.llegir
Valor("CALCUL_RECTA")+"");control.escriure("CALCUL_RECTA2",control.llegirValor("L001")-input.llegir("I003")+
"");control.escriure("TEMPS_2",control.llegirValor("CALCUL_RECTA2")/control.llegirValor("CALCUL_RECTA")+"")
;control.escriure("P000", input.llegir("I005")+"");control.escriure("COMPARAT",input.llegir("I004")/control.llegir
Valor("P000")+"");
```

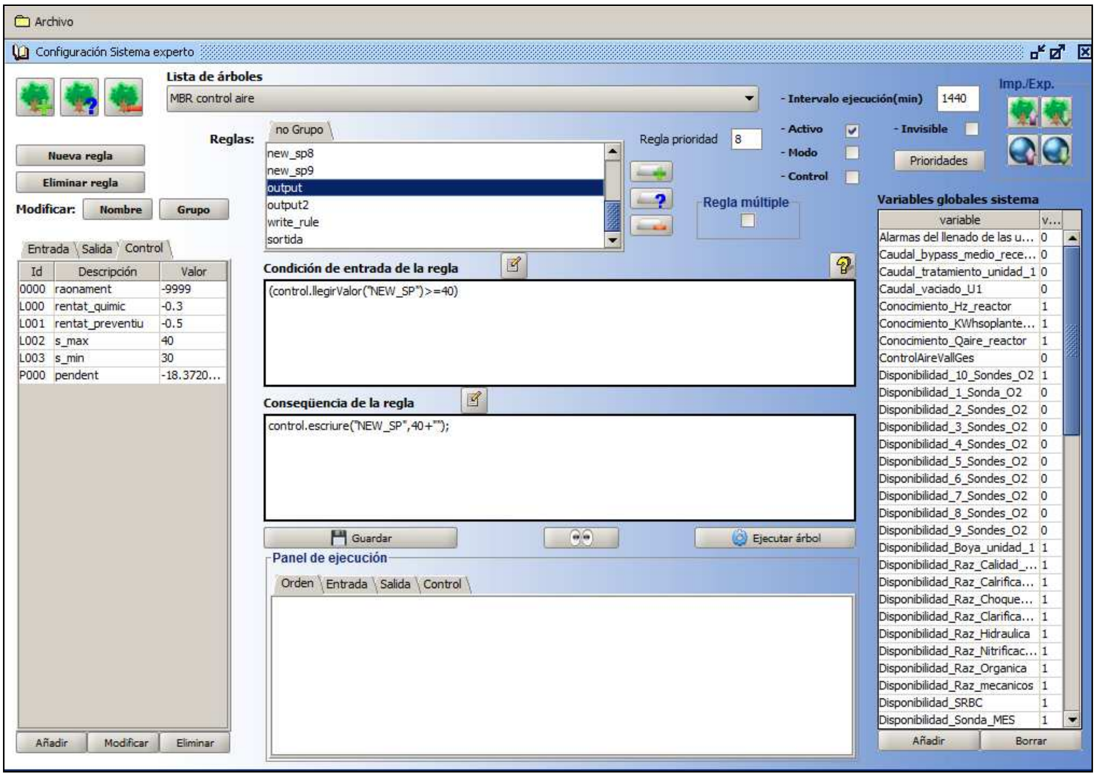
Variables globales sistema

variable	v...
Alarmas del llenado de las u...	0
Caudal_bypass_medio_rece...	0
Caudal_tratamiento_unidad_1	0
Caudal_vaciado_U1	0
Conocimiento_Hz_reactor	1
Conocimiento_KWhsoplante...	1
Conocimiento_Qaire_reactor	1
ControlAireVallGes	0
Disponibilidad_10_Sondes_O2	1
Disponibilidad_1_Sonda_O2	0
Disponibilidad_2_Sondes_O2	0
Disponibilidad_3_Sondes_O2	0
Disponibilidad_4_Sondes_O2	0
Disponibilidad_5_Sondes_O2	0
Disponibilidad_6_Sondes_O2	0
Disponibilidad_7_Sondes_O2	0
Disponibilidad_8_Sondes_O2	0
Disponibilidad_9_Sondes_O2	0
Disponibilidad_Boya_unidad_1	1
Disponibilidad_Raz_Calidad_...	1
Disponibilidad_Raz_Calrifica...	1
Disponibilidad_Raz_Choque...	1
Disponibilidad_Raz_Clarifica...	1
Disponibilidad_Raz_Hidraulica	1
Disponibilidad_Raz_Nitrificac...	1
Disponibilidad_Raz_Organica	1
Disponibilidad_Raz_mecanicos	1
Disponibilidad_SRBC	1
Disponibilidad_Sonda_MES	1

Figure 8.2. Control system screen shot: entry variables (left) and rule condition/consequence panels (centre).

Figure 8.3 is a screen shot of the control variables (left side), where s_max and s_min correspond to the maximum and minimum set points for membrane aeration (in terms of blower frequency). They were set by the user and could be modified during the operation/calibration phases.

After checking the maximum and minimum aeration set points, the control compared the slope ratio (SR) to a set of reference values; different control actions correspond to different ranges of SR. In Figure 8.4 “COMPARAT” represents the SR calculated as the ratio of the permeability slope of the previous four days divided by the permeability slope of the previous 14 days; the control action was saved as a new variable, “NEW_SP”, which was the new aeration set point after applying the control action (aeration increase or decrease). For example, in Figure 8.4, if 0.9 < "COMPARAT" ≤ 1.1 , the new set point will be the input value "I002" (previous day's value) plus zero (0), because the control action associated with the range is maintaining the aeration set point.



Lista de árboles: MBR control aire

- Intervalo ejecución(min): 1440

Reglas: new_sp8, new_sp9, output, output2, write_rule, sortida

Regla prioridad: 8

- Activo ☑
- Modo ☐
- Control ☐
- Invisible ☐

Id	Descripción	Valor
0000	raonament	-9999
L000	rentat_quimic	-0.3
L001	rentat_preventiu	-0.5
L002	s_max	40
L003	s_min	30
P000	pendent	-18.3720...

Condición de entrada de la regla

```
(control.llegirValor("NEW_SP")>=40)
```

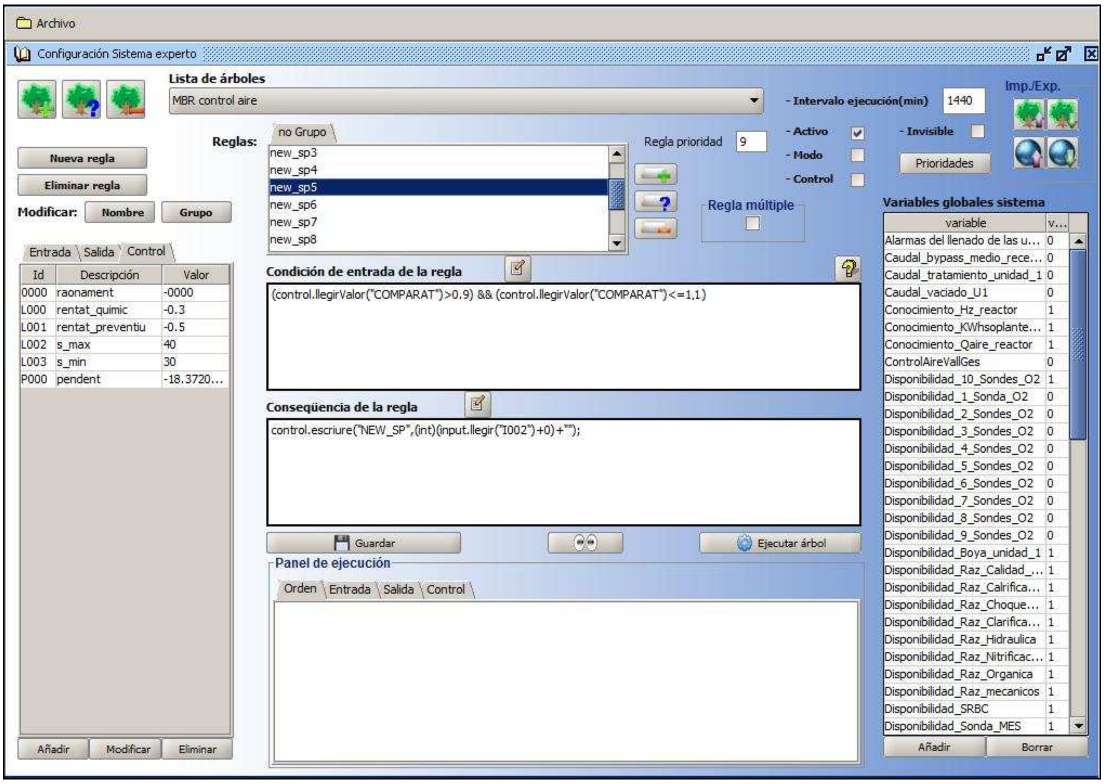
Conseqüencia de la regla

```
control.escriure("NEW_SP",40+"");
```

Variables globales sistema

variable	v...
Alarmas del llenado de las u...	0
Caudal_bypass_medio_rece...	0
Caudal_tratamiento_unidad_1	0
Caudal_vaciado_U1	0
Conocimiento_Hz_reactor	1
Conocimiento_KWhsoplante...	1
Conocimiento_Qaire_reactor	1
ControlAireVallGes	0
Disponibilidad_10_Sondes_O2	1
Disponibilidad_1_Sonda_O2	0
Disponibilidad_2_Sondes_O2	0
Disponibilidad_3_Sondes_O2	0
Disponibilidad_4_Sondes_O2	0
Disponibilidad_5_Sondes_O2	0
Disponibilidad_6_Sondes_O2	0
Disponibilidad_7_Sondes_O2	0
Disponibilidad_8_Sondes_O2	0
Disponibilidad_9_Sondes_O2	0
Disponibilidad_Boya_unidad_1	1
Disponibilidad_Raz_Calidad_...	1
Disponibilidad_Raz_Calrifica...	1
Disponibilidad_Raz_Choque...	1
Disponibilidad_Raz_Clarifica...	1
Disponibilidad_Raz_Hidraulica	1
Disponibilidad_Raz_Nitrificac...	1
Disponibilidad_Raz_Organica	1
Disponibilidad_Raz_mecanicos	1
Disponibilidad_SRBC	1
Disponibilidad_Sonda_MES	1

Figure 8.3. Control system screen shot: control variables (left) and rule condition/consequence panels (centre).



Lista de árboles: MBR control aire

- Intervalo ejecución(min): 1440

Reglas: new_sp3, new_sp4, new_sp5, new_sp6, new_sp7, new_sp8

Regla prioridad: 9

- Activo ☑
- Modo ☐
- Control ☐
- Invisible ☐

Id	Descripción	Valor
0000	raonament	-0000
L000	rentat_quimic	-0.3
L001	rentat_preventiu	-0.5
L002	s_max	40
L003	s_min	30
P000	pendent	-18.3720...

Condición de entrada de la regla

```
(control.llegirValor("COMPARAT")>0.9) && (control.llegirValor("COMPARAT")<=1,1)
```

Conseqüencia de la regla

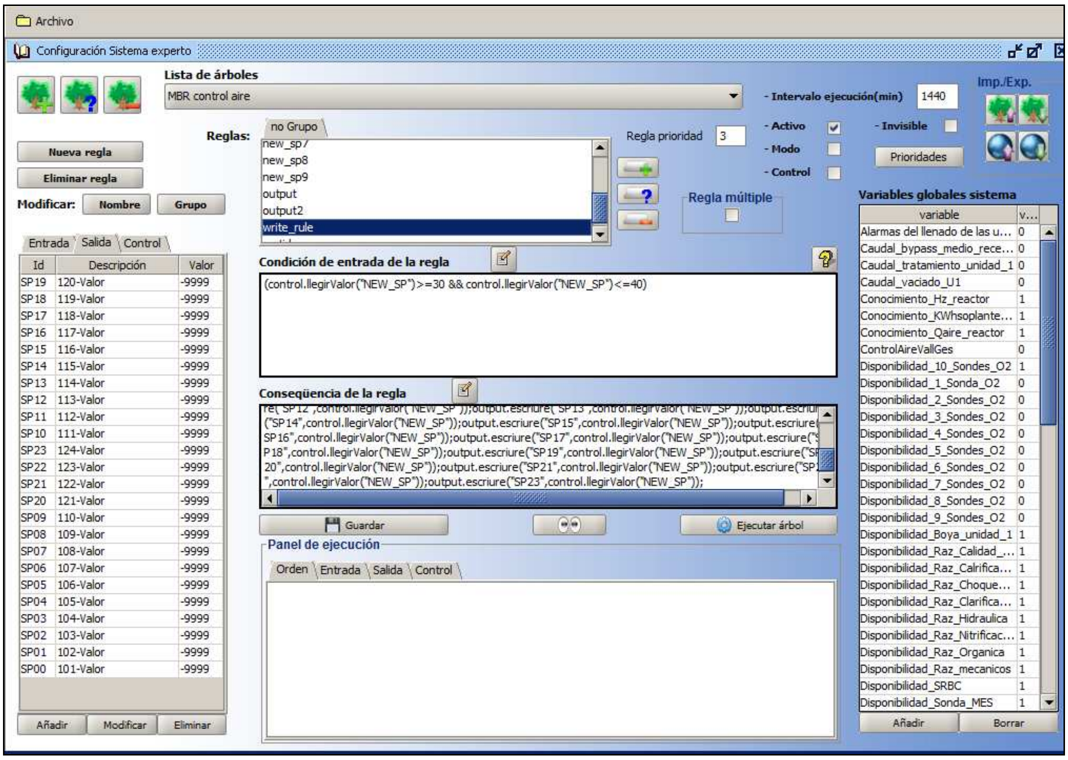
```
control.escriure("NEW_SP",(int)(input.llegir("I002")+0)+"");
```

Variables globales sistema

variable	v...
Alarmas del llenado de las u...	0
Caudal_bypass_medio_rece...	0
Caudal_tratamiento_unidad_1	0
Caudal_vaciado_U1	0
Conocimiento_Hz_reactor	1
Conocimiento_KWhsoplante...	1
Conocimiento_Qaire_reactor	1
ControlAireVallGes	0
Disponibilidad_10_Sondes_O2	1
Disponibilidad_1_Sonda_O2	0
Disponibilidad_2_Sondes_O2	0
Disponibilidad_3_Sondes_O2	0
Disponibilidad_4_Sondes_O2	0
Disponibilidad_5_Sondes_O2	0
Disponibilidad_6_Sondes_O2	0
Disponibilidad_7_Sondes_O2	0
Disponibilidad_8_Sondes_O2	0
Disponibilidad_9_Sondes_O2	0
Disponibilidad_Boya_unidad_1	1
Disponibilidad_Raz_Calidad_...	1
Disponibilidad_Raz_Calrifica...	1
Disponibilidad_Raz_Choque...	1
Disponibilidad_Raz_Clarifica...	1
Disponibilidad_Raz_Hidraulica	1
Disponibilidad_Raz_Nitrificac...	1
Disponibilidad_Raz_Organica	1
Disponibilidad_Raz_mecanicos	1
Disponibilidad_SRBC	1
Disponibilidad_Sonda_MES	1

Figure 8.4. Control system screen shot: control variables (left) and rule condition/consequence panels (centre).

In Figure 8.5 the output variables can be observed on the left side. There are 24 set points, one for each hour of the day. The new aeration set point “NEW_SP” was assigned to the entire set of output variables, but previously the new set point had been double checked to see that it was within the maximum and minimum permitted. Finally, the text that would appear on-line through the web-based interface was automatically created (Figure 8.6).



Lista de árboles: MBR control aire

- Intervalo ejecución(min): 1440
- Activo ☑
- Invisible ☐
- Modo ☐
- Control ☐

Reglas: no Grupo
new_sp7
new_sp8
new_sp9
output
output2
write_rule

Regla prioridad: 3

Regla múltiple ☐

Condición de entrada de la regla

```
(control.llegirValor("NEW_SP")>=30 && control.llegirValor("NEW_SP")<=40)
```

Conseqüencia de la regla

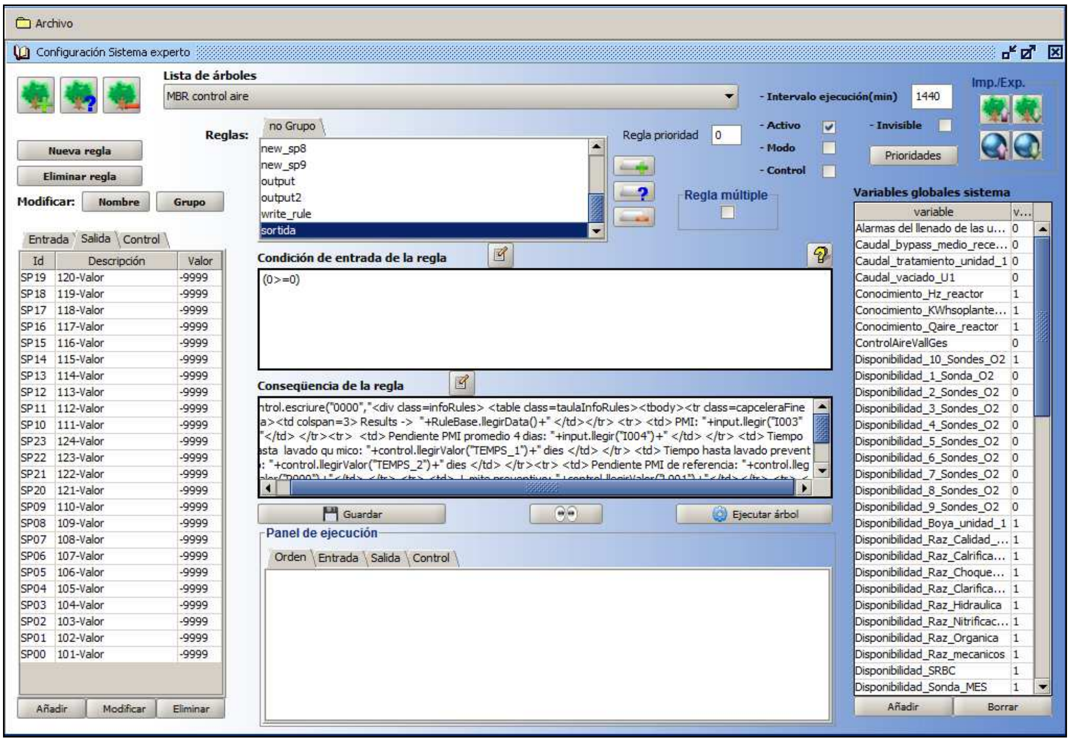
```
re("SP12",control.llegirValor("NEW_SP"));output.escriure("SP13",control.llegirValor("NEW_SP"));output.escriu
("SP14",control.llegirValor("NEW_SP"));output.escriure("SP15",control.llegirValor("NEW_SP"));output.escriure(
SP16",control.llegirValor("NEW_SP"));output.escriure("SP17",control.llegirValor("NEW_SP"));output.escriure("
P18",control.llegirValor("NEW_SP"));output.escriure("SP19",control.llegirValor("NEW_SP"));output.escriure("SP
20",control.llegirValor("NEW_SP"));output.escriure("SP21",control.llegirValor("NEW_SP"));output.escriure("SP2
",control.llegirValor("NEW_SP"));output.escriure("SP23",control.llegirValor("NEW_SP"));
```

Id	Descripción	Valor
SP19	120-Valor	-9999
SP18	119-Valor	-9999
SP17	118-Valor	-9999
SP16	117-Valor	-9999
SP15	116-Valor	-9999
SP14	115-Valor	-9999
SP13	114-Valor	-9999
SP12	113-Valor	-9999
SP11	112-Valor	-9999
SP10	111-Valor	-9999
SP23	124-Valor	-9999
SP22	123-Valor	-9999
SP21	122-Valor	-9999
SP20	121-Valor	-9999
SP09	110-Valor	-9999
SP08	109-Valor	-9999
SP07	108-Valor	-9999
SP06	107-Valor	-9999
SP05	106-Valor	-9999
SP04	105-Valor	-9999
SP03	104-Valor	-9999
SP02	103-Valor	-9999
SP01	102-Valor	-9999
SP00	101-Valor	-9999

Variables globales sistema

variable	v...
Alarmas del llenado de las u...	0
Caudal_bypass_medio_rece...	0
Caudal_tratamiento_unidad_1	0
Caudal_vaciado_U1	0
Conocimiento_Hz_reactor	1
Conocimiento_KWhsoplante...	1
Conocimiento_Qaire_reactor	1
ControlAireVallGes	0
Disponibilidad_10_Sondes_O2	1
Disponibilidad_1_Sonda_O2	0
Disponibilidad_2_Sondes_O2	0
Disponibilidad_3_Sondes_O2	0
Disponibilidad_4_Sondes_O2	0
Disponibilidad_5_Sondes_O2	0
Disponibilidad_6_Sondes_O2	0
Disponibilidad_7_Sondes_O2	0
Disponibilidad_8_Sondes_O2	0
Disponibilidad_9_Sondes_O2	0
Disponibilidad_Boya_unidad_1	1
Disponibilidad_Raz_Calidad_...	1
Disponibilidad_Raz_Calrifica...	1
Disponibilidad_Raz_Choque...	1
Disponibilidad_Raz_Clarifica...	1
Disponibilidad_Raz_Hidraulica	1
Disponibilidad_Raz_Nitrificac...	1
Disponibilidad_Raz_Organica	1
Disponibilidad_Raz_mecanicos	1
Disponibilidad_SRBC	1
Disponibilidad_Sonda_MES	1

Figure 8.5. Control system screen shot: output variables (left) and rule condition/consequence panels (centre).



Lista de árboles: MBR control aire

- Intervalo ejecución(min): 1440
- Activo ☑
- Invisible ☐
- Modo ☐
- Control ☐

Reglas: no Grupo
new_sp8
new_sp9
output
output2
write_rule
sortida

Regla prioridad: 0

Regla múltiple ☐

Condición de entrada de la regla

```
(0>=0)
```

Conseqüencia de la regla

```
ntrol.escriure("0000","<div class=infoRules> <table class=taulaInfoRules><tbody><tr class=capceleraFine
a><td colspan=3> Results ->  "+RuleBase.llegirData()+" </td></tr> <tr> <td> PMI: "+input.llegir("I003"
"</td> </tr><tr>  <td> Pendiente PMI promedio 4 dias: "+input.llegir("I004")+" </td> </tr> <td> Tiempo
asta  lavado qu mico: "+control.llegirValor("TEMPS_1")+" dies </td> </tr> <td> Tiempo hasta lavado prevent
: "+control.llegirValor("TEMPS_2")+" dies </td> </tr><tr> <td> Pendiente PMI de referencia: "+control.lleg
```

Id	Descripción	Valor
SP19	120-Valor	-9999
SP18	119-Valor	-9999
SP17	118-Valor	-9999
SP16	117-Valor	-9999
SP15	116-Valor	-9999
SP14	115-Valor	-9999
SP13	114-Valor	-9999
SP12	113-Valor	-9999
SP11	112-Valor	-9999
SP10	111-Valor	-9999
SP23	124-Valor	-9999
SP22	123-Valor	-9999
SP21	122-Valor	-9999
SP20	121-Valor	-9999
SP09	110-Valor	-9999
SP08	109-Valor	-9999
SP07	108-Valor	-9999
SP06	107-Valor	-9999
SP05	106-Valor	-9999
SP04	105-Valor	-9999
SP03	104-Valor	-9999
SP02	103-Valor	-9999
SP01	102-Valor	-9999
SP00	101-Valor	-9999

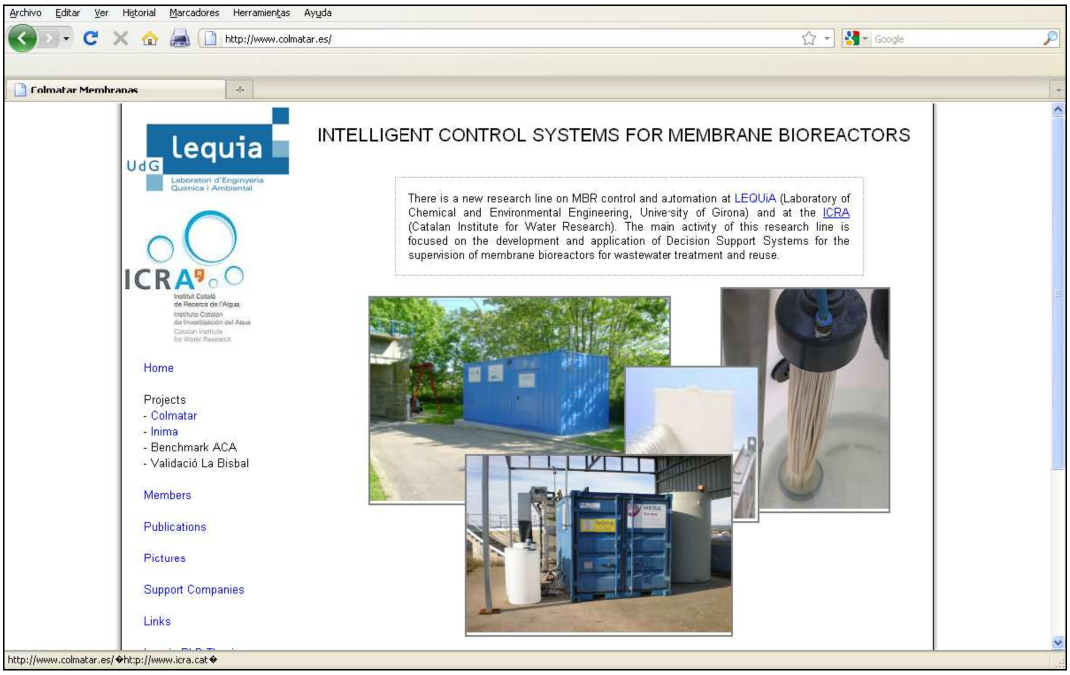
Variables globales sistema

variable	v...
Alarmas del llenado de las u...	0
Caudal_bypass_medio_rece...	0
Caudal_tratamiento_unidad_1	0
Caudal_vaciado_U1	0
Conocimiento_Hz_reactor	1
Conocimiento_KWhsoplante...	1
Conocimiento_Qaire_reactor	1
ControlAireVallGes	0
Disponibilidad_10_Sondes_O2	1
Disponibilidad_1_Sonda_O2	0
Disponibilidad_2_Sondes_O2	0
Disponibilidad_3_Sondes_O2	0
Disponibilidad_4_Sondes_O2	0
Disponibilidad_5_Sondes_O2	0
Disponibilidad_6_Sondes_O2	0
Disponibilidad_7_Sondes_O2	0
Disponibilidad_8_Sondes_O2	0
Disponibilidad_9_Sondes_O2	0
Disponibilidad_Boya_unidad_1	1
Disponibilidad_Raz_Calidad_...	1
Disponibilidad_Raz_Calrifica...	1
Disponibilidad_Raz_Choque...	1
Disponibilidad_Raz_Clarifica...	1
Disponibilidad_Raz_Hidraulica	1
Disponibilidad_Raz_Nitrificac...	1
Disponibilidad_Raz_Organica	1
Disponibilidad_Raz_mecanicos	1
Disponibilidad_SRBC	1
Disponibilidad_Sonda_MES	1

Figure 8.6. Control system screen shot: output variables (left) and rule condition/consequence panels (centre).

8.2 Web-based interface

The web interface was designed to allow any (registered) user to remotely access all the MBR pilot plants run by LEQUiA (UdG), to view on-line data, to download historical data and to remotely actuate the pilot plants.



INTELLIGENT CONTROL SYSTEMS FOR MEMBRANE BIOREACTORS

There is a new research line on MBR control and automation at LEQUiA (Laboratory of Chemical and Environmental Engineering, University of Girona) and at the ICRA (Catalan Institute for Water Research). The main activity of this research line is focused on the development and application of Decision Support Systems for the supervision of membrane bioreactors for wastewater treatment and reuse.

Home

Projects
- Colmatar
- Inima
- Benchmark ACA
- Validació La Bisbal

Members

Publications

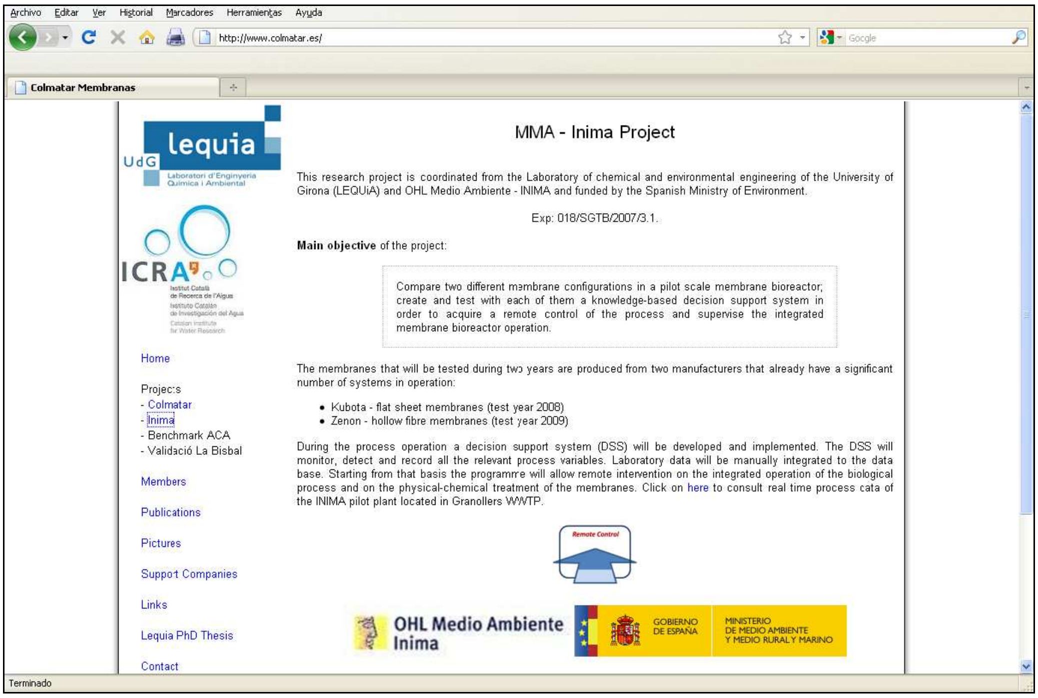
Pictures

Support Companies

Links

Figure 8.7. Home page: *www.colmatar.es*.

By following the link on the left side of the home page (Figure 8.7), it was possible to enter the page devoted to the project, which was funded by the Spanish Ministry of the Environment (MMA) and carried out in collaboration with OHL-Medio Ambiente INIMA S.A.U. (Figure 8.8).



MMA - Inima Project

This research project is coordinated from the Laboratory of chemical and environmental engineering of the University of Girona (LEQUiA) and OHL Medio Ambiente - INIMA and funded by the Spanish Ministry of Environment.

Exp: 018/SGTB/2007/3.1.

Main objective of the project:

Compare two different membrane configurations in a pilot scale membrane bioreactor; create and test with each of them a knowledge-based decision support system in order to acquire a remote control of the process and supervise the integrated membrane bioreactor operation.

The membranes that will be tested during two years are produced from two manufacturers that already have a significant number of systems in operation:

- Kubota - flat sheet membranes (test year 2008)
- Zenon - hollow fibre membranes (test year 2009)

During the process operation a decision support system (DSS) will be developed and implemented. The DSS will monitor, detect and record all the relevant process variables. Laboratory data will be manually integrated to the data base. Starting from that basis the programme will allow remote intervention on the integrated operation of the biological process and on the physical-chemical treatment of the membranes. Click on here to consult real time process data of the INIMA pilot plant located in Granollers WWTP.

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- Inima
- Benchmark ACA
- Validació La Bisbal

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Support Companies

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Lequia PhD Thesis

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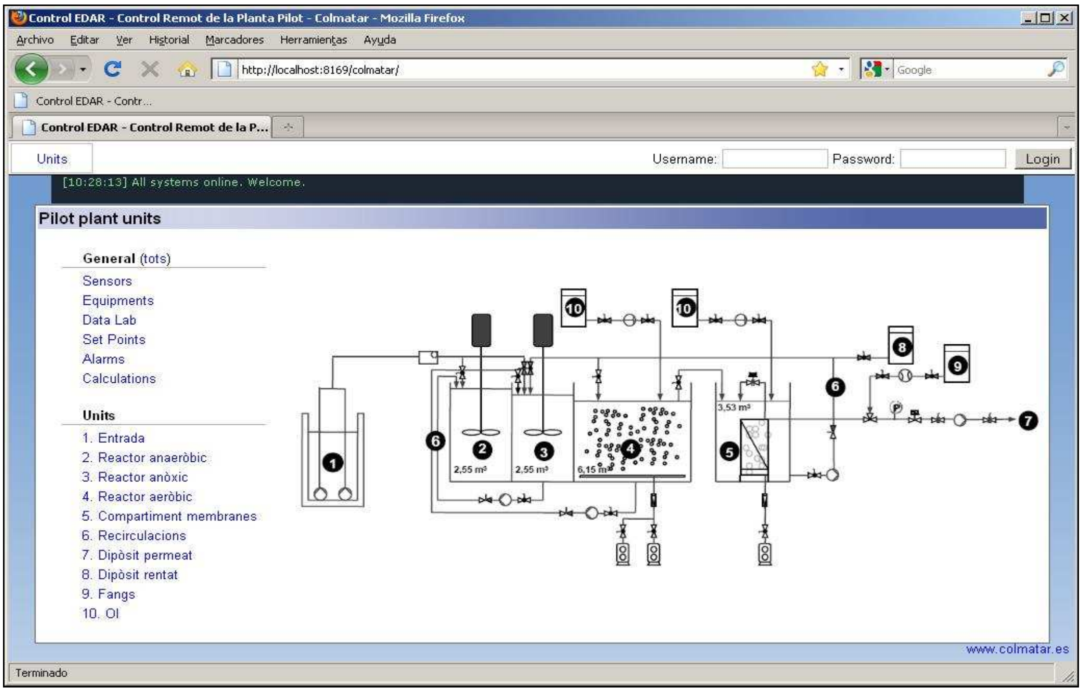
Figure 8.8. The Inima Project web page.

Clicking on the arrow at the bottom of the page would open the remote control of the pilot plant (Figure 8.9). It was then possible to observe the pilot plant scheme and access the restricted area with username and password.

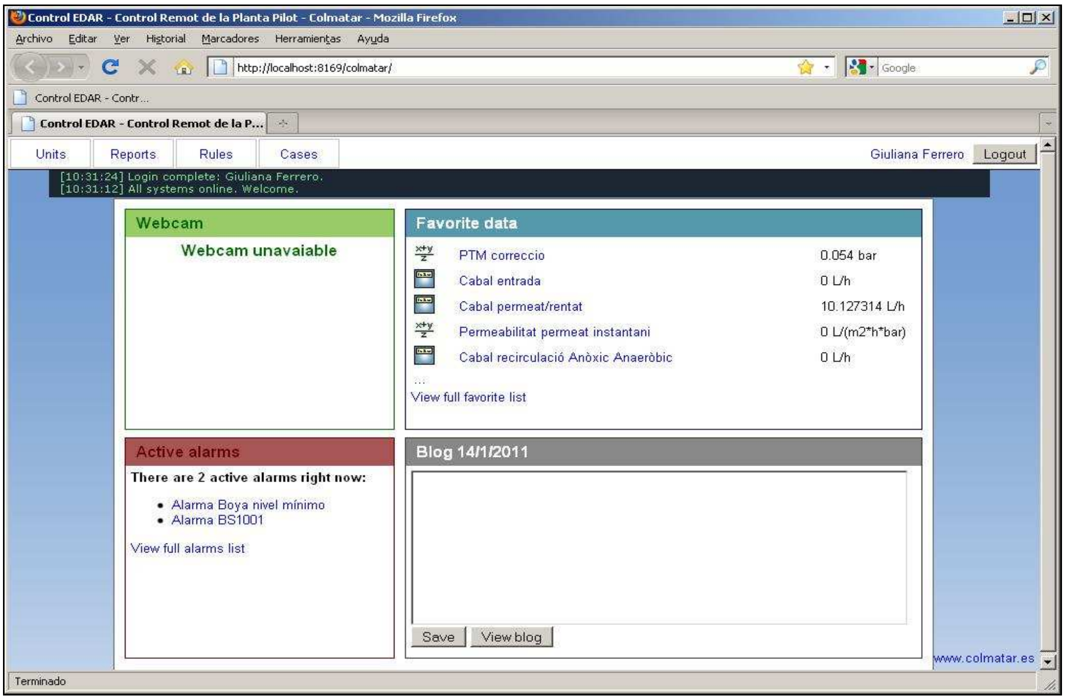


[10:28:13] All systems online. Welcome.

Pilot plant units

Figure 8.9. Pilot plant remote control system.

The main user personal page (Figure 8.10) contained a list of favourite variables (Figure 8.11) and active alarms. A blog where all the users could write comments, and in particular note down the manual control actions taken, was also available, as was an on-line view of the pilot plant.



[10:31:24] Login complete: Giuliana Ferrero.
[10:31:12] All systems online. Welcome.

Webcam unavaiable

PTM correccio	0.054 bar
Cabal entrada	0 L/h
Cabal permeat/rentat	10.127314 L/h
Permeabilitat permeat instantani	0 L/(m2*h*bar)
Cabal recirculació Anòxic Anaeròbic	0 L/h

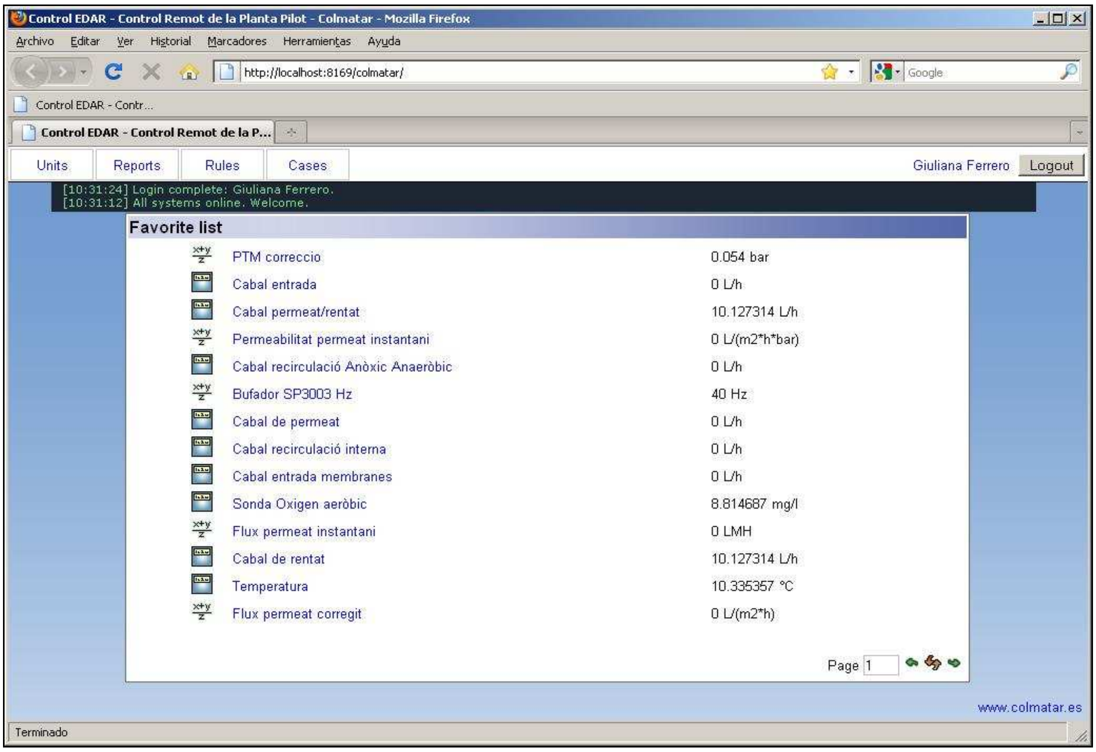
...
View full favorite list

There are 2 active alarms right now:

- Alarma Boya nivel mínimo
- Alarma BS1001

View full alarms list

Figure 8.10. Home page of the remote control.



```
[10:31:24] Login complete: Giuliana Ferrero.
[10:31:12] All systems online. Welcome.
```

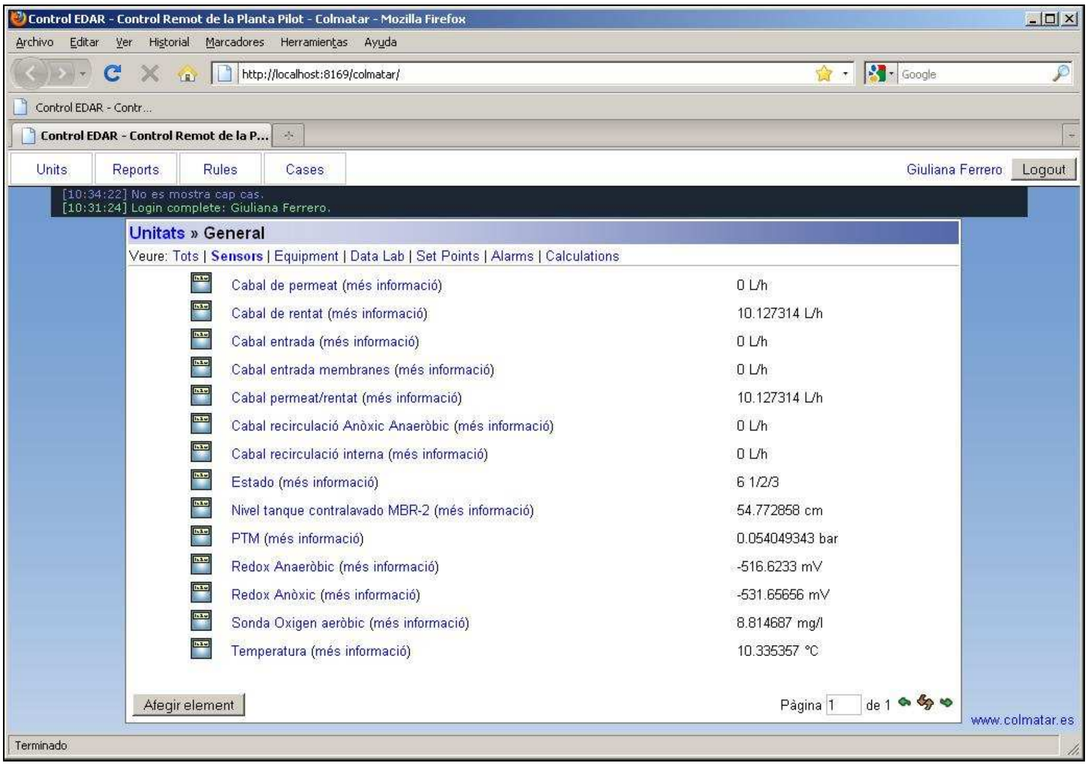
Favorite list

PTM correccio	0.054 bar
Cabal entrada	0 L/h
Cabal permeat/rentat	10.127314 L/h
Permeabilitat permeat instantani	0 L/(m2*h*bar)
Cabal recirculació Anòxic Anaeròbic	0 L/h
Bufador SP3003 Hz	40 Hz
Cabal de permeat	0 L/h
Cabal recirculació interna	0 L/h
Cabal entrada membranes	0 L/h
Sonda Oxigen aeròbic	8.814687 mg/l
Flux permeat instantani	0 LMH
Cabal de rentat	10.127314 L/h
Temperatura	10.335357 °C
Flux permeat corregit	0 L/(m2*h)

Page 1

Figure 8.11. List of favourite variables.

Once in the personal space it was possible to view on-line all existing data, from sensors such as temperature and flow meters (Figure 8.12), to the current state of the equipment (Figure 8.13), set points (Figure 8.14) and alarms (Figure 8.15).



```
[10:34:22] No es mostra cap cas.
[10:31:24] Login complete: Giuliana Ferrero.
```

Unitats » General

Veure: Tots | **Sensors** | Equipment | Data Lab | Set Points | Alarms | Calculations

Cabal de permeat (més informació)	0 L/h
Cabal de rentat (més informació)	10.127314 L/h
Cabal entrada (més informació)	0 L/h
Cabal entrada membranes (més informació)	0 L/h
Cabal permeat/rentat (més informació)	10.127314 L/h
Cabal recirculació Anòxic Anaeròbic (més informació)	0 L/h
Cabal recirculació interna (més informació)	0 L/h
Estado (més informació)	6 1/2/3
Nivel tanque contralavado MBR-2 (més informació)	54.772858 cm
PTM (més informació)	0.054049343 bar
Redox Anaeròbic (més informació)	-516.6233 mV
Redox Anòxic (més informació)	-531.65656 mV
Sonda Oxigen aeròbic (més informació)	8.814687 mg/l
Temperatura (més informació)	10.335357 °C

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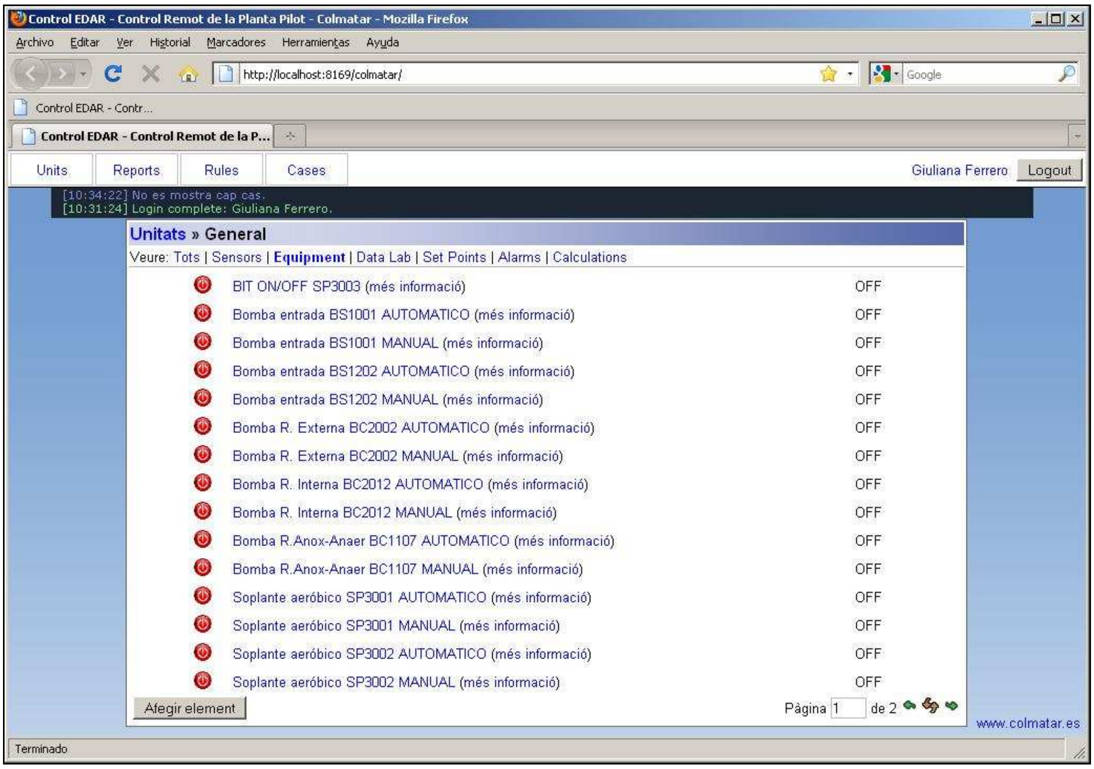
Figure 8.12. List of sensors.



[10:34:22] No es mostra cap cas.
[10:31:24] Login complete: Giuliana Ferrero.

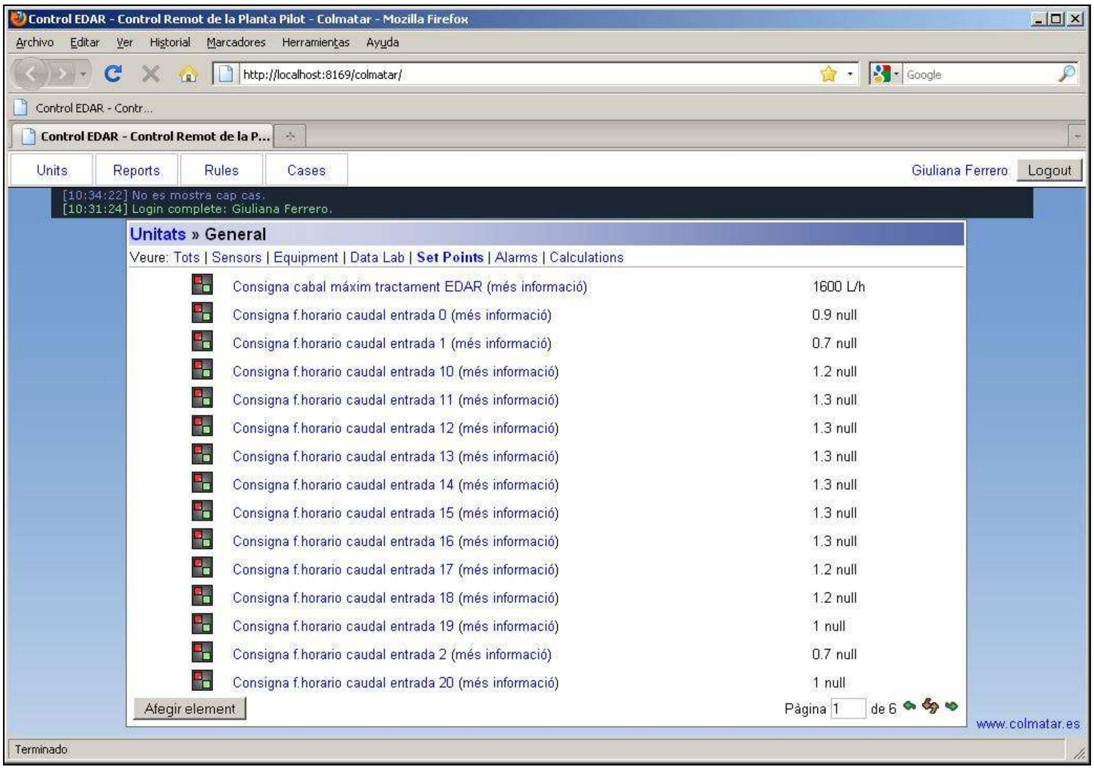
Unitats » General

Veure: Tots | Sensors | **Equipment** | Data Lab | Set Points | Alarms | Calculations

BIT ON/OFF SP3003 (més informació)	OFF
Bomba entrada BS1001 AUTOMATICO (més informació)	OFF
Bomba entrada BS1001 MANUAL (més informació)	OFF
Bomba entrada BS1202 AUTOMATICO (més informació)	OFF
Bomba entrada BS1202 MANUAL (més informació)	OFF
Bomba R. Externa BC2002 AUTOMATICO (més informació)	OFF
Bomba R. Externa BC2002 MANUAL (més informació)	OFF
Bomba R. Interna BC2012 AUTOMATICO (més informació)	OFF
Bomba R. Interna BC2012 MANUAL (més informació)	OFF
Bomba R.Anox-Anaer BC1107 AUTOMATICO (més informació)	OFF
Bomba R.Anox-Anaer BC1107 MANUAL (més informació)	OFF
Soplante aeróbico SP3001 AUTOMATICO (més informació)	OFF
Soplante aeróbico SP3001 MANUAL (més informació)	OFF
Soplante aeróbico SP3002 AUTOMATICO (més informació)	OFF
Soplante aeróbico SP3002 MANUAL (més informació)	OFF

Figure 8.13. List of equipment (on/off, automatic/manual).

All the users with administrator rights were able to directly take actions with respect to the pilot plant by changing set points or, for example, the function modes of specific equipment from automatic to manual.



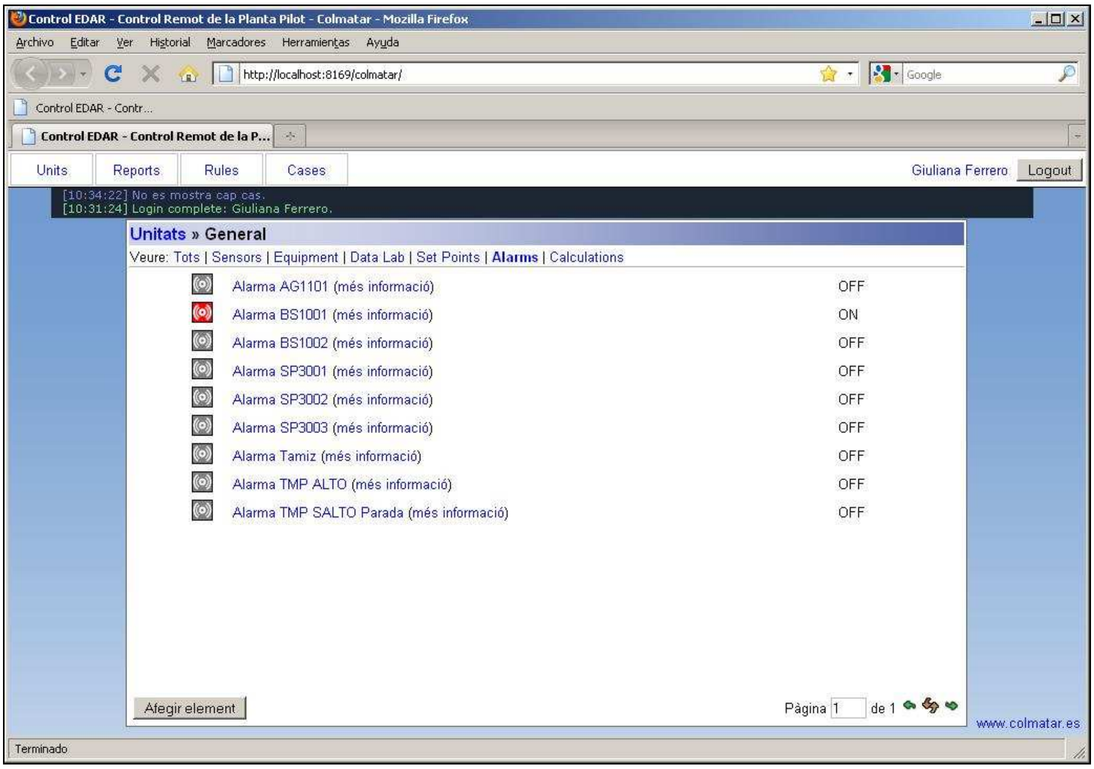
[10:34:22] No es mostra cap cas.
[10:31:24] Login complete: Giuliana Ferrero.

Unitats » General

Veure: Tots | Sensors | Equipment | Data Lab | **Set Points** | Alarms | Calculations

Consigna cabal màxim tractament EDAR (més informació)	1600 L/h
Consigna f.horario caudal entrada 0 (més informació)	0.9 null
Consigna f.horario caudal entrada 1 (més informació)	0.7 null
Consigna f.horario caudal entrada 10 (més informació)	1.2 null
Consigna f.horario caudal entrada 11 (més informació)	1.3 null
Consigna f.horario caudal entrada 12 (més informació)	1.3 null
Consigna f.horario caudal entrada 13 (més informació)	1.3 null
Consigna f.horario caudal entrada 14 (més informació)	1.3 null
Consigna f.horario caudal entrada 15 (més informació)	1.3 null
Consigna f.horario caudal entrada 16 (més informació)	1.3 null
Consigna f.horario caudal entrada 17 (més informació)	1.2 null
Consigna f.horario caudal entrada 18 (més informació)	1.2 null
Consigna f.horario caudal entrada 19 (més informació)	1 null
Consigna f.horario caudal entrada 2 (més informació)	0.7 null
Consigna f.horario caudal entrada 20 (més informació)	1 null

Figure 8.14. List of favourite variables.



```
[10:34:22] No es mostra cap cas.
[10:31:24] Login complete: Giuliana Ferrero.
```

Unitats » **General**

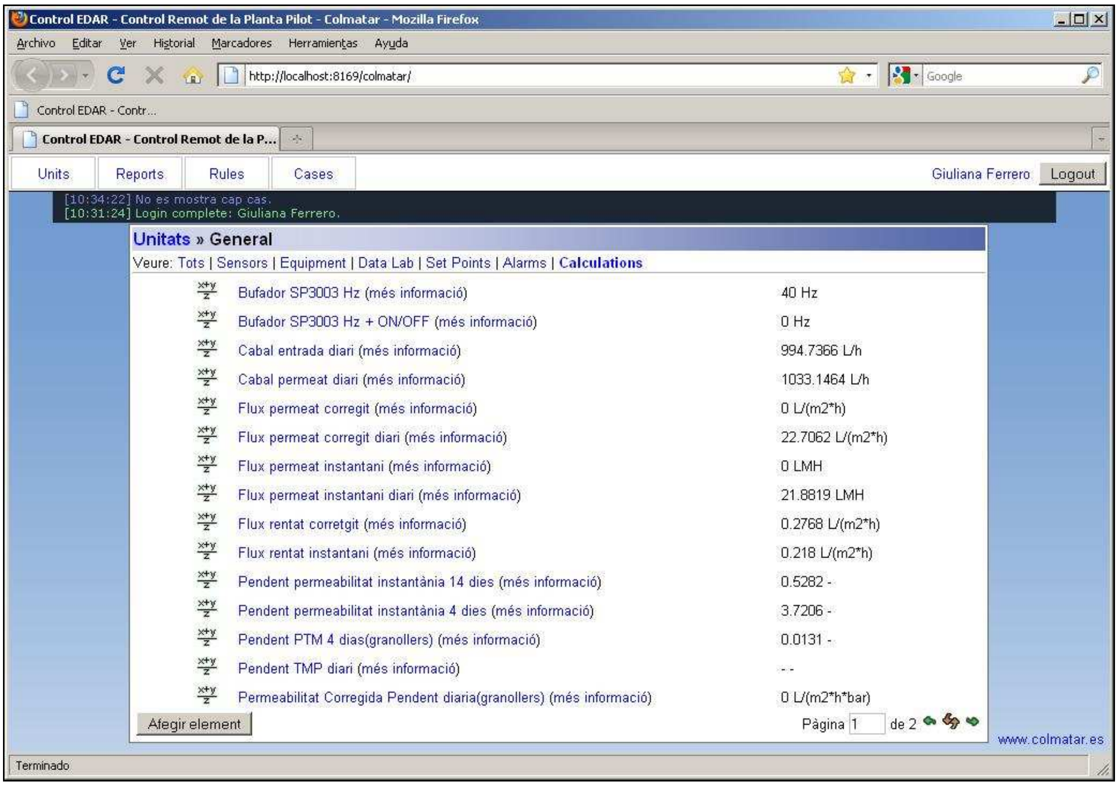
Veure: Tots | Sensors | Equipment | Data Lab | Set Points | **Alarms** | Calculations

Alarma AG1101 (més informació)	OFF
Alarma BS1001 (més informació)	ON
Alarma BS1002 (més informació)	OFF
Alarma SP3001 (més informació)	OFF
Alarma SP3002 (més informació)	OFF
Alarma SP3003 (més informació)	OFF
Alarma Tamiz (més informació)	OFF
Alarma TMP ALTO (més informació)	OFF
Alarma TMP SALTO Parada (més informació)	OFF

Pàgina 1 de 1

Figure 8.15. List of favourite variables.

As previously explained, the system calculated in real time data that were not directly available from the PLC but that were useful for a correct understanding of the process. A complete list of the calculations is shown in Figure 8.16.



```
[10:34:22] No es mostra cap cas.
[10:31:24] Login complete: Giuliana Ferrero.
```

Unitats » **General**

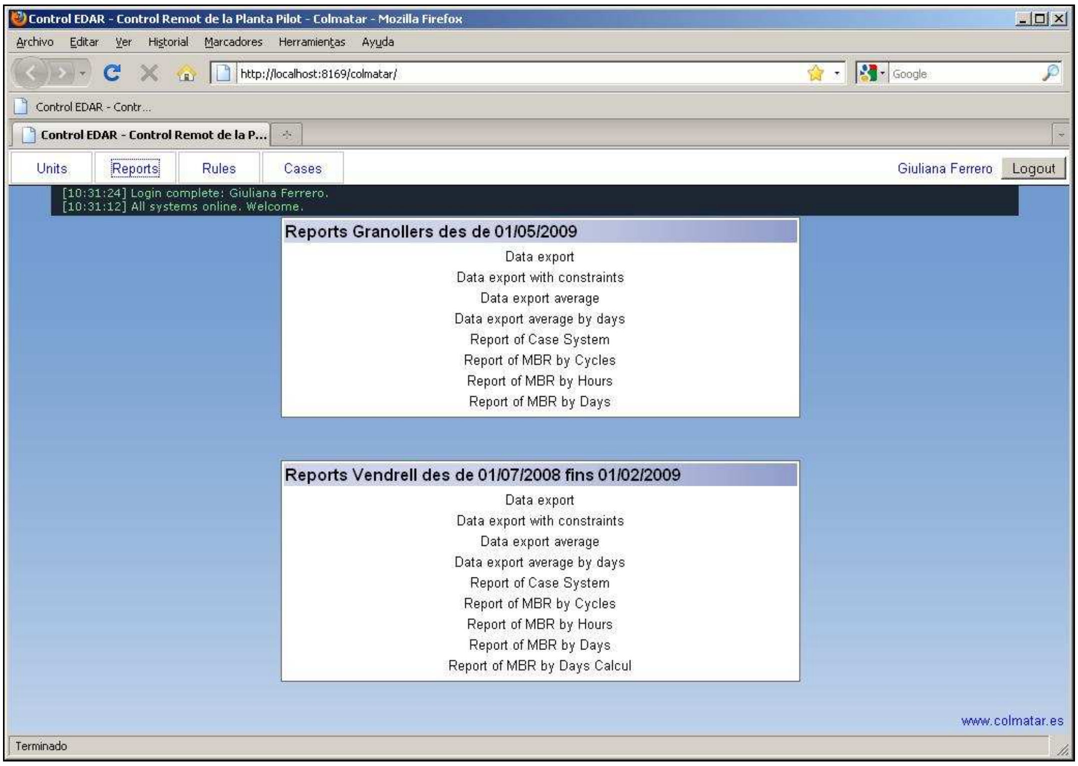
Veure: Tots | Sensors | Equipment | Data Lab | Set Points | Alarms | **Calculations**

Bufador SP3003 Hz (més informació)	40 Hz
Bufador SP3003 Hz + ON/OFF (més informació)	0 Hz
Cabal entrada diari (més informació)	994.7366 L/h
Cabal permeat diari (més informació)	1033.1464 L/h
Flux permeat corregit (més informació)	0 L/(m2*h)
Flux permeat corregit diari (més informació)	22.7062 L/(m2*h)
Flux permeat instantani (més informació)	0 LMH
Flux permeat instantani diari (més informació)	21.8819 LMH
Flux rentat corretgit (més informació)	0.2768 L/(m2*h)
Flux rentat instantani (més informació)	0.218 L/(m2*h)
Pendent permeabilitat instantània 14 dies (més informació)	0.5282 -
Pendent permeabilitat instantània 4 dies (més informació)	3.7206 -
Pendent PTM 4 dias(granollers) (més informació)	0.0131 -
Pendent TMP diari (més informació)	- -
Permeabilitat Corregida Pendent diaria(granollers) (més informació)	0 L/(m2*h*bar)

Pàgina 1 de 2

Figure 8.16. List of favourite variables.

Another very important feature of the control system was data export. Comma separated value (CSV*)* files containing raw data saved every 10 second or five minutes could be downloaded for any of the system variables (Figure 8.17).



[10:31:24] Login complete: Giuliana Ferrero.
[10:31:12] All systems online. Welcome.

Reports Granollers des de 01/05/2009

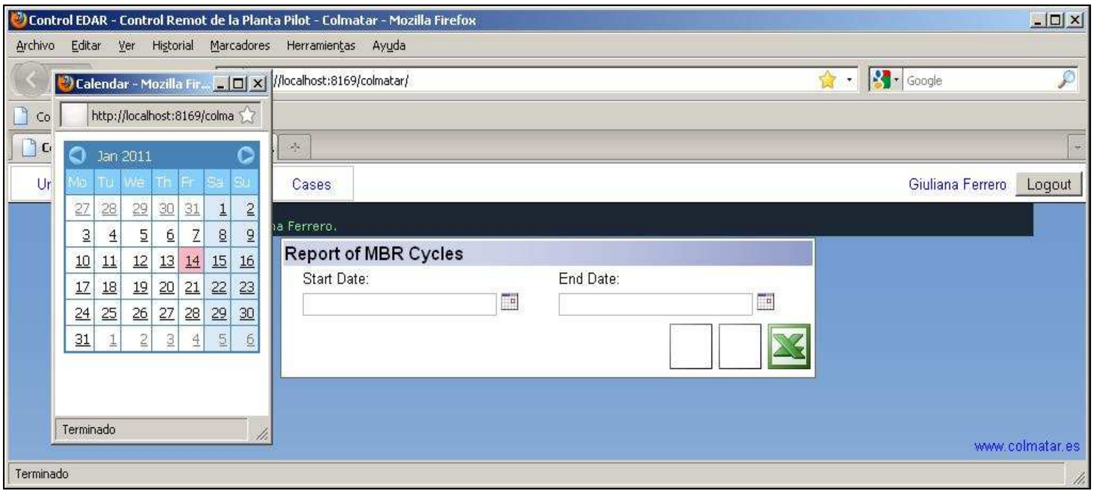
Data export
Data export with constraints
Data export average
Data export average by days
Report of Case System
Report of MBR by Cycles
Report of MBR by Hours
Report of MBR by Days

Reports Vendrell des de 01/07/2008 fins 01/02/2009

Data export
Data export with constraints
Data export average
Data export average by days
Report of Case System
Report of MBR by Cycles
Report of MBR by Hours
Report of MBR by Days
Report of MBR by Days Calcul

Figure 8.17. Report download.

A simple data filter could be also applied while downloading data by establishing constraints (maximum and minimum values). Any data not contained in the selected range were automatically excluded (Figure 8.19) and reports with average values per cycle (Figure 8.18), hour or day could be downloaded. In this last case the system would calculate at the time all the average values required for the selected frame using the raw data saved in MySqL and apply the data filtering process explained in section 7.2.

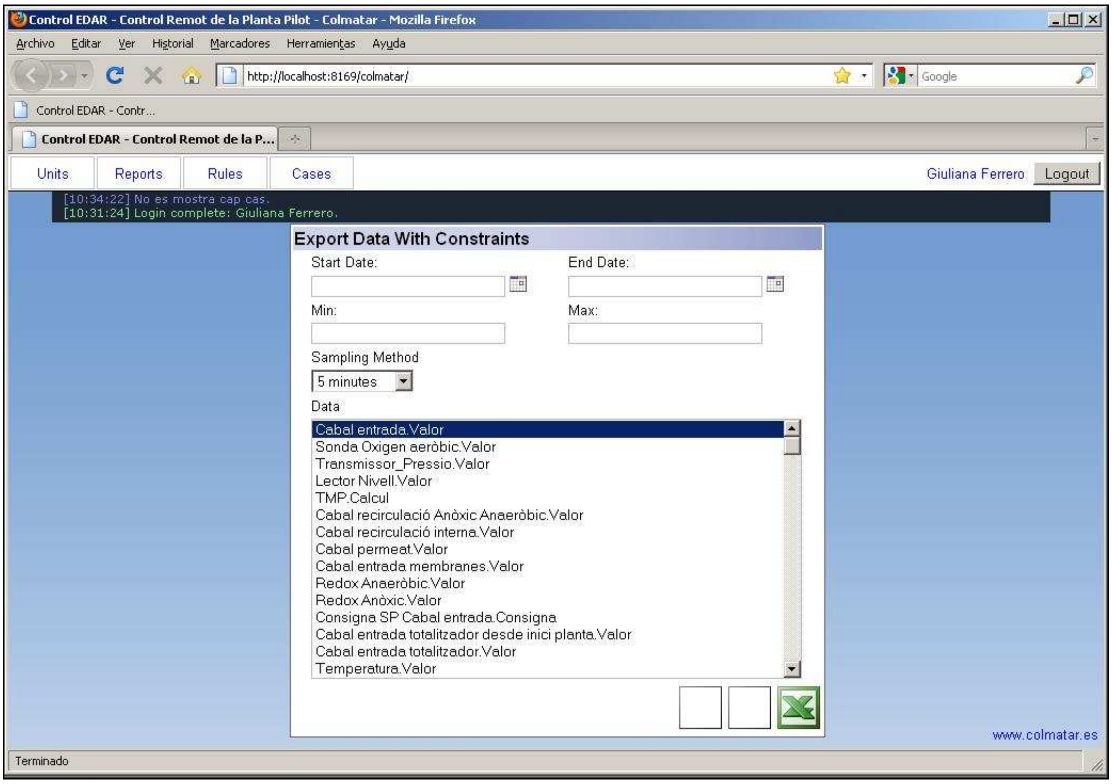


Report of MBR Cycles

Start Date:

End Date:

Figure 8.18. Report download.



```
[10:34:22] No es mostra cap cas.
[10:31:24] Login complete: Giuliana Ferrero.
```

Export Data With Constraints

Start Date:

End Date:

Min:

Max:

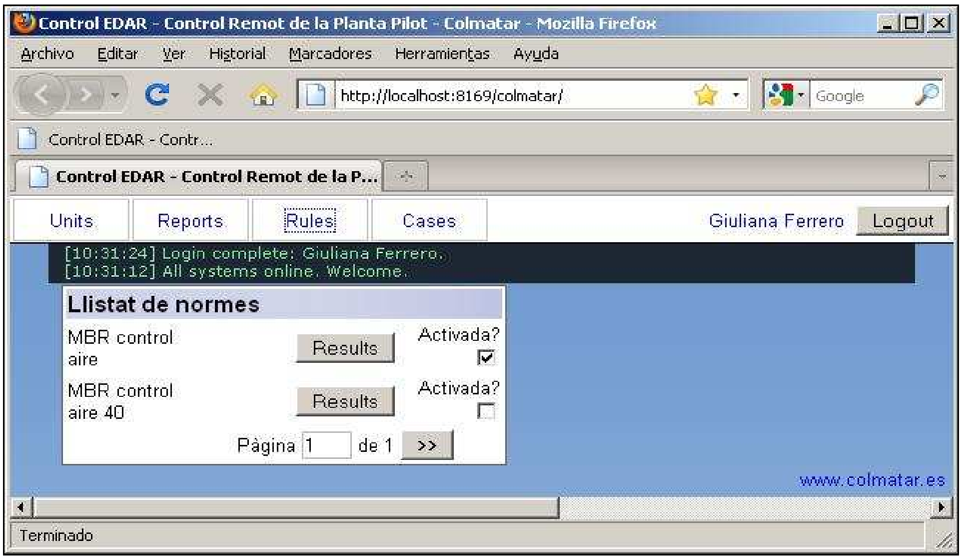
Sampling Method: 5 minutes

Data

- Cabal entrada.Valor
- Sonda Oxigen aeròbic.Valor
- Transmissor_Pressio.Valor
- Lector Nivell.Valor
- TMP.Calcul
- Cabal recirculació Anòxic Anaeròbic.Valor
- Cabal recirculació interna.Valor
- Cabal permeat.Valor
- Cabal entrada membranes.Valor
- Redox Anaeròbic.Valor
- Redox Anòxic.Valor
- Consigna SP Cabal entrada.Consigna
- Cabal entrada totalitzador desde inici planta.Valor
- Cabal entrada totalitzador.Valor
- Temperatura.Valor

Figure 8.19. Data export (with constraints).

Finally, it was possible to manually activate or deactivate control rules by selecting those that were desired from a complete list of all the programmed rules (Figure 8.20). The results of implementation of the control rules were calculated as extensible markup language (XML) files. These could be visualised on-line (Figure 8.21) and were automatically saved in MySqL. The control action was shown by clicking on the "Results" button in the control rules frame (Figure 8.22).



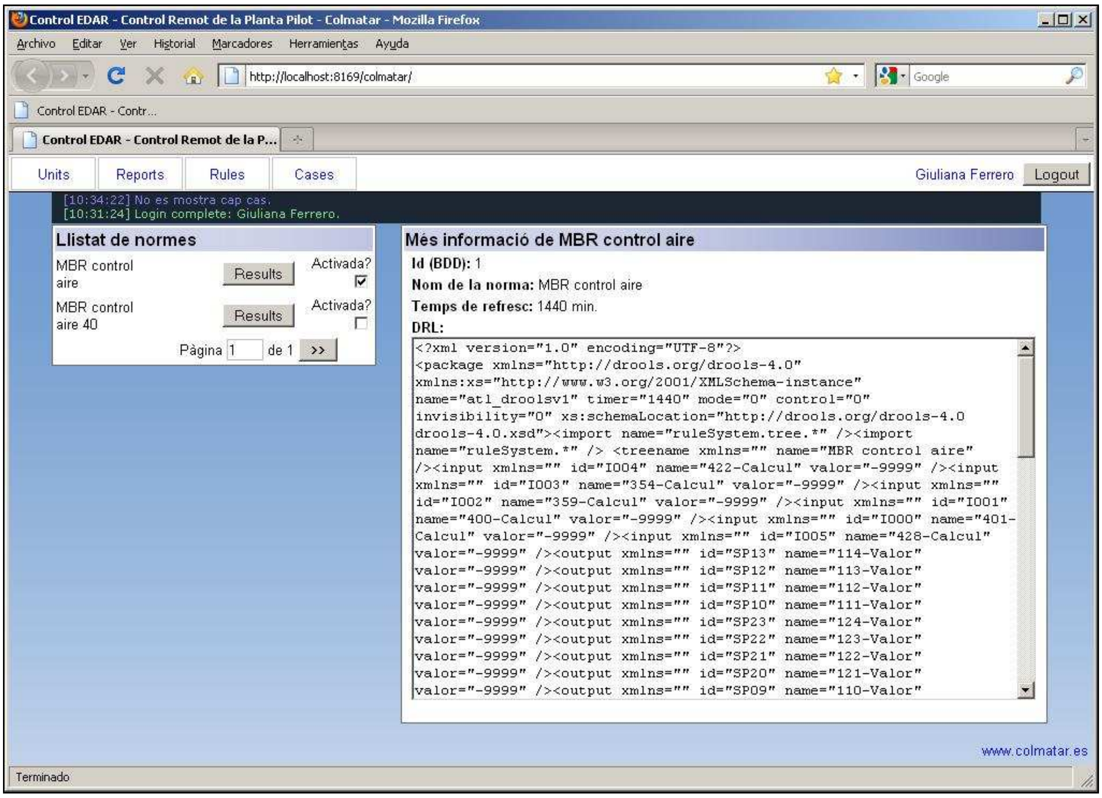
```
[10:31:24] Login complete: Giuliana Ferrero.
[10:31:12] All systems online. Welcome.
```

Llistat de normes

MBR control aire	Results	Activada? ☑
MBR control aire 40	Results	Activada? ☐

Pàgina 1 de 1 >>

Figure 8.20. Control rules activation.



```
[10:34:22] No es mostra cap cas.
[10:31:24] Login complete: Giuliana Ferrero.
```

Llistat de normes

MBR control aire — Activada? ☑

MBR control aire 40 — Activada? ☐

Pàgina 1 de 1

Més informació de MBR control aire

Id (BDD): 1

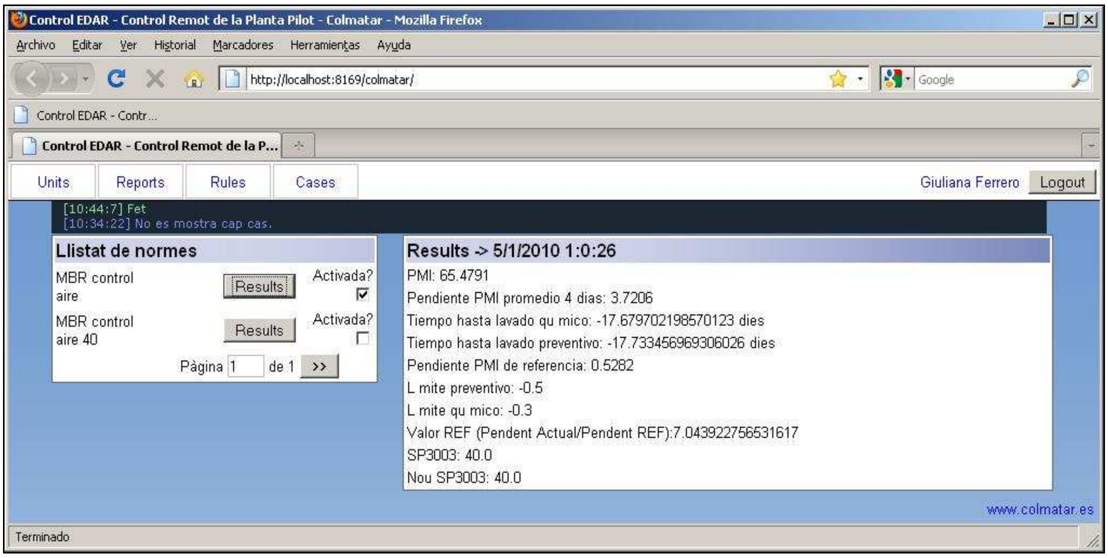
Nom de la norma: MBR control aire

Temps de refresc: 1440 min.

DRL:

```
<?xml version="1.0" encoding="UTF-8"?>
<package xmlns="http://drools.org/drools-4.0"
xmlns:xs="http://www.w3.org/2001/XMLSchema-instance"
name="atl_droolsv1" timer="1440" mode="0" control="0"
invisibility="0" xs:schemaLocation="http://drools.org/drools-4.0
drools-4.0.xsd"><import name="ruleSystem.tree.*" /><import
name="ruleSystem.*" /> <treename xmlns="" name="MBR control aire"
/><input xmlns="" id="I004" name="422-Calcul" valor="-9999" /><input
xmlns="" id="I003" name="354-Calcul" valor="-9999" /><input xmlns=""
id="I002" name="359-Calcul" valor="-9999" /><input xmlns="" id="I001"
name="400-Calcul" valor="-9999" /><input xmlns="" id="I000" name="401-
Calcul" valor="-9999" /><input xmlns="" id="I005" name="428-Calcul"
valor="-9999" /><output xmlns="" id="SP13" name="114-Valor"
valor="-9999" /><output xmlns="" id="SP12" name="113-Valor"
valor="-9999" /><output xmlns="" id="SP11" name="112-Valor"
valor="-9999" /><output xmlns="" id="SP10" name="111-Valor"
valor="-9999" /><output xmlns="" id="SP23" name="124-Valor"
valor="-9999" /><output xmlns="" id="SP22" name="123-Valor"
valor="-9999" /><output xmlns="" id="SP21" name="122-Valor"
valor="-9999" /><output xmlns="" id="SP20" name="121-Valor"
valor="-9999" /><output xmlns="" id="SP09" name="110-Valor"
```

Figure 8.21. Control rules (XML file).



```
[10:44:7] Fet
[10:34:22] No es mostra cap cas.
```

Llistat de normes

MBR control aire — Activada? ☑

MBR control aire 40 — Activada? ☐

Pàgina 1 de 1

Results -> 5/1/2010 1:0:26

```
PMI: 65.4791
Pendiente PMI promedio 4 dias: 3.7206
Tiempo hasta lavado qu mico: -17.679702198570123 dies
Tiempo hasta lavado preventivo: -17.733456969306026 dies
Pendiente PMI de referencia: 0.5282
L mite preventivo: -0.5
L mite qu mico: -0.3
Valor REF (Pendent Actual/Pendent REF):7.043922756531617
SP3003: 40.0
Nou SP3003: 40.0
```

Figure 8.22. Control rules (results).

CHAPTER 9
CONCLUSIONS

9. Conclusions

The main objective of this thesis has been achieved. A control system that automatically regulates the air-scour flow rate to reduce energy requirements in membrane bioreactors for wastewater treatment has been developed and partially validated at pilot scale.

A better understanding of MBR processes and operation, i.e. biological processes and the filtration process, has been achieved through experimentation at semi-industrial pilot scale with real wastewater and with different membrane configurations. The wide range of operational conditions experimented with has made it possible to design and implement a robust control system able to adapt to multiple scenarios. Different experiments with various air-scour patterns have been carried out, e.g. variable air-flow (air flow proportional to the permeate flow) and constant air-scour flow.

An air-scour control, as part of a more complex knowledge-based (KB) control system, has been developed, and the key variables to be measured, controlled and manipulated have been identified. The three levels of the control system have been developed accordingly: the data gathering and signal processing level was defined so as to eliminate outliers and calculate averages and trends in the key parameters; a feedback control algorithm for air-scour reduction was developed; and supervision (or safety) rules were defined to ensure the robustness of the control system.

The air-scour control system was implemented, adapted to different membrane characteristics and validated in a semi-industrial pilot scale plant. The system made it possible to achieve a maximum energy saving of about 20%, with respect to the minimum aeration recommended by the membrane suppliers, without visibly resulting in membrane fouling interference. Throughout the entire study BNR was monitored and no reduction in nutrient removal was associated with the air-scour control system.

Further research is currently being carried out in order to refine the knowledge based supervision module and to validate the control system at full scale.

This thesis led to a patent application approved by the Spanish Intellectual Property Authority on October 22nd 2010 (ES 2333837) and to the publication of several papers. The outcomes have been presented at various national and international conferences, contributing to an enhancement of local and international knowledge of the problems analysed. In the future, they could form the basis for synergies and collaboration between research groups that have been proactively working on the same issues.

CHAPTER 10

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ANNEXES

RESULTS OF THE FILTRATION PROCESS

Experimentation with flat sheet membranes

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Air-flow
MAY 2008		bar	$L \cdot h^{-1}$	$L \cdot h^{-1}$	$L \cdot m^{-2} \cdot h^{-1}$	$LMH \cdot bar^{-1}$	°C	$m^3 \cdot h^{-1}$
FILTRATION / RELAXATION 9 minutes / 1 minute	29/04/08 – 18/05/08	DATA NOT SAVED IN THE PLC MEMORY						
	19/05/08	-0.072	893.42	804	22	333.04		33
	20/05/08	-0.066	859.98	774	21	340.78	20.6	33
	21/05/08	-0.063	850.43	765	21	352.00		33
	22/05/08	-0.045	640.32	576	16	382.55	20.3	33
	23/05/08	-0.063	863.59	777	22	353.17		33
	24/05/08	-0.063	865.59	779	22	414.52		33
	25/05/08	-0.065	861.93	776	22	345.97		33
	26/05/08	-0.069	887.71	799	22	334.86	20.3	33
	27/05/08	-0.067	852.51	767	21	350.34		33
	28/05/08	-0.072	883.63	795	22	316.25		33
	29/05/08	-0.127	1210.08	1089	30	253.12	21.6	33
	30/05/08	-0.155	1210.25	1089	30	207.63		33
	31/05/08	-0.170	1145.35	1031	29	176.78		33

Δ TMP	-136 %						
Δ Permeability					-46.9 %		
Δ Inflow/Permeate flow		+28.2%	+28.2%				
Δ Air flow							0
Δ T						+1	

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Air-flow
JUNE 2008		bar	$L \cdot h^{-1}$	$L \cdot h^{-1}$	$L \cdot m^{-2} \cdot h^{-1}$	$LMH \cdot bar^{-1}$	°C	$m^3 \cdot h^{-1}$
FILTRATION / RELAXATION 9 minutes / 1 minute	1/06/08	-0.172	1063.79	958	27	160.95	21.6	33
	2/06/08	-0.146	931.82	839	23	165.88		33
	3/06/08	-0.073	980.91	883	25	348.54		33
	4/06/08	-0.061	1223.17	1101	31	524.87		33
	5/06/08	-0.063	1158.9	1043	29	495.6		33
	6/06/08	-0.060	1179.23	1061	29	501.71		33
	7/06/08	-0.146	843.45	759	21	232.60		33
	8/06/08	-0.163	605.37	545	15	98.96		33
	9/06/08	-0.175	1010.70	910	25	177.60		33
	10/06/08	-0.144	923.84	832	23	195.94		33
	11/06/08	-0.134	778.76	701	19	158.50		33
								33
	25/06/08	-0.017	979.17	881	25	1406.32		33
	26/06/08	-0.030	958.66	863	25	884.67		33
	27/06/08	-0.046	950.20	855	25	558.25		33
	28/06/08	-0.061	941.56	847	25	417.96		33
	29/06/08	-0.088	931.20	838	24	294.68		33
	30/06/08	-0.114	933.20	840	24	220.05		33

Δ TMP	+33.7%						
Δ Permeability					+36.7%		
Δ Inflow/Permeate flow		-12.3%	-12.3%				
Δ Air flow							0
Δ T							

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Air-flow
JULY 2008		bar	$L\cdot h^{-1}$	$L\cdot h^{-1}$	$L\cdot m^{-2}\cdot h^{-1}$	$LMH\cdot bar^{-1}$	°C	$m^3\cdot h^{-1}$
FILTRATION / RELAXATION 9 minutes / 1 minute	3/07/08*	-0.141	935.71	842	25	176.09		33
	4/07/08*	-0.150	935.85	842	25	167.78		33
	5/07/08*	-0.152	938.12	844	25	165.97		33
	6/07/08*	-0.151	935.82	842	25	166.30		33
	7/07/08*	-0.154	934.47	841	25	163.96		33
	8/07/08*	-0.153	924.32	832	25	163.51		33
	9/07/08*	-0.130	859.80	774	25	175.22		33
	10/07/08*	-0.133	878.28	791	20	178.15		33
	11/07/08*	-0.127	867.93	781	22.8	186.86		33
	12/07/08*	-0.091	740.68	667	19.5	223.14		33
	13/07/08*	-0.090	736.39	663	19.4	223.24		33
	14/07/08*	-0.078	749.32	674	19.7	271.43		33
	15/07/08*	-0.066	771.96	695	19.3	315.22		33
	16/07/08*	-0.064	764.79	688	19.1	315.95		33
	17/07/08	-0.046	757.02	681	18.9	361.45		54
	18/07/08	-0.031	769.05	692	19.2	658.51		54
	19/07/08	-0.028	767.85	691	19.2	825.07		54
	20/07/08	-0.026	762.51	686	19.1	813.54		54
	21/07/08	-0.024	723.62	651	18.1	748.02		54
	22/07/08	-0.019	652.12	587	16.3	849.24		54
	23/07/08	-0.018	750.1	675	18.8	1014.07		54
	24/07/08	-0.020	710	639	17.8	900.19		54
	25/07/08	-0.019	724.51	652	18.1	938.03		54
	26/07/08	DATA NOT SAVED IN THE PLC MEMORY						54
	27/07/08							54
	28/07/08	-0.018	777.30	700	19.43	1075.50		54
	29/07/08	-0.017	765.82	689	19.15	1095.42		54
	30/07/08	-0.017	763.22	687	19.08	1122.86		54
	31/07/08	-0.015	766.57	690	19.16	1237.45		54

▨ *ex situ* chemical cleaning on the 17th. Blower exchanged for new one.

* 38.4 m^2 membrane surface (should have been 40 m^2 but two membranes damaged).

Δ TMP	+89.4%						
Δ Permeability					+603%		
Δ Inflow/Permeate flow		-18%	-18%				
Δ Air flow							+63.6%
Δ T							

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow
AUGUST 2008		bar	L·h^{-1}	L·h^{-1}	L·m^{-2}·h^{-1}	LMH·bar^{-1}	LMH·bar^{-1}	ºC	m^3·h^{-1}
FILTRATION / RELAXATION 9 minutes / 1 minute	1/08/08	-0.015	730.82	658	18.27	1251.35	1012.09	27.5	54
	2/08/08	-0.015	773.02	696	19.33	1291.41	1065.53	27.7	54
	3/08/08	-0.015	766.14	690	19.15	1279.91	1055.61	27.7	54
	4/08/08	-0.018	865.27	779	21.63	1233.84	991.15	27.8	54
	5/08/08	-0.020	962.61	866	24.07	1220.79	985.33	28.1	54
	6/08/08	-0.020	962.61	866	24.07	1193.45	1002.51	27.4	54
	7/08/08	-0.020	972.35	875	24.31	1202.19	1007.52	27.6	54
	8/08/08	-0.021	981.10	883	24.53	1174.14	963.46	27.8	54
	9/08/08	-0.021	981.82	884	24.55	1180.99	966.63	27.7	54
	10/08/08	-0.021	980.71	883	24.52	1180.82	965.44	27.7	54
	11/08/08	-0.020	981.37	883	24.53	1197.62	1014.13	27.7	54
	12/08/08	-0.020	981.05	883	24.53	1197.22	1001.69	28.2	54
	13/08/08	-0.020	991.83	893	24.80	1241.35	1020.24	27.9	54
	14/08/08	-0.021	979.37	882	24.48	1149.09	978.26	27.1	49.5
	15/08/08	-0.022	981.31	883	24.53	1107.78	931.09	27.3	49.5
	16/08/08	-0.022	980.29	882	24.51	1097.25	930.33	27.3	49.5
	17/08/08	-0.021	955.37	860	23.88	1138.49	949.58	27.3	49.5
	18/08/08	-0.025	1067.49	961	26.69	1072.55	889.31	27.4	49.5
	19/08/08	-0.029	1176.89	1059	29.42	1005.55	845.06	27.4	49.5
	20/08/08	-0.030	1178.05	1060	29.45	989.18	813.70	27.6	49.5
	21/08/08	-0.030	1177.61	1060	29.44	973.90	823.53	27.1	49.5
	22/08/08	-0.029	1188.33	1070	29.71	1016.75	847.09	27.7	49.5
	23/08/08	-	-	-	-	-	-	27.5	49.5
	24/08/08	-	-	-	-	-	-	27.5	49.5
	25/08/08	-0.034	1188.74	1070	29.72	873.37	731.74	27.2	49.5
	26/08/08	-0.036	1207.57	1087	30.19	843.50	712.50	26.6	49.5
	27/08/08	-0.034	1148.31	1033	28.71	834.28	719.20	26.5	49.5
	28/08/08	-0.035	1203.90	1084	30.10	861.16	730.67	26.6	49.5
	29/08/08	-0.037	1149.25	1034	28.73	773.53	658.09	26.7	49.5
	30/08/08	-0.037	1149.34	1035	28.73	774.56	658.09	26.7	49.5
	31/08/08	-0.038	1152.34	1037	28.81	767.86	642.55	26.7	49.5

▨ Pilot plant out of order due to external recycle pump failure.

Δ TMP	-153 %							
Δ Permeability					-38.6 %			
Δ Permeability (T)						-36.51 %		
Δ Inflow/Permeate flow		+57.7%	+57.6%					
Δ Air flow								-2.7%
Δ T							-0.8	

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Air-flow	T
SEPTEMBER 2008		bar	$L \cdot h^{-1}$	$L \cdot h^{-1}$	$L \cdot m^{-2} \cdot h^{-1}$	$LMH \cdot bar^{-1}$	$m^3 \cdot h^{-1}$	°C
FILTRATION / RELAXATION 9 minutes / 1 minute	1/09/08	-0.039	1157.97	1042	27.8	750.91	49.5	27
	2/09/08	-0.040	1158.33	1043	27.8	731.89	49.5	26.6
	3/09/08	-0.040	1160.52	1045	27.9	727.41	45	27.1
	4/09/08	-0.038	1146.92	1032	27.5	779.69	45	27.3
	5/09/08	-0.040	1158.71	1043	27.8	754.82	45	26.5
	6/09/08	-0.040	1153.66	1038	27.7	743.62	45	26
	7/09/08	-0.041	1162.39	1046	27.9	724.53	45	26
	8/09/08	-0.041	1149.13	1034	27.6	729.77	45	25.8
	9/09/08	-0.041	1149.65	1035	27.6	730.49	49.5 / 45*	26.2
	10/09/08	-0.041	1140.72	1027	27.4	736.20	49.5 / 45*	26.2
	11/09/08	-0.041	1144.05	1030	27.5	737.28	47.7	26
	12/09/08	-0.042	1159.88	1044	27.8	719.70	49.5 / 45*	25.9
	13/09/08	-0.044	1163.63	1047	27.9	687.72	47.7	25.5
	14/09/08	-0.045	1163.84	1048	27.9	680.69	47.7	25.5
	15/09/08	-0.044	1165.30	1049	28.0	693.82	47.7	25.5
	16/09/08	-0.043	1159.66	1044	27.8	711.74	49.5 / 45*	24.8
	17/09/08	-0.042	1163.64	1047	27.9	718.61	47.7	25
	18/09/08	-0.042	1160.21	1044	29.01	717.90	49.5 / 45*	25.5
	19/09/08	-0.042	1164.38	1048	29.11	719.59	47.7	25.6
	20/09/08	-0.042	1163.53	1047	29.09	717.72	47.7	25.5
	21/09/08	-0.043	1166.85	1050	29.17	719.46	47.7	25.5
	22/09/08	-0.042	1153.09	1038	28.83	714.99	49.5 / 45*	25.3
	23/09/08	-0.0419	1118.53	1033.27	27.96	690.54	49.5 / 45*	23.8
	24/09/08	-0.0422	1112.37	1022.61	27.81	684.69	45	23
	25/09/08	-0.0437	1148.72	1040.49	28.72	683.74	45	23.4
	26/09/08	-0.0442	1071.95	972.65	26.80	678.33	45	24.2
	27/09/08	-0.0446	1146.74	1036.88	28.67	673.50	45	23.5
	28/09/08	-0.0446	1146.93	1036.54	28.67	669.82	45	23.5
	29/09/08	-0.0444	1145.13	1033.62	28.63	672.46	45	22.7
	30/09/08	-0.0456	1174.29	1037.21	29.36	663.93	45	23

* 49.5 from 10.00 to 16.00 during peak flow hours and 45 during rest of day.

Δ TMP	-16.9%						
ΔPermeability					- 11,6 %		
Δ Inflow/Permeate flow		~0	~0				
Δ Air flow						-9%	
Δ T							- 4

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow
OCTOBER 2008		bar	$L\cdot h^{-1}$	$L\cdot h^{-1}$	$L\cdot m^{-2}\cdot h^{-1}$	$LMH\cdot bar^{-1}$	$LMH\cdot bar^{-1}$	ºC	$m^3\cdot h^{-1}$
FILTRATION / RELAXATION 9 minutes / 1 minute	01/10/08	-0.0458	1171.70	1038.78	29.3	663.56	-	22.6	45
	02/10/08	-0.0468	1186.00	1037.43	29.7	651.78	-	22.8	45
	03/10/08	-0.0420	1090.94	978.36	27.3	674.63	-	23.1	38*
	04/10/08	-0.0500	1202.84	1036.73	30.1	617.31	587.21	22.0	38
	05/10/08	-0.0518	1203.70	1036.62	30.1	596.06	559.04	22.6	38
	06/10/08	-0.0507	1187.17	1022.85	29.7	609.50	563.74	23.3	38
	07/10/08	-0.0494	1190.63	1036.36	29.8	627.34	572.02	23.6	38
	08/10/08	-0.0466	1134.72	984.62	28.4	629.19	574.90	23.8	38
	09/10/08	-0.0514	1184.93	1036.06	29.6	592.41	552.99	22.8	38
	10/10/08	-0.0472	1129.01	989.77	28.2	609.91	563.06	23.3	38
	11/10/08	-0.0520	1188.45	1036.56	29.7	588.46	543.48	23.2	38
	12/10/08	-0.0528	1188.71	1036.58	29.7	578.16	529.07	23.6	38
	13/10/08	-0.0535	1198.12	1035.74	30.0	574.09	514.12	24.6	38
	14/10/08	-0.0558	1207.73	1046.47	30.3	558.81	498.97	24.4	38
	15/10/08	-0.0575	1222.23	1046.96	30.4	544.03	491.83	24.3	38
	16/10/08	-0.0571	1200.66	1033.26	30.1	542.80	489.64	24.4	38
	17/10/08	-0.0557	1165.12	1034.81	30.1	568.46	506.13	24.7	38
	18/10/08	-0.0583	1226.00	1038.94	30.5	562.97	525.43	23.8	38
	19/10/08	-0.0598	1232.53	1037.79	30.7	542.82	504.31	23.3	38
	20/10/08	-0.0574	1234.56	1035.62	30.3	543.82	492.33	24.0	38
	21/10/08	-0.0592	1258.29	1037.12	30.9	528.46	478.37	24.0	38
	22/10/08	-0.0541	1133.08	1036.57	28.0	542.23	498.89	23.4	38
	23/10/08	-0.0509	1030.40	914.18	24.2	506.93	486.73	21.7	38
	24/10/08	-0.0530	1052.21	934.60	25.7	507.21	488.24	21.5	38
	25/10/08	-0.0671	1196.49	1035.30	28.5	449.81	423.97	22.4	38
	26/10/08	-0.0857	1149.00	1023.48	28.5	356.49	335.37	22.5	38
	27/10/08	-0.0845	1134.68	1038.67	28.5	356.22	336.19	22.4	38
	28/10/08	-0.0894	1094.45	1038.56	28.2	327.04	315.43	21.4	38
	29/10/08	-0.1196	950.37	889.03	23.9	238.51	251.02	18.7	45
	30/10/08	-0.1103	1001.38	907.03	25.1	232.42	256.74	16.2	45
	31/10/08	-0.0790	1039.60	939.80	26.3	457.59	481.10	17.9	38

*Installation of frequency inverter for membrane air blower. Pilot plant out of order for three hours.

▨ Chemical cleanings: 23/10 (NaClO al 0,5%); 29/10 (NaClO al 0,75%); ex situ cleaning 31/10.

Δ TMP	- 161 % (29/10) -18.1% (22/10)						
Δ Permeability				-64 %(29/10) -18.2 %(22/10)			
Δ Permeability (T)					-57.2% (29/10) -15% (22/10)		
Δ Inflow/Permeate flow		~0	~0				
Δ Air flow							-15 %
Δ T						- 4.7	

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow	
NOVEMBER 2008		bar	$L \cdot h^{-1}$	$L \cdot h^{-1}$	$L \cdot m^{-2} \cdot h^{-1}$	$LMH \cdot bar^{-1}$	$LMH \cdot bar^{-1}$	ºC	$m^3 \cdot h^{-1}$	
FILTRATION / RELAXATION = 9 minutes / 1 minute	01/11/08	-0.0358	1210.30	1037.55	30.5	883.70	922.56	18.3	37.1	CONSTANT AIR-FLOW
	02/11/08	-0.0315	1137.17	927.25	28.6	920.59	957.81	18.5	37.1	
	03/11/08	-0.0353	1184.20	1025.82	29.9	869.85	923.14	17.6	37.1	
	04/11/08	-0.0381	1163.32	1023.73	28.6	878.67	923.44	18.0	37.1	
	05/11/08	-0.0379	1121.28	1024.24	28.2	851.07	897.64	17.9	37.1	
	06/11/08	-0.0419	1165.46	1035.13	28.7	846.77	890.97	18.0	37.1	
	07/11/08	-0.0418	1157.96	1037.44	29.8	810.70	849.25	18.1	37.1	
	08/11/08	-0.0383	1130.76	996.50	26.9	850.91	896.65	18.3	37.1	
	09/11/08	-0.0429	1251.03	817.00	31.9	820.72	847.46	18.3	37.1	
	10/11/08	-0.0419	1143.16	1141.67	28.8	848.66	872.49	18.4	37.1	
	11/11/08	-0.0427	1123.79	1037.81	28.8	851.21	876.42	19.1	37.8	VARIABLE AIR FLOW
	12/11/08	-0.0434	1174.26	1036.31	29.4	846.42	897.52	18.9	37.8	
	13/11/08	-0.0425	1145.91	1063.88	27.9	840.48	890.72	18.4	37.8	
	14/11/08	-0.0437	1124.05	1034.19	28.5	826.42	868.06	18.0	37.8	
	15/11/08	-0.0401	1127.62	1040.02	28.7	825.49	864.37	18.1	37.8	
	16/11/08	-0.0440	1091.37	1043.62	28.5	814.68	853.17	18.2	37.8	
	17/11/08	-0.0431	1146.89	1024.38	28.1	852.44	895.38	18.1	35.6	
	18/11/08	-0.0449	1143.14	1033.55	29.4	821.00	868.94	17.8	35.6	
	19/11/08	-0.0433	1135.02	1035.37	28.29	836.41	880.35	17.8	35.6	
	20/11/08	-0.0437	1140.39	1034.42	27.22	861.95	923.79	17.5	35.6	
	21/11/08	-0.0421	1139.32	1035.47	28.37	819.70	879.12	17.3	35.6	
	22/11/08	-0.0369	1147.73	1037.33	26.59	849.86	902.61	17.9	35.6	
	23/11/08	-0.0419	1167.19	1037.22	27.14	847.78	896.54	18.0	35.6	
	24/11/08	-0.0423	1144.80	1026.75	27.35	828.59	888.05	17.3	35.6	
	25/11/08	-0.0388	1115.42	1021.18	27.81	780.56	859.91	16.2	35.6	
	26/11/08	-0.0423	974.26	890.87	29.10	746.60	835.10	15.8	35.6	
	27/11/08	-0.0414	1147.01	1049.98	28.24	726.94	818.47	15.1	35.6	
	28/11/08	-0.0427	1129.97	1035.16	28.27	702.27	797.17	14.8	35.6	
	29/11/08	-0.0426	1132.74	1033.59	28.38	701.42	792.16	14.9	35.6	
	30/11/08	-0.0423	1127.99	1032.90	28.27	711.61	795.84	15.3	35.6	

Δ TMP	-18.2%							
Δ Permeability					- 19.5%			
Δ Permeability (T)						- 13.7%		
Δ Inflow/Permeate flow		~ 0	~ 0					
Δ Air flow								- 4%
Δ T							- 3	

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow	
DECEMBER 2008		bar	$L \cdot h^{-1}$	$L \cdot h^{-1}$	$L \cdot m^{-2} \cdot h^{-1}$	$LMH \cdot bar^{-1}$	$LMH \cdot bar^{-1}$	ºC	$m^3 \cdot h^{-1}$	
FILTRATION / RELAXATION = 9 minutes / 1 minute										C. V.
	10/12/08	-0.0499	1266.96	1116.93	31.95	578.74	640.47	15.26	35.8	
	11/12/08	-0.0487	1150.65	1040.27	32.53	541.08	615.07	13.89	35.8	
	12/12/08	-0.0565	1241.91	1128.19	31.08	538.35	609.46	14.06	35.8	CONSTANT FLOW (aeration ,inflow/permeate flow)
	13/12/08	-0.0255	989.77	899.68	24.82	858.50	967.44	14.37	38.5	
	14/12/08	-0.0268	989.40	899.65	24.82	818.63	931.96	13.91	38.5	
	15/12/08	-0.0276	988.93	899.71	24.83	620.89	746.21	13.75	38.5	
	16/12/08	-0.0294	988.20	899.83	24.84	761.17	900.01	14.05	38.5	
	17/12/08	-0.0283	990.39	899.61	24.83	779.99	914.26	14.45	38.5	
	18/12/08	-0.0296	989.30	899.58	24.84	753.64	882.29	14.72	39.9	
	19/12/08	-0.0320	991.44	899.56	24.89	701.93	818.41	14.70	34.0	
	20/12/08	-0.0332	989.11	899.63	24.81	676.88	792.03	14.76	32.3	
	21/12/08	-0.0358	989.59	899.69	24.83	623.09	730.79	14.78	31.6	
	22/12/08	-0.0362	990.31	898.78	24.82	635.47	598.77	14.29	37.1	
	23/12/08	-0.0320	990.98	899.54	24.84	753.69	-	-	38.5	
	24/12/08	-0.0254	990.24	899.35	24.85	915.67	-	-	38.5	
	25/12/08	-0.0246	990.82	899.41	24.85	941.59	-	-	38.5	
	26/12/08	-0.0316	991.18	898.99	24.85	760.31	-	-	38.5	
	27/12/08	-0.0314	991.35	900.12	24.85	752.98	-	-	38.5	
	28/12/08	-0.0335	991.54	899.19	24.84	714.44	-	-	38.5	
	29/12/08	-0.0312	990.54	899.07	24.82	764.01	-	-	38.5	
	30/12/08	-0.0318	989.20	899.52	24.82	757.32	-	-	38.5	
	31/12/08	-0.0295	989.98	899.01	24.82	816.90	-	-	38.5	

▨ Data not reliable: problems with the PLC.

■ Rotative sieve fault: pilot plant out of order.

☐ Automatic control.

Δ TMP	- 40.9 %							
Δ Permeability					+ 41.1 %			
Δ Permeability (T)						- 6.5 %		
Δ Inflow/Permeate flow		- 21.9 %	- 19.5%					
Δ Air flow								~ 0
Δ T							- 0.21	

Experimentation with hollow fibre membranes

		TMP	Permeate flow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow	
JANUARY 2009		bar	$L\cdot h^{-1}$	$L\cdot m^{-2}\cdot h^{-1}$	$LMH\cdot bar^{-1}$	$LMH\cdot bar^{-1}$	ºC	$m^3\cdot h^{-1}$	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	01/01/09	-0.0108	-	-	-	-	15.3	38	CONSTANT FLOW
	02/01/09	-0.0233	994.85	24.9	-	-	15.0	38	
	03/01/09	-0.0507	994.85	24.9	555.3	475.3	14.9	38	
	04/01/09	-0.0316	994.85	24.9	902.1	764.8	14.0	38	
	05/01/09	-0.0216	994.85	24.9	-	-	13.3	38	
	06/01/09	-0.0267	994.85	24.9	499.1	826.7	13.0	38	
	07/01/09	-0.0266	995.71	24.9	-	-	12.7	38	
	08/01/09	-0.0312	994.85	24.9	921.9	722.8	11.4	38	
	09/01/09	-0.0306	994.85	24.9	963.8	788.1	12.5	38	
	10/01/09	-0.0154	-	-	-	-	12.7	38	
	11/01/09	-0.0293	994.85	24.9	966.2	780.1	13.2	38	
	12/01/09	-0.0025	-	-	-	-	12.5	38	
	13/01/09	-0.0138	-	-	-	-	13.2	38	
	14/01/09	-0.0325	995.71	24.9	836.0	692.7	13.4	38	
	15/01/09	-0.0305	996.57	24.9	932.6	795.8	14.0	38	
	16/01/09	-0.0535	995.71	24.9	535.4	453.4	14.2	38	
	17/01/09	-0.0399	996.57	24.9	713.1	599.1	14.1	38	
	18/01/09	-0.0235	995.71	24.9	-	-	15.6	38	
	19/01/09	-0.0384	995.71	24.9	737.6	626.0	14.2	38	
	20/01/09	-0.0002	-	-	-	-	13.1	38	
	21/01/09	-0.0510	995.71	24.9	569.8	478.5	13.8	38	
	22/01/09	-0.0370	994.85	24.9	711.1	621.6	16.1	38	

Δ TMP	- 242%						
Δ Permeability				+28.1%			
Δ Permeability (T)					+30.8%		
Δ Permeate flow		0	0				
Δ Air flow							0
Δ T						+ 0.8	

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow	
MAY 2009		bar	L·h^{-1}	L·h^{-1}	L·m^{-2}·h^{-1}	LMH·bar^{-1}	LMH·bar^{-1}	ºC	m^3·h^{-1}	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	05/05/09	-0.007	999.17	1000.02	21.2	1286.9	1285.3	22.3	19.6	CONSTANT FLOW
	06/05/09	-0.007	1000.21	999.96	21.2	1233.4	1264.8	22.9	19.6	
	07/05/09	-0.005	1000.76	999.96	21.2	1140.1	1203.1	23.4	19.6	
	08/05/09	-0.016	998.63	999.98	21.2	1136.5	1103.5	23.2	19.6	
	09/05/09	-0.020	999.36	999.94	21.2	1020.5	975.9	23.0	19.6	
	10/05/09	-0.022	999.35	1000.00	21.2	963.1	911.1	22.9	19.6	
	11/05/09	-0.025	1039.86	999.92	22.1	897.4	847.3	22.7	19.6	
	12/05/09	-0.025	1076.92	999.96	22.8	915.1	844.2	23.8	19.6	
	13/05/09	-0.027	1076.85	999.85	22.8	866.0	802.5	23.6	19.6	
	14/05/09	-0.023	1075.86	999.92	22.8	835.6	806.6	22.8	19.6	
	15/05/09	-0.017	1077.57	1000.01	22.9	1200.4	1185.6	21.8	19.6	
	16/05/09	-0.022	1077.11	1000.00	22.8	1021.8	988.8	21.9	19.6	
	17/05/09	-0.023	1076.64	999.95	22.8	984.2	940.5	22.3	19.6	
	18/05/09	-0.027	1075.49	999.89	22.8	868.5	827.1	22.4	19.6	
	19/05/09	-0.027	1076.34	999.87	22.9	861.5	812.6	23.0	19.6	
	20/05/09	-0.023	1076.57	999.84	22.8	1009.8	941.6	23.5	19.6	
	21/05/09	-0.022	1077.98	999.81	22.9	1046.9	988.2	24.0	19.6	
	22/05/09	-0.021	1075.61	999.85	22.8	1092.5	1003.1	24.5	19.6	
	23/05/09	-0.025	1075.76	1000.14	22.8	931.2	845.0	24.2	19.6	
	24/05/09	-0.027	1074.03	999.88	22.8	855.0	772.2	24.4	19.6	
	25/05/09	-0.031	1074.38	999.85	22.8	738.2	669.4	24.3	19.6	
	26/05/09	-0.033	1076.55	999.94	22.5	687.1	622.3	24.3	19.6	
	27/05/09	-0.032	1076.56	1001.06	22.9	745.9	677.5	24.2	17.9	
	28/05/09	-0.032	1074.68	999.84	22.9	739.7	674.1	24.1	17.9	
	29/05/09	-0.017	1076.45	999.67	22.8	720.6	714.3	24.3	17.9	
	30/05/09	-0.017	1075.47	999.78	22.8	1155.3	1105.5	23.9	17.9	
	31/05/09	-0.031	1075.56	999.82	22.9	746.8	691.4	23.5	17.9	

▨ Pilot plant out of order.

Δ TMP	- 342%							
Δ Permeability					- 41.9%			
Δ Permeability (T)						- 46.2%		
Δ Inflow/Permeate flow		+ 7.5%	~ 0					
Δ Air flow								- 8.7%
Δ T							+ 1.2	

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow	
JUNE 2009		bar	$L\cdot h^{-1}$	$L\cdot h^{-1}$	$L\cdot m^{-2}\cdot h^{-1}$	$LMH\cdot bar^{-1}$	$LMH\cdot bar^{-1}$	ºC	$m^3\cdot h^{-1}$	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	01/06/09	-0.049	1077.7	998.1	22.8	399.0	375.8	22.8	17.9	CONSTANT FLOW
	02/06/09	-0.032	1076.1	1000.0	22.8	641.0	575.8	24.2	17.9	
	03/06/09	-0.037	1079.3	1000.0	22.9	539.3	489.1	24.4	17.9	
	04/06/09	-0.035	1068.9	1000.1	23.0	570.4	514.6	24.7	16.4	
	05/06/09	-0.031	1078.5	1001.1	23.1	634.2	577.7	24.2	16.4	
	06/06/09	-0.039	1069.7	1000.3	23.1	519.7	488.0	23.2	16.4	
	07/06/09	-0.046	1071.7	1000.0	23.0	437.6	409.7	23.2	16.4	
	08/06/09	-0.050	1078.2	999.2	22.9	403.9	380.3	23.0	16.4	
	09/06/09	-0.052	1073.5	998.8	23.0	402.0	368.3	24.2	16.7	
	10/06/09	-0.049	1081.2	1000.5	23.0	434.6	390.7	24.8	16.7	
	11/06/09	-0.051	1084.6	1000.2	23.0	419.4	376.7	25.1	16.1	
	12/06/09	-0.047	1071.9	1000.0	23.2	459.2	413.8	24.8	16.1	
	13/06/09	-0.043	1068.7	1000.3	23.0	476.6	413.4	26.0	16.4	
	14/06/09	-0.039	1077.5	1000.3	23.1	492.6	424.1	26.4	16.7	
	15/06/09	-0.044	1081.3	1000.0	23.0	454.2	391.1	26.6	17.6	
	16/06/09	-0.057	1074.4	999.7	23.0	377.3	322.8	26.8	18.5	
	17/06/09	-0.059	1072.8	999.2	22.9	313.4	265.9	26.9	20.2	
	18/06/09	-0.064	1074.3	999.4	22.8	328.0	277.8	27.1	20.2	
	19/06/09	-0.068	1071.4	999.9	22.9	311.7	266.0	27.1	19	
	20/06/09	-0.075	1076.6	998.8	22.9	284.8	246.1	26.6	18.2	
	21/06/09	-0.084	1070.2	998.8	23.0	253.9	224.6	25.4	17.6	
	22/06/09	-0.092	1074.0	1000.2	23.0	234.3	210.2	25.1	16.4	
	23/06/09	-0.094	1072.5	1000.0	23.0	232.8	206.0	25.7	15.9	
	24/06/09	-0.099	1076.9	999.8	23.0	224.1	197.9	25.8	15.9	
	25/06/09	-0.107	1079.6	999.8	23.0	205.7	181.3	25.7	15.9	
	26/06/09	-0.105	1078.9	999.4	23.2	208.1	180.0	26.3	20.2	
	27/06/09	-0.111	1077.6	1000.0	23.1	196.8	169.6	26.5	19	
	28/06/09	-0.119	1078.6	999.9	23.1	194.2	162.9	26.1	18.2	
	29/06/09	-	-	-	-	-	-	-	-	
	30/06/09	-	-	-	-	-	-	-	-	

▨ Pilot out of order for more than 1 hour.

Δ TMP	- 142.8%							
Δ Permeability					- 51.3%			
Δ Permeability (T)						-56.7 %		
Δ Inflow/Permeate flow		~ 0	~ 0					
Δ Air flow								- 18%
Δ T							+ 3.3	

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	Permeability (T)	T	Air-flow	
JULY 2009		bar	$L \cdot h^{-1}$	$L \cdot h^{-1}$	$L \cdot m^{-2} \cdot h^{-1}$	$LMH \cdot bar^{-1}$	$LMH \cdot bar^{-1}$	ºC	$m^3 \cdot h^{-1}$	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	01/07/09	-0.124	1059.4	898.0	22.4	172.0	27.6	145.1	15.9	CONSTANT FLOW
	02/07/09	-0.132	1061.8	893.9	22.5	164.4	27.9	138.2	15.9	
	03/07/09	-0.136	1060.8	852.2	22.5	156.7	27.8	131.6	15.9	
	04/07/09	-0.144	1058.8	900.8	22.4	148.7	28.1	124.0	15.9	
	05/07/09	-0.154	1059.3	858.7	22.4	139.1	27.3	118.2	15.9	
	06/07/09	-0.145	1061.5	907.1	22.6	150.0	27.4	126.6	15.9	
	07/07/09	-0.148	1055.8	894.3	22.5	145.5	27.1	123.6	15.9	
	08/07/09	-0.153	1060.9	883.4	22.6	142.4	26.3	123.1	15.9	
	09/07/09	-0.149	1059.3	834.1	22.4	144.1	25.4	128.0	15.9	
	10/07/09	-0.143	1061.6	822.0	22.5	149.9	25.9	131.7	15.9	
	11/07/09	-0.147	1059.2	815.7	22.5	141.6	25.8	124.3	15.9	
	12/07/09	-0.144	1052.7	764.4	22.3	143.0	26.1	124.9	15.9	
	13/07/09	-0.143	1052.0	776.0	22.3	145.9	27.2	123.7	15.9	
	14/07/09	-0.163	1051.8	897.7	22.3	131.9	28.1	109.9	15.9	
	15/07/09*	-0.181	1056.8	886.2	22.4	118.3	27.9	99.1	15.9	
	16/07/09	-0.194	1055.4	880.1	22.4	108.9	28.0	90.8	15.9	
	17/07/09	-0.211	1050.8	895.3	22.3	99.3	27.8	82.8	15.9	
	18/07/09	-0.243	1042.9	873.5	22.1	87.4	26.0	76.7	15.9	
	19/07/09	-0.228	1041.2	825.8	22.0	92.4	26.3	80.8	15.9	
	20/07/09	-0.224	1030.1	838.3	21.9	88.1	26.0	77.7	15.9	
	21/07/09	-0.226	1045.5	897.3	22.2	92.5	27.5	78.5	15.9	
	22/07/09	-0.227	1037.8	849.7	22.0	90.3	27.5	76.5	15.9	
	23/07/09	-0.228	1030.9	842.6	21.9	89.0	28.8	73.0	15.9	
	24/07/09	-0.226	1036.2	790.4	22.0	90.4	29.2	73.6	20.2	
	25/07/09	-0.240	1037.1	822.1	22.0	86.2	28.2	71.9	19	
	26/07/09	-0.251	1029.7	806.2	21.8	82.2	27.2	70.4	18.4	
	27/07/09	-	-	-	-	-	-	-	18.2	
	28/07/09	-	-	-	-	-	-	-	-	
	29/07/09	-	-	-	-	-	-	-	-	
	30/07/09	-	-	-	-	-	-	-	-	

▨ Power cut for several hours.

* Internal recycle pump breaks down at 18.30.

Δ TMP	- 102.4%							
Δ Permeability					- 52.2%			
Δ Permeability (T)							-51.5 %	
Δ Inflow/Permeate flow		~ 0	~ 0	~ 0				
Δ Air flow								-21%
Δ T						-0.4		

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Permeability (T)	Air-flow	
AUGUST 2009		bar	$L\cdot h^{-1}$	$L\cdot h^{-1}$	$L\cdot m^{-2}\cdot h^{-1}$	$LMH\cdot bar^{-1}$	ºC	$LMH\cdot bar^{-1}$	$m^{3}\cdot h^{-1}$	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	01/08/09	-0.2339	1045.5	993.0	22.2	89.6	28.9	72.7	15.9	CONSTANT FLOW
	02/08/09	-0.2583	1043.5	997.2	22.1	80.9	28.0	67.2	15.9	
	03/08/09	-0.2699	1040.5	994.1	22.0	77.5	27.2	65.8	17	
	04/08/09	-0.2583	1047.9	996.1	22.2	80.3	27.5	67.4	18.20	
	05/08/09	-0.2524	1033.6	990.8	21.9	80.2	29.2	64.5	19.6	
	06/08/09	-0.2607	1035.6	992.3	22.0	77.7	29.3	62.5	18.20	
	07/08/09	-0.2697	1022.0	996.0	21.7	74.5	29.0	60.8	17	
	08/08/09	-0.3037	1035.8	995.8	21.9	65.9	28.2	54.8	18.20	
	09/08/09	-0.3308	1022.3	999.0	21.6	59.5	27.9	49.8	19.6	
	10/08/09	-0.3137	1034.6	992.2	22.0	65.7	27.4	54.9	20.2	
	11/08/09	-0.3115	1025.5	993.0	21.7	65.0	27.4	55.5	20.2	
	12/08/09	-0.3212	1018.6	997.1	21.6	61.8	27.6	55.5	18.4	
	13/08/09	-0.3306	1016.3	998.3	21.5	60.0	28.0	52.3	17.6	
	14/08/09	-0.2989	1009.9	997.1	21.4	66.6	28.4	50.4	17	
	15/08/09	-0.298	1027.4	995.9	21.8	68.3	28.1	55.3	15.9	
	16/08/09	-0.3151	1009.5	994.1	21.4	62.6	27.7	57.3	15.9	
	17/08/09	-0.305	1017.6	996.5	21.5	65.3	27.8	53.3	15.9	
	18/08/09	-0.3024	1016.6	996.3	21.5	66.1	28.0	56.3	15.9	
	19/08/09	-0.3236	1021.2	996.9	21.6	61.7	28.3	55.7	15.9	
	20/08/09	-0.3406	1001.1	993.3	21.2	56.8	28.5	51.9	15.9	
	21/08/09	-0.312	1012.9	996.3	21.4	60.7	28.6	47.3	17	
	22/08/09	-0.2956	1003.2	998.0	21.2	64.7	28.2	50.3	22.2	
	23/08/09	-0.2939	1001.0	985.4	21.2	64.0	28.4	54.8	22.2	
	24/08/09	-0.2969	1021.0	993.2	21.6	65.4	28.1	54.0	20.2	
	25/08/09	-0.3047	1018.4	998.5	21.6	63.6	28.0	55.5	19.6	
	26/08/09	-	-	-	-	-	-	-	19.6	
	27/08/09	-0.0362	1065.3977	999.0929	22.6	593.1	28.8	484.2	19.6	

▨ Recovery chemical cleaning.

Δ TMP	- 30.3%							
Δ Permeability					- 29%			
Δ Permeability (T)							-23.7 %	
Δ Inflow/Permeate flow		~ 0	~ 0	~ 0				
Δ Air flow								-21%
Δ T						-0.9		

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Permeability (T)	Air-flow	
SEPTEMBER 2009		bar	L·h^{-1}	L·h^{-1}	L·m^{-2}·h^{-1}	LMH·bar^{-1}	°C	LMH·bar^{-1}	m^3·h^{-1}	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	1/9/09									CONSTANT FLOW
	2/9/09									
	3/9/09	-0.0939	1061.8	994.8	22.7	249.8	29.4	199.3	19.6	
	4/9/09	-0.0763	1066.6	998.7	22.8	276.9	28.8	224.4	19.6	
	6/9/09	-0.0913	1069.6	995.6	22.6	232.1	27.1	196.0	19.6	
	7/9/09	-0.1093	1064.4	996.2	22.5	196.0	26.8	169.0	19.6	
	8/9/09	-0.1142	1060.3	999.1	22.4	188.2	27.1	160.4	19.6	
	9/9/09	-0.1024	1056.9	991.0	22.4	207.2	26.9	179.3	19.6	
	10/9/09	-0.0993	1059.3	992.1	22.5	212.6	26.3	184.4	19.6	
	11/9/09	-0.0933	1064.4	993.4	22.5	226.8	26.5	197.7	19.6	
	12/9/09	-0.1624	1042.4	935.4	22.0	140.3	25.9	123.9	19.6	
	13/9/09*									
	14/9/09	-0.1785	1044.0	990.4	22.0	123.7	25.5	111.5	19.6	
	15/9/09	-0.1915	1032.7	990.4	21.9	119.9	24.0	110.5	19.6	
	16/9/09	-0.1028	1042.7	992.1	22.1	201.6	23.7	187.3	19.6	
	17/9/09	-0.0746	1053.8	992.2	22.3	282.7	24.2	257.0	19.6	
	18/9/09	-0.0686	1068.4	995.6	22.6	296.5	23.6	274.3	19.6	
	19/9/09*									
	20/9/09	-0.0729	1051.2	991.2	22.3	276.6	23.8	254.0	19.6	
	21/9/09	-0.0547	1001.1	995.2	21.2	308.6	24.7	280.0	19.6	
	22/9/09	-0.0703	1068.9	1019.1	22.6	296.3	25.3	263.6	19.6	
	23/9/09	-0.0694	1087.7	1035.7	23.0	315.9	25.5	280.2	19.6	
	24/9/09	-0.0665	1083.9	1021.7	22.9	327.1	25.6	289.2	19.6	
	25/9/09	-0.0643	1057.4	1021.0	22.4	331.4	26.0	289.5	19.6	
	26/9/09	-0.0648	1065.8	1029.0	22.5	340.2	25.9	297.2	19.6	
	27/9/09	-0.0804	1074.8	1036.4	22.8	287.7	24.9	258.2	19.6	
	28/9/09	-00999	1073.9	1038.9	22.8	231.2	25.1	207.1	19.6	
	29/9/09	-0.0919	1076.5	1020.0	22.8	231.3	25.2	205.2	19.6	

▨ Pilot plant out of order.

* Data not saved.

Δ TMP	+2.1%							
Δ Permeability					-7.4%			
Δ Permeability (T)							+3.1 %	
Δ Inflow/Permeate flow		~ 0	~ 0	~ 0				
Δ Air flow								0
Δ T						-4.2		

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Permeability (T)	Air-flow	
OCTOBER 2009		bar	L·h^{-1}	L·h^{-1}	L·m^{-2}·h^{-1}	LMH·bar^{-1}	°C	LMH·bar^{-1}	m^{3}·h^{-1}	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	1/10/09	-0.1107	1085.8	1039.9	23.0	196.3	25.1	175.5	19.6	CONSTANT FLOW
	2/10/09	-0.1159	1053.6	1020.5	22.3	181.7	25.0	164.3	19.6	
	3/10/09	-0.1270	1061.1	1029.7	22.4	166.9	25.1	150.2	19.6	
	4/10/09	-0.1101	893.1	851.3	18.9	163.4	24.5	148.2	19.6	
	5/10/09	-0.1459	1172.2	1208.4	24.8	160.5	25.8	141.8	19.6	
	6/10/09	-0.1373	1138.2	1168.9	24.1	166.2	26.2	144.4	19.6	
	7/10/09	-0.1472	1052.0	1008.2	22.3	147.6	26.0	128.7	19.6	
	8/10/09	-0.1601	1051.8	1021.8	22.3	133.4	26.7	115.2	19.6	
	9/10/09	-0.1680	1022.2	1014.4	21.6	121.5	26.6	105.3	19.6	
	10/10/09	-0.1819	999.9	1033.2	21.1	108.6	26.2	94.9	19.6	
	11/10/09	-0.2377	926.6	1008.1	19.6	81.6	24.9	73.4	19.6	
	12/10/09	-0.2621	921.9	1000.4	19.5	67.5	25.1	60.6	19.6	
	13/10/09	-0.2711	895.5	986.5	18.9	64.0	24.5	58.3	19.6	
	14/10/09	-0.2858	960.0	1013.2	20.3	67.3	23.7	62.6	19.6	
	15/10/09	-0.2466	1052.4	1034.9	22.3	86.4	23.3	81.8	19.6	
	16/10/09	-0.2532	1028.9	1018.9	21.8	80.9	22.3	78.3	19.6	
	17/10/09	-0.2790	1031.3	1035.2	21.9	75.8	22.2	73.0	19.6	
	18/10/09	-0.2753	1027.8	1029.8	21.8	74.6	22.1	72.2	19.6	
	19/10/09	-0.2281	888.4	839.3	18.8	75.6	21.7	74.1	19.6	
	20/10/09	-0.0836	1241.5	1168.3	26.3	299.0	21.1	296.4	19.6	
	21/10/09	-0.0570	1071.5	1029.7	22.7	384.5	21.1	380.3	19.6	
	22/10/09	-0.0783	1118.7	1088.3	23.7	291.6	19.9	295.5	19.6	
	23/10/09	-0.0853	1106.2	1053.0	23.4	253.3	19.2	262.8	19.6	
	24/10/09	-0.0885	1211.8	1186.0	25.7	264.4	22.0	255.4	19.6	
	25/10/09	-0.0756	1079.5	1040.8	22.8	265.6	22.8	253.6	19.6	
	26/10/09	-0.0742	1091.2	1029.2	23.3	278.3	23.3	261.0	19.6	
	27/10/09	-0.0987	1203.0	1223.7	25.8	250.4	23.0	233.1	19.6	
	28/10/09	-0.0933	1146.4	1160.2	24.3	240.4	23.6	224.1	19.6	
	29/10/09	-0.0955	1191.1	1209.9	25.3	266.7	24.1	246.7	19.6	
	30/10/09	-0.0918	1163.3	1107.9	24.8	248.0	23.9	227.5	19.6	
	31/10/09	-0.0870	1076.0	1040.9	22.9	242.6	22.9	228.4	19.6	

▨ Chemical cleaning

Δ TMP	+27%							
Δ Permeability					+23.6%			
Δ Permeability (T)							+30.1 %	
Δ Inflow/Permeate flow		~ 0	~ 0	~ 0				
Δ Air flow								0
Δ T						-2.2		

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Permeability (T)	Air-flow	
NOVEMBER 2009		bar	$L \cdot h^{-1}$	$L \cdot h^{-1}$	$L \cdot m^{-2} \cdot h^{-1}$	$LMH \cdot bar^{-1}$	°C	$LMH \cdot bar^{-1}$	$m^3 \cdot h^{-1}$	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	1/11/09	-	-	-	-	-	-	-	-	CONSTANT FLOW
	2/11/09	-0.0953	1112.2	1054.3	23.6	225.7	22.8	213.7	19.6	
	3/11/09	-0.0917	1034.5	1010.0	21.9	216.4	22.2	207.9	19.6	
	4/11/09	-0.0964	1060.1	1041.0	22.4	211.0	22.1	203.6	19.6	
	5/11/09	-0.1013	1036.5	1040.4	22.0	202.2	21.2	198.9	19.6	
	6/11/09	-0.1106	1032.3	1091.1	21.9	184.9	19.9	188.4	19.6	
	7/11/09	-0.1094	1066.9	1033.7	22.6	190.9	20.6	191.1	19.6	
	8/11/09	-0.1148	1052.1	765.4	22.3	182.6	0.0	188.3	19.6	
	9/11/09	-0.1189	1028.6	1298.9	21.8	168.9	0.0	175.4	19.6	
	10/11/09	-0.1179	1094.3	1038.2	23.1	187.6	18.0	200.4	19.6	
	11/11/09	-0.1244	1036.7	991.4	21.9	166.8	18.3	175.3	19.6	
	12/11/09	-0.1373	1182.7	1172.2	25.0	174.1	19.9	176.9	19.6	
	13/11/09	-0.1329	1069.0	1067.3	22.6	165.8	20.2	168.0	19.6	
	14/11/09	-0.1166	1021.2	962.5	21.6	173.9	20.3	175.6	19.6	
	15/11/09	-0.1477	1075.9	1059.9	22.8	149.8	20.2	152.1	19.6	
	16/11/09	-0.1249	948.7	917.7	20.1	151.9	19.6	156.0	19.6	
	17/11/09	-0.1460	1151.3	1172.8	24.5	163.5	20.0	165.2	19.6	
	18/11/09	-0.1320	1062.0	1015.0	22.5	164.9	20.7	165.7	19.6	
	19/11/09	-0.1392	1052.5	991.9	22.3	155.3	20.6	156.2	18.4	
	20/11/09	-0.1582	1074.7	1027.7	22.7	146.1	20.5	148.0	17.6	
	21/11/09	-	1214.0	1146.5	25.7	115.5	20.8	115.0	18.4	
	22/11/09	-	1197.2	1133.8	25.3	107.0	20.8	106.8	19.6	
	23/11/09	-	1326.7	1282.5	28.1	119.6	19.9	121.9	19.6	
	24/11/09	-0.2103	1317.1	1262.7	27.9	125.2	19.5	128.7	19.6	
	25/11/09	-0.1443	975.2	853.7	20.6	136.4	18.5	144.6	18.4	
	26/11/09	-	-	-	-	-	-	-	17.6	
	27/11/09	-0.1506	1136.6	1107.8	24.0	155.6	20.2	157.4	16.1	
	28/11/09	-0.1550	1087.0	1050.6	23.0	143.7	19.6	147.8	15.9	
	29/11/09	-0.1627	1099.6	1042.6	23.3	139.2	18.6	146.5	15.9	
	30/11/09	-0.1734	1104.8	1062.5	23.4	131.6	17.4	143.3	15.9	

Δ TMP	-81%							
Δ Permeability					-41.7%			
Δ Permeability (T)							-32.9%	
Δ Inflow/Permeate flow		~ 0	~ 0	~ 0				
Δ Air flow								-20.5%
Δ T						-5.4		

		TMP	Permeate flow	Inflow	Flux (LMH)	Permeability	T	Permeability (T)	Air-flow	
DECEMBER 2009		bar	$L\cdot h^{-1}$	$L\cdot h^{-1}$	$L\cdot m^{-2}\cdot h^{-1}$	$LMH\cdot bar^{-1}$	°C	$LMH\cdot bar^{-1}$	$m^3\cdot h^{-1}$	
FILTRATION / BACKWASH = 10 minutes / 40 seconds	1/12/09	-0.1801	1084.1	1143.2	23.0	124.4	16.7	137.8	17.0	CONSTANT FLOW
	2/12/09	-0.1819	1094.1	1178.0	23.1	124.4	16.9	135.5	18.2	
	3/12/09	-0.1673	1096.8	1200.3	23.2	135.3	17.8	145.5	19.6	
	4/12/09	-0.1780	1089.3	1197.0	23.1	127.1	16.8	140.4	19.6	
	5/12/09	-0.1815	1083.1	1165.2	22.9	124.1	17.0	136.5	19.6	
	6/12/09	-0.1884	1086.6	1006.1	23.0	119.7	17.3	130.9	18.4	
	7/12/09	-0.1919	1079.6	1158.3	22.8	117.6	17.1	129.2	19.6	
	8/12/09	-0.1853	1106.8	1054.6	23.4	123.9	18.7	129.9	19.6	
	9/12/09	-0.2072	1082.4	1177.5	22.9	109.4	17.6	118.6	19.0	
	10/12/09	-0.2310	1078.7	1136.3	22.8	99.3	17.6	108.2	19.0	
	11/12/09	-0.2553	1089.7	1052.5	23.0	90.3	18.0	97.1	19.6	
	12/12/09	-0.2886	1066.2	1071.1	22.6	78.2	17.5	85.4	19.6	
	13/12/09	-0.3133	1021.0	1063.6	21.6	66.3	16.6	74.1	19.6	
	14/12/09	-0.3019	981.8	952.7	20.8	63.4	15.7	72.6	19.6	
	15/12/09	-0.2883	1036.0	990.6	21.9	71.2	15.7	81.8	19.6	
	16/12/09	-0.2538	1048.4	991.4	22.2	82.2	15.0	95.1	19.6	
	17/12/09	-0.2583	1043.8	990.5	22.1	79.9	15.3	91.5	18.2	
	18/12/09	-0.2914	1030.8	987.4	21.8	69.1	15.2	79.7	17.0	
	19/12/09	-0.3528	1013.2	987.7	21.4	55.7	15.0	64.6	16.1	
	20/12/09	-0.3926	990.3	986.1	20.9	49.1	14.0	58.0	17.0	
	21/12/09	-0.3930	962.3	985.6	20.4	47.1	13.5	55.6	18.2	
	22/12/09	-0.3722	974.4	986.5	20.7	49.7	14.0	58.9	18.2	
	23/12/09	-0.3829	972.3	975.5	20.7	48.1	14.0	56.8	17.9	
	24/12/09	-0.3387	998.6	986.4	21.1	57.4	15.2	66.6	17.0	
	25/12/09	-0.3674	991.6	989.2	21.0	52.7	15.5	61.0	15.9	
	26/12/09	-0.3614	995.0	994.8	21.1	53.6	15.8	61.9	15.9	
	27/12/09	-0.3491	956.2	993.8	20.3	50.4	15.7	57.7	15.9	
	28/12/09	-0.3429	988.3	945.1	21.1	56.0	16.5	61.4	15.9	
	29/12/09	-0.3123	958.1	992.5	20.3	58.4	18.2	64.2	15.9	
	30/12/09	-0.2954	1010.7	993.6	21.4	67.1	18.8	72.3	15.9	
	31/12/09	-0.3047	1033.1	994.7	21.9	65.5	18.5	71.2	15.9	

Δ TMP	-69.2%							
Δ Permeability					-47.3%			
Δ Permeability (T)							-48.3%	
Δ Inflow/Permeate flow		~ 0	~ 0	~ 0				
Δ Air flow								-20.5%
Δ T						+1.8		

RESULTS OF THE BIOLOGICAL NUTRIENT REMOVAL PROCESS

Experimentation with flat sheet membranes

	INFLUENT										
Day	TN	TSS	VSS	COD_T	COD_S	BOD_5	NH_4^+	PO_4^{3-}	TOC	TC	IC
28/4/08	-	468	328	733	-	447	-	-	-	-	-
29/4/08	56	164	-	652	-	398	64	>3.5	-	-	-
30/4/08	-	228	212	685	-	418	56	-	-	-	-
5/5/08	51	104	104	597	-	364	76	>3.5	-	-	-
8/5/08	62.9	62	62	512	406	312	64	>3.5	33.5	156.7	123.2
12/5/08	29	42	42	233	189	142	25.9	-	18.7	98.93	80.22
14/5/08	57.1	-	-	416	177	254	45.6	3.52	16.8	120.6	103.8
19/5/08	45.8	-	-	479	109	292	36.70	4.03	25.1	123.3	98.24
21/5/08	42.6	130	122	382	155	233	38.30	4.96	23.60	60.67	37.07
26/5/08	34.9	118	118	317	103	193	28.00	2.04	15.56	116.30	100.80
28/5/08	-	102	82	339	176	207	27.90	2.31	14.21	137.40	123.20
2/6/08	-	180	150	712	162	434	20.00	1.81	12.58	138.00	125.50
4/6/08	-	186	174	393	198	240	30.00	3.12	21.31	159.90	138.60
9/6/08	-	316	312	726	231	443	30	3.67	38.28	194.60	156
11/6/08	-	236	232	426	188	260	42	-	-	-	-
26/6/08	66.8	136	112	354	263	216	57.8	3.34	16.8	142.6	125.7
30/6/08	56.1	148	140	562	373	343	45.6	5.87	16	131.3	115.3
2/7/08	69.9	222	192	476	315	290	51.5	6.56	158	326.5	168
7/7/08	70	164	156	833	436	508	47.4	8.38	15.9	136.5	120.7
9/7/08	114	158	148	560	335	342	57	6.7	35.8	158.6	122.8
14/7/08	55.8	48	32	176	138	107	37.6	6.92	18.8	116.4	97.6
16/7/08	75.8	238	122	354	227	216	39	7.04	-	-	-
21/7/08	67.6	222	216	557	227	340	42	13.52	15	126	111
23/7/08	75.7	224	-	552	256	337	45.6	9.32	15.8	129	113.2
30/07/08	87.3	200	188	422	198	257	54	11.5	13.8	135.5	121.7
4/08/08	74.1	294	234	592	226	-	47.2	8.52	4.63	62.82	58.18
6/08/08	71.2	140	140	436	214	151	48.2	6.64	-	-	-
11/08/08	73.1	116	116	477	319	-	53	11.2	-	-	-
13/08/08	72.5	196	196	477	287	255	53.8	6.32	3.15	127	123.8
18/08/08	-	220	220	583	275	-	52.4	12.48	1.68	125.7	124.1
20/08/08	72.8	100	100	589	287	-	53	12.14	6.68	126.9	120.2

	INFLUENT										
Day	TN	TSS	VSS	COD_T	COD_S	BOD_5	NH_4^+	PO_4^{3-}	TOC	TC	IC
25/08/08	52.3	268	204	416	242	-	37.2	5.94	24.3	117	92.86
1/9/08	47.7	152	152	455	222	278	35.4	5.24	18.7	112	93.29
3/9/08	61.6	140	140	369	207	225	43.2	4.62	16.9	109	92.14
8/9/08	69.5	144	144	383	221	234	54	4.22	-	-	-
18/9/08	59.9	256	156	526	202	321	39.8	10.5	14.5	136.5	121.9
22/9/08	55.4	253	253	501	204	306	40.8	5.26	20.8	112.6	101.8
25/09/08	62.4	144	144	409	235	249	49.2	-	13	136.3	123.3
30/09/08	61.2	232	208	532	232	325	42	3.69	9.43	132.8	123.4
2/10/08	60.2	216	-	430	205	262	49	3.02	4.05	128.2	124.2
6/10/08	65.5	180	180	462	233	282	51	2.27	19	143.6	127.7
8/10/08	61.4	180	-	460	246	281	50.8	2.67	-	-	-
13/10/08	82.2	465	380	791	266	483	48.2	2.30	141	142.9	1.905
15/10/08	59.5	144	144	413	230	252	45.7	2.80	2.5	75.93	73.43
20/10/08	76.1	176	-	533	251	325	49.5	2.26	25.4	148.1	122.8
22/10/08	82.1	142	-	316	174	193	38.4	2.18	15.4	127.2	111.8
27/10/08	64.1	-	-	497	181	303	35	2.25	18.3	145.6	127.3
3/11/08	41.9	381	357	381	108	232	31.0	1.02	15.2	100.7	85.59
6/11/08	53.9	300	248	643	176	392	43.2	1.43	22.7	130.5	107.8
11/11/08	51.8	316	266	371	150	226	29.6	2.30	9.91	111.4	101.5
17/11/08	64.4	392	300	523	136	319	20.3	2.57	7.12	109	101.9
19/11/08	50.4	200	184	398	183	243	26.8	1.65	7.66	110.5	102.8
25/11/08	53.1	184	-	398	139	243	28.7	1.77	7.79	109.4	101.6
11/12/08	45.3	88	-	289	190	176	31.5	2.11	-	-	-
15/12/08	51.4	228	-	461	217	281	34.1	2.29	-	-	-
17/12/08	49.3	168	168	411	254	121	35.5	2.01	-	-	-
29/12/08	36.2	104	104	296	199	181	-	1.08	-	-	-

	EFFLUENT										
Day	TSS	COD_S	BOD_5	TN	NH_4^+	NO_3^-	NO_2^-	PO_4^{3-}	TOC	TC	IC
29/4/08	7	18	3.8	-	-	-	-	-	-	-	-
30/4/08	0.6	20	4.2	-	1	15.9	1	-	-	-	-
5/5/08	0	21	4.4	10	0	10.2	0	3.5	-	-	-
8/5/08	3	37	7.8	-	0.5	9.5	0	-	3.849	65.2	61.35
12/5/08	0	8	1.7	-	0.6	9.7	0	-	0.915	31.21	30.3
14/5/08	-	12	2.5	-	1.2	16.6	1	3.3	1.647	45.77	44.12
19/5/08	-	32	6.7	-	1.7	12.9	0	3.3	3.785	56.08	52.29
21/5/08	2.7	2	0.4	-	3	8.6	0	3.0	3.45	56.00	52.54
26/5/08	0.3	21	4.4	-	3.20	12.2	0	2.8	4.67	54.93	50.26
28/5/08	0.3	19	3.9	-		9.0	0	1.8	3.5	81.2	77.69
2/6/08	0	20	4.2	-	0	5.8	1	2.9	11.45	98.41	86.96
4/6/08	0.3	18	3.8	-	3	6.1	0	2	10	99	89
9/6/08	0	19	3.9	-	0	5.6	3	2	11	110	99
11/6/08	1	31	6.5	-	0	7.1	1	-	-	-	-
26/6/08	0.3	21.8	4.6	42.6	0.03	24.6	0.15	4.2	13	67.65	54.65
30/6/08	1	21.4	4.5	20.7	1.47	12.5	0.13	0.7	10.09	79.57	69.48
2/7/08	1.3	18.2	3.8	24.7	0.05	16.5	0.01	2.4	58.94	146.3	87.31
7/7/08	0.7	23.7	4.9	79.5	0	18.9	0.02	7.2	7.42	73.98	66.56
9/7/08	0.3	20.9	4.4	47.6	0	25.8	0.01	7.4	7.65	75.43	67.79
14/7/08	1	19	3.9	26.3	0.04	18.52	0.07	2.8	12.14	65.23	53.08
16/7/08	0	17.2	3.6	40.1	0	24.6	0	5.8	9.841	71.24	61.4
21/7/08	0.67	18.7	3.9	33.5	0	20.6	0.01	7.7	7.31	122.6	115.3
23/7/08	1.67	21.2	4.4	36.8	0	23.2	0.01	8.5	5.33	64.08	58.75
30/07/08	2	20.9	4.4	36.8	0.55	22	0.08	8.5	11.26	74.67	63.41
4/08/08	0	23.4	-	34.5	0.04	24.0	0.01	9.0	9.46	117.60	108.10
6/08/08	1.67	19	10	24.2	0.05	20.8	0.01	7.1	9.04	72.10	63.07
11/08/08	2.67	20.4	-	19.1	0.05	23.0	0.01	7.8	2.25	75.51	73.26
13/08/08	0	20.3	3	22.6	0.03	16.9	0.07	7.9	7.50	77.95	70.45
18/08/08	2.67	19.1	-	-	0.03	20.2	0.01	9.5	6.68	126.9	120.2
20/08/08	4.67	18.8	-	22.7	0.02	19	0.01	8.1	4.84	69.26	64.42
25/08/08	10.5	32.3	-	20.2	6.14	14.9	0.01	6.6	3.58	67.06	63.48
1/9/08	0	17.9	3.8	16.9	0	13.4	0.01	3.4	4.43	63.49	59.05
3/9/08	0	16.6	3.5	11	0	10.9	0.01	8.1	-	-	-
8/9/08	0.3	17.8	3.7	21.9	0.07	18.2	0.01	3.9	2.98	59.05	56.08
18/9/08	1.33	15.3	3.2	13.1	0.02	12.8	0.01	4.2	5.82	75.16	69.34

	EFFLUENT										
Day	TSS	COD_S	BOD_5	TN	NH_4^+	NO_3^-	NO_2^-	PO_4^{3-}	TOC	TC	IC
22/9/08	0.7	16.8	3.5	14.6	0.02	11.4	0.01	3.6	4.56	63.82	59.26
25/09/08	0.67	14.5	3.0	20	0.02	19.8	0.01	-	6.27	60.87	54.61
30/09/08	1	14.8	3.1	20.8	0.02	14.1	0.01	1.2	12.14	78.54	66.39
2/10/08	0	10	2.1	19	0.03	15.5	-	1.2	8.60	71.87	63.27
6/10/08	0	13.9	2.9	20.1	0.02	14.3	0.01	4.1	8.38	75.16	66.78
8/10/08	0	15	3.2	20.2	0.01	16.7	0.01	1.4	-	-	-
13/10/08	0	16.3	3.4	16.3	0.02	12.7	0.01	0.8	9.14	76.21	67.07
15/10/08	0.7	13.2	2.8	17.2	0.03	13.9	0.01	0.9	140.8	144.7	3.84
20/10/08	0	12.8	2.7	17.6	0.02	15.2	0	1.3	6.55	71.06	64.51
22/10/08	0	14.1	3.0	16.1	0.02	13.5	0.01	1.3	4.52	72.07	67.56
27/10/08	-	14.7	3.1	16.8	0.1	14.5	0	1.2	11.81	81.78	69.97
3/11/08	1.7	11.1	2.3	17.1	0.03	13.1	0	0.9	5.58	46.65	41.07
6/11/08	0.7	15.4	3.2	20.4	0.01	17.3	0	0.9	5.81	66.55	60.74
11/11/08	11.9	13.5	2.8	13.5	0.03	13.0	0	0.6	6.42	67.17	60.75
17/11/08	0	15.1	3.2	14.8	0.01	11.1	0.01	0.2	68.03	70.03	1.99
19/11/08	0.67	14.8	3.1	12.5	0.01	10.4	0.01	-	8.09	76.99	68.9
25/11/08	1.33	15	3.2	18.5	0.01	13.6	0.01	0.5	14.68	77.29	62.61
11/12/08	0	15.6	3.2	13.1	0.01	10.7	0.02	0.7	-	-	-
15/12/08	0	14.4	3.1	18.9	0	18.9	0.01	0.6	-	-	-
17/12/08	0	8.36	1	13	0	11.9	0.10	0.5	-	-	-
29/12/08	0.33	0.75	0.2	5.61	0.06	6.78	-	0.4	-	-	-

	ANAEROBIC		ANOXIC		AEROBIC		MEMBRANES				
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS	Filtrab	EPS tot	EPS/VSS
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mL	mgEPS/L	mgEPS/gVSS
30/07/08	5660	3301	8180	-	9880	-	12400	-	7	123.44	22.06
1/08/08	6120	4460	8320	5940	9920	7020	12320	8480	9	-	-
4/08/08	6160	4520	8640	6380	10400	6840	12920	9160	10	-	-
6/08/08	5860	4260	8640	6300	10180	7260	12660	8880	10	176.79	19.30
8/08/08	3620	2740	8780	6260	10240	7220	13080	9160	8	-	-
11/08/08	3480	2700	8220	6160	10640	7160	13140	9120	12	-	-
13/08/08	6200	4560	8420	5980	9780	6920	12320	8660	12.5	-	-
18/08/08	4340	3380	8080	5860	10180	7340	13000	9260	11	290.53	33.55
20/08/08	7560	5700	8380	6160	9800	7100	12200	8740	12	-	-
22/08/08	6560	4960	8240	6040	9920	7300	12720	9120	14	-	-
25/08/08	5460	4160	6940	5120	8140	5980	10860	7940	14.5	-	-
27/08/08	5900	4420	7460	5500	9240	6740	11820	8480	12.5	-	-
1/9/08	7400	4080	7440	6160	8940	6680	11760	8540	13.5	-	-
3/9/08	5720	4460	7380	5560	9760	7240	12380	8880	11	-	-
5/9/08	6500	4620	7640	5740	9540	7040	12120	8620	13.5	-	-
8/9/08	6980	5240	8480	5580	10880	8040	13820	9869	12	-	-
10/9/08	6780	5020	8040	5840	10200	7260	12920	9100	16	-	-
12/9/08	6560	4780	8200	5860	10400	7240	13280	9080	14	-	-
16/9/08	6400	4580	9320	6540	11940	8160	14720	10140	16	362.46	36.1
18/9/08	7620	5420	9520	6500	12120	8320	14120	9560	13	-	-
22/9/08	8020	5680	9880	6840	12700	8700	15760	10680	14	-	-
24/9/08	7320	5160	9480	6540	11560	7860	14900	10000	18	244.84	23.59
29/9/08	7420	4760	8380	5920	10560	7440	13280	9060	13	-	-
1/10/08	7000	4960	8760	6060	10240	7100	13480	9240	14	-	-
3/10/08	7220	4760	8300	5800	9520	6660	13100	8940	14	-	-
7/10/08	7780	5460	8240	5740	9940	6860	13060	8880	18	-	-
9/10/08	6220	4520	7940	5600	9700	6780	12880	8880	14	341.2	38.42
13/10/08	8040	5860	8740	6240	10120	7080	13220	9080	15	-	-
15/10/08	7300	5300	9160	6520	11000	7680	14380	9940	16	-	-
17/10/08	7800	5540	9100	6440	10420	7340	13.960	9560	14	-	-
20/10/08	6820	4840	9220	6400	11080	7580	14.400	9680	13	-	-
22/10/08	7140	5100	8840	6340	10140	7020	12.660	8920	17	-	-
24/10/08	6540	4680	8500	5920	9360	6460	12.020	8220	20	-	-
27/10/08	7140	5140	8960	6320	10280	7180	13.240	9100	-	-	-
3/11/08	8180	5880,0	8520	6020	9480	6220	12.060	8380	13	-	-
5/11/08	7640	5460,0	7720	5460	8940	6180	11.820	8080	17	-	-
7/11/08	7318	5133	7860	5640	9400	6620	12.580	8080	15	-	-
10/11/08	6180	4360	6900	4920	8540	5680	14.180	9500	13	-	-
12/11/08	6340	4400	6920	5340	9360	6940	12.320	8220	18	151.52	15.95
14/11/08	7320	5140	8140	5580	9400	6560	13.240	8980	13	-	-
17/11/08	9860	6780	9820	6720	10880	7600	14.920	10160	10	-	-
19/11/08	11200	7220	10780	7940	11940	8280	15.700	10740	12	343.59	33.82
21/11/08	8880	5680	9900	6880	11380	10340	15320	10340	11	-	-
25/11/08	8060	7940	9200	6460	9980	7080	13.160	9300	17	-	-
27/11/08	7240	4980	8260	5680	9460	6400	13.400	9060	12	-	-
12/12/08	9560	6620	10940	7380	14240	9580	16660	11000	4	159.81	23.82
15/12/08	6460	4900	6940	4760	10680	7200	13960	9220	7	-	-
17/12/08	7110	4850	7750	5650	10210	6930	13180	8890	-	204.21	22.15
18/12/08	7760	4800	8560	6540	9740	6660	12400	8560	8	-	-
23/12/08	9680	6680	9160	6280	8820	6060	10580	7260	12	-	-
29/12/08	8700	6040	10060	6900	9820	7520	12280	8460	11.5	-	-

	Composite sample		Grab sample								Composite sample			
	Influent		Anaerobic		Anoxic		Aerobic		Membranes		Effluent			
	TN	NH_4^+	NO_3^-	NO_2^-	NO_3^-	NO_2^-	NO_3^-	NO_2^-	NO_3^-	NO_2^-	NO_3^-	NO_2^-	TN	NH_4^+
30/07/08	-	-	0.3	0.028	6.65	0.231	15.88	0.271	17.1	0.317	22	0.08	-	-
6/08/08	-	-	0.37	0.065	5.85	0.193	15.22	0.142	15.54	0.174	20.8	0.006	-	-
11/08/08	-	-	1.11	0.044	10.9	0.217	19.68	0.162	19.58	0.216	23.0	0.012	-	-
13/08/08	-	-	0.20	0.041	3.74	0.204	10.04	0.117	10.06	0.145	16.9	0.07	-	-
20/08/08	-	-	0.30	0.036	4.88	0.132	11.2	0.088	10.5	0.122	19	0.01	-	-
22/08/08	-	-	-	0.061	7.85	0.184	17	0.103	16.42	0.129	-	-	-	-
25/08/08	-	-	0.24	0.028	3.49	0.298	11.24	0.175	11.34	0.209	14.86	0.01	-	-
27/08/08	-	-	0.35	0.025	2.49	0.222	9.58	0.174	9.37	0.223	-	-	-	-
1/9/08	47.7	35.4	0.26	0.03	0.595	0.085	10.82	0.113	11.26	0.094	13.44	0.006	16.9	0
3/9/08	61.6	43.2	0.28	0.03	0.657	0.287	18.06	0.148	19.18	0.166	10.9	0.006	11	0
8/9/08	69.5	54	0.01	0.03	2.94	0.156	13.24	0.082	13.28	0.099	18.2	0.009	21.9	0.065
10/9/08	-	-	0.94	0.06	4.48	0.137	13.28	0.08	14.8	0.075	-	-	-	-
12/9/08	-	-	0.5	0.05	3.37	0.097	10.76	0.066	11.08	0.059	-	-	-	-
16/9/08	-	-	0.12	0.02	1.12	0.144	7.64	0.092	7.14	0.141	-	-	-	-
18/9/08	59.9	39.8	-	-	-	-	-	-	-	-	12.8	0.01	13.1	0.022
22/9/08	55.4	40.8	0.18	0.04	2.36	0.219	12.74	0.118	12.66	0.12	11.36	0.01	14.6	0.023
24/9/08	-	-	0.24	0.03	3.77	0.124	11.06	0.082	11.92	0.096	-	-	-	-
25/9/08	62.4	49.2	-	-	-	-	-	-	-	-	19.88	0.005	20	0.021
29/9/08	-	-	0.19	0.024	0.507	0.063	9.24	0.075	9.74	0.071	-	-	-	-
30/9/08	61.2	42	-	-	-	-	-	-	-	-	14.06	0.007	20.8	0.024

	Composite sample		Grab sample												Composite sample			
	Influent		Anaerobic			Anoxic			Aerobic			Membranes			Effluent			
	TN	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	TN	NH_4^+
1/10/08	-	-	0.26	0.038	-	0.207	0.04	-	6.74	0.061	-	6.84	0.068	-	-	-	-	-
2/10/08	60.2	49	-	-	-	-	-	-	-	-	-	-	-	-	15.54	-	19	0.027
3/10/08	-	-	0.12	-	-	2.59	-	-	11.2	-	-	9.3	-	-	-	-	-	-
6/10/08	65.5	51	-	-	-	-	-	-	-	-	-	-	-	-	14.34	0.006	20.1	0.024
7/10/08	-	-	0.45	-	-	4.05	-	-	12.74	-	-	11.98	-	-	-	-	-	-
8/10/08	61.4	50.8	-	-	-	-	-	-	-	-	-	-	-	-	16.74	0.007	20.2	0.012
13/10/08	82.2	48.2	0.28	0.033	-	0.245	0.025	-	9.52	0.063	-	9.66	0.064	-	12.66	0.005	16.3	0.021
15/10/08	59.5	45.7	0.18	0.028	-	2.82	0.094	-	10.18	0.069	-	10.48	0.069	-	13.9	0.009	17.2	0.029
20/10/08	76.1	49.5	0.17	0.039	4.93	4.82	0.137	4.92	12.06	0.06	0.259	12.52	0.08	0.27	15.16	0.004	17.6	0.020
22/10/08	82.1	38.4	0.02	0.014	13.3	2.27	0.123	5.96	10.18	0.04	0.147	10.36	0.059	0.23	13.5	0.006	16.1	0.020
27/10/08	64.1	35	-	-	-	-	-	-	-	-	-	-	-	-	14.5	0.004	16.8	0.1
3/11/08	41.9	31.0	-	-	-	-	-	-	-	-	-	-	-	-	13.1	0.003	17.1	0.03
6/11/08	53.9	43.2	-	-	-	-	-	-	-	-	-	-	-	-	17.3	0.006	20.4	0.01
7/11/08	-	-	2.74	0.215	0.97	8.43	0.19	2.39	14.1	0.073	0.204	14.66	0.066	0.02	-	-	-	-
11/11/08	51.8	29.6	-	-	-	-	-	-	-	-	-	-	-	-	13.0	0.005	13.5	0.03
12/11/08	-	-	2.45	0.311	15.4	8.09	0	6.12	13.9	0.13	0.181	13.8	0.174	-	-	-	-	-
14/11/08	-	-	0.07	0.023	9.95	2.52	0.264	4.73	6.52	0.142	0.524	7.24	0.255	0.32	-	-	-	-
17/11/08	64.4	20.3	0.08	0.031	12.4	1.97	0.062	1.36	7.44	0.055	0.024	5.66	0.082	0.92	11.1	0.006	14.8	0.01
19/11/08	50.4	26.8	-	-	-	5.64	0.097	1.81	7.44	0.055	0.024	5.66	0.082	0.92	12.5	0.01	10.4	0.006
21/11/08	-	-	0.96	0.083	5.9	5.34	0.097	2.21	9.75	0.079	0.887	10.7	0.087	0.02	-	-	-	-
25/11/08	53.1	28.7	0.59	0.077	2.81	-	-	-	9.46	0.085	0.138	9.17	0.091	0.02	18.5	0.009	13.6	0.006
27/11/08	-	-	6.37	0.01	1.02	12.2	0.094	3.56	16.5	0.063	0.017	16.8	0.084	0.10	-	-	-	-
12/12/08	-	-	1.46	0.118	8.86	4.23	0.167	6.14	9.02	0.177	0.208	-	-	-	-	-	-	-
15/12/08	51	34.10	6.6	0.089		11	0.079	2.86	14.98	0.087	<2	15.02	0.11	<2	18.90	0.009	18.90	0<2
17/12/08	49	35.50	-	-	-	-	-	-	-	-	-	-	-	-	11.94	0.108	13.00	0.00
18/12/08	-	-	5.26	0.102	<2	7.71	0.099	<2	9.2	0.074	<2	9.12	0.098	<2	-	-	-	-
23/12/08	-	-	3.66	0.037	1.44	7.34	0.026	-	7.34	0.026	-	7.34	0.026	<2	-	-	-	-
29/12/08	36.2	-	0.1	0.019	-	2.23	0.066	2.41	4.1	0.049	<2	4.2	0.048	-	6.78	0.008	5.61	0.06

Experimentation with hollow fibre membranes

	INFLUENT							
Day	TSS	VSS	COD_T	COD_S	BOD_5	TN	NH_4^+	PO_4^{3-}
7/4/09	310	-	574	440	344	-	51.7	-
9/4/09	480	460	864	362	518	59.8	42.8	8.39
14/4/09	350	350	705	271	251	62.4	35.9	5.02
16/4/09	360	340	755	332	453	62.1	40.3	6.74
21/4/09	380	380	511	263	307	63.2	42.90	6.62
22/4/09	290	290	659	409	465	63.4	42.6	8.4
29/4/09	760	580	1298	323	779	77	54.1	10.88
4/5/09	420	420	585	296	351	63.3	47.8	8.14
7/5/09	450	450	787	304	472	74.4	48.50	8.58
12/5/09	340	320	731	356	420	92.7	44.20	10.82
14/5/09	620	600	668	296	401	116	52	12
19/5/09	520	500	986	361	427	89.0	56.5	9.2
21/5/09	620	560	1043	344	626	112.0	62.9	18.9
26/5/09	500	480	928	325	399	93	57.60	12.12
28/5/09	290	290	753	325	452	68	45.40	13
4/6/09	260	260	576	384	346	57.5	45.1	9.4
11/6/09	400	400	747	379	448	88.1	51.7	20.4
16/6/09	580	580	1131	396	262	109.0	69.7	12.1
19/6/09	790	730	1300	382	780	149.0	99.0	17.7
25/6/09	350	350	794	366	476	101.0	65.2	10.0
30/6/09	280	280	1171	522	703	80.8	54.4	12.8
3/7/09	400	400	729	387	437	78.2	56.7	13.36
7/7/09	500	500	624	366	374	83.1	46.6	7.72
10/7/09	460	460	670	330	402	68.6	44.7	8.08
14/7/09	460	370	847	373	508	71	53.6	11.84
16/7/09	400	400	830	335	498	68.4	51.9	16.76
21/7/09	360	360	641	375	385	88.8	87.4	16.2
23/7/09	430	430	809	373	485	74	65.4	15.48
28/7/09	330	330	893	391	536	85.5	56.3	13.6
30/7/09	360	360	970	417	582	74.4	64.2	9.5
4/8/09	600	600	1018	416	611	96.9	60.0	16.6
6/8/09	140	140	820	440	492	85.4	71.0	16.2

	INFLUENT							
Day	TSS	VSS	COD_T	COD_S	BOD_5	TN	NH_4^+	PO_4^{3-}
11/8/09	150	150	476	316	286	73.3	53.8	10.1
13/8/09	250	230	708	388	425	81.7	75.2	11.8
18/8/09	280	280	694	425	416	77.6	80.2	11.8
20/8/09	340	330	742	401	445	95.7	74.6	14.7
25/8/09	320	320	896	372	538	77.8	53.2	-
27/8/09	770	680	1330	413	798	102	74.2	24.6
1/9/09	1270	1100	2999	427	1799	130	88.60	23.40
8/9/09	1070	760	1781	395	1069	123	73.20	22.12
10/9/09	1160	1050	1882	402	1129	122	80.80	17.84
15/9/09	520	470	796	337	478	75.2	65.00	29.64
17/9/09	310	310	1039	424	623	83.3	63.00	16.98
22/9/09	260	130	708	366	425	78.2	66	17.48
24/9/09	470	420	915	375	549	75.1	46.1	15.28
29/9/09	740	660	1136	397	682	103	63.8	8.36
1/10/09	1060	940	1675	403	1005	93.6	49.2	27.96
6/10/09	930	730	1248	407	749	95.4	51.9	19.08
9/10/09	1150	930	2156	518	1294	175	61.9	20.12
14/10/09	-	-	1257	482	754	70.8	43.9	17.48
16/10/09	1430	1180	2096	384	1258	151	58.1	27.8
21/10/09	400	160	755	397	453	64	36.6	13.12
23/10/09	280	280	395	196	237	45	22.5	9.2
30/10/09	560	560	749	333	449	77.9	52.1	14.24
4/11/09	240	240	680	382	408	63.8	46.2	12.64
6/11/09	340	260	833	426	500	184	48.2	17.48
11/11/09	420	420	936	485	562	122	47.7	11.88
13/11/09	1020	960	1674	439	1004	128	47.4	27.8
18/11/09	620	460	1027	400	616	-	59.2	20.28
20/11/09	300	300	998	392	599	94.1	53.6	17.92
27/11/09	960	738	1474	355	884	116	57.4	28.84
1/12/09	440	260	730	361	438	94.8	45.4	17.72
3/12/09	400	400	905	413	543	80.4	54.2	16.52
10/12/09	440	400	1009	354	605	72.6	41.3	15.6
15/12/09	500	450	1361	380	817	70.1	45.8	19.6
17/12/09	670	490	1412	412	847	68	43.7	18.8
29/12/09	390	340	710	357	426	71	46.9	17.1

	EFFLUENT							
Day	TSS	COD_S	BOD_5	TN	NH_4^+	NO_3^-	NO_2^-	PO_4^{3-}
7/4/09	2	24.7	14.8	-	1.85	7.33	-	-
9/4/09	0	25.7	15.4	23.9	2.04	14.2	0.51	6.11
14/4/09	0	19.3	0.0	17.9	7.98	6.94	0.115	5.5
16/4/09	0	23.8	14.3	15.4	5.39	8.3	-	2.41
21/4/09	0	22.5	13.5	26	0.168	15.0	-	5.42
22/4/09	0	25.8	2.8	17.6	0.228	11.1	-	6.72
29/4/09	2	29.1	17.46	36.7	0.091	18.0	0.035	15.56
4/5/09	2	22.7	13.62	19.8	0.1	13.8	0.013	5.3
7/5/09	0	22.4	13.44	12.5	0.097	12.5	-	4.86
12/5/09	1	23.7	0	15	0.11	10.9	-	3.14
14/5/09	2	21.90	13.14	15.30	0.14	12.90	-	3.76
19/5/09	0	23.20	0	18.90	0.11	14.00	-	7.88
21/5/09	0	28.40	17.04	23.00	0.20	17.10	0.07	8.60
26/5/09	0	25.3	0	20.4	0.1	15.5	-	4.7
28/5/09	0	26.5	15.90	15.4	0.1	11.6	0.0	5.1
4/6/09	0	24.9	14.9	15.0	0.14	10.00	0.03	8.0
11/6/09	1	22.8	13.7	12.3	0.19	8.75	0.05	4.0
16/6/09	0	25.9	0	17.5	0.14	16.30	0.02	6.0
19/6/09	0	27.4	16.4	17.4	0.19	11.30	0.05	1.6
25/6/09	1	24.6	14.8	23.3	0.18	15.60	0.04	5.2
30/6/09	0	23.6	14.16	15.9	0.222	10.6	-	2.43
3/7/09	0	27.8	16.68	15.9	0.215	10.6	0.035	3.9
7/7/09	2	25.3	15.18	18.6	0.147	11.2	-	4.36
10/7/09	0	23.6	14.16	15.6	0.142	11.4	0.027	6.05
14/7/09	0	21.5	12.9	21.2	0.097	14.3	-	7.44
16/7/09	2	25.1	15.06	21	0.105	13.6	0.031	4.72
21/7/09	0	24.6	14.76	20.2	0.68	14.4	0.278	5.52
23/7/09	0	27.3	16.38	15	0.148	7.78	0.02	9.04
28/7/09	0	24.3	14.58	14.80	0.06	10.20	0.013	1.33
30/7/09	0	26.9	16.14	14.00	0.11	11.70	0.027	2.24
4/8/09	0	26.5	15.9	14.80	0.10	9.58	-	2.25
6/8/09	0	27.6	16.56	18.10	0.18	12.80	0.03	4.80
11/8/09	0	25.6	15.36	22.90	0.14	17.30	-	10.32
13/8/09	0	15.6	9.36	15.60	0.12	10.00	0.022	10.20
18/8/09	0	20.9	12.54	13.30	0.09	7.78	0.021	6.92

	EFFLUENT							
Day	TSS	COD_S	BOD_5	TN	NH_4^+	NO_3^-	NO_2^-	PO_4^{3-}
20/8/09	0	18.3	10.98	14.70	0.14	10.60	0.026	8.18
25/8/09	1	21.1	12.66	16.10	0.16	11.50	-	-
27/8/09	0	26.6	15.96	20.7	0.09	17.8	0.017	9.6
1/9/09	0	29.2	17.5	36.5	1.71	0.23	-	2.70
8/9/09	0	23.0	13.8	14.0	12.50	0.43	0.08	0.86
10/9/09	2	33.9	20.3	8.5	0.23	4.21	0.03	0.26
15/9/09	5	41.1	24.7	24.9	14.30	3.96	0.17	12.68
17/9/09	5	27.3	16.4	15.7	0.18	10.90	0.02	4.66
22/9/09	3	23.2	13.9	16.9	0.124	8.53	0.01	3.22
24/9/09	1	23.0	13.8	11.8	0.447	8.40	0.05	7.26
29/9/09	3	26.3	15.8	21.7	1.91	1.06	0.11	2.95
1/10/09	1	28.3	16.98	34.7	1.3	0.629	0.207	2.15
6/10/09	0	27.2	16.32	8.07	1.01	3.03	0.299	1.08
9/10/09	0	27.5	16.5	10.3	0.885	5.21	0.124	1.132
14/10/09	0	29.9	17.94	8.31	2.87	0.562	0.051	0.56
16/10/09	0	28.1	16.86	11	1.91	4.94	1.29	0.54
21/10/09	1	24	14.4	12.1	0.151	5.32	0.032	0.84
23/10/09	0	23.5	14.1	12	0.115	5.69	0.053	0.75
30/10/09	0	22.2	13.32	19.1	0.148	10.09	0.054	7.04
4/11/09	0	23.9	14.3	14.7	0.106	9.69	0.043	6.72
6/11/09	2	23.9	14.3	11.7	0.128	10.3	0.044	4.24
11/11/09	3	25.6	15.4	17.6	0.143	12.8	0.091	2.5
13/11/09	0	28.5	17.1	7.93	0.1	4.12	0.014	4.6
18/11/09	5	28.9	17.3	-	0.829	10.8	-	6.92
20/11/09	0	27.7	16.6	13.3	0.129	7.1	0.026	8.12
27/11/09	0	26.3	15.8	13.5	0.207	8.03	0.425	9.04
1/12/09	1	22	13.2	12.1	0.068	7.78	0.075	7.04
3/12/09	3	22.9	13.7	15.3	0.223	9.96	-	7.3
10/12/09	0	24.8	14.9	9.91	0.078	6.35	0.186	8.64
15/12/09	0	24.3	14.58	11.1	0.088	6.67	0.1	1.284
17/12/09	0	24.8	14.88	13.7	0.097	6.73	0.032	0.964
29/12/09	0	22.6	13.56	10.7	0.085	6.5	0.051	1.5

	ANAEROBIC		ANOXIC		AEROBIC		MEMBRANES				
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS	Filtrab	EPS tot	EPS/VSS
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mL	mgEPS/L	mgEPS/gVSS
7/4/09	-	-	3540	-	4100	-	4840	-	-	-	-
9/4/09	4980	3920	4320	3460	4700	3720	5600	4520	4	-	-
14/4/09	5000	3960	6760	5200	8200	6200	10600	8020	5	-	-
16/4/09	5200	4020	7480	5620	9180	6940	11220	8340	5	503.15	59.90
22/4/09	7100	5400	8440	6340	10100	7520	12240	9040	6	-	-
29/4/09	6180	4280	7880	5560	8740	5980	10480	7100	5	-	-
30/4/09	6940	4980	8760	6200	9920	7040	12260	8660	5	-	-
4/5/09	6860	4920	9860	7000	12880	9180	15620	11120	5	-	-
5/5/09	7240	5420	9700	7080	11620	8540	13820	9840	7	196.89	20.35
7/5/09	7260	5460	9860	7260	12300	8860	14340	10260	8	-	-
11/5/09	6220	4620	7740	5780	8840	6500	10480	7680	8	-	-
12/5/09	6220	4740	8100	6000	10340	7640	12480	9080	9	-	-
14/5/09	6680	5140	8580	6420	11140	8440	13660	10160	8	121.74	13.41
19/5/09	7220	5420	10340	7680	13180	9680	17040	12440	7	-	-
21/5/09	6740	5100	7560	5680	9940	7380	14560	10720	7	-	-
26/5/09	4600	3600	6700	5100	9880	7300	12080	8880	13	245.17	27.55
28/5/09	4800	-	6840	-	8980	-	11740	-	8	-	-
4/6/09	5400	4200	6380	4820	6160	4840	7160	5360	14	-	-
9/6/09	4740	3820	6180	4980	6260	4760	7680	5800	12	-	-
11/6/09	4700	3200	5100	3900	7240	5520	7940	5980	10	-	-
16/6/09	7000	5400	7840	6020	8360	6360	10180	7620	18	-	-
19/6/09	10320	-	8380	-	10320	-	12640	-	18	-	-
25/6/09	5420	-	7720	-	10540	-	12660	-	15	-	-
3/7/09	6260	4840	6280	4720	7740	5920	10880	9700	15	-	-
7/7/09	6060	4720	7440	5760	9340	7140	12420	8740	17	-	-
10/7/09	5180	4080	6820	5500	8920	6820	11200	8740	15	-	-
14/7/09	4600	3340	6520	4880	7760	5780	9300	6960	13	67.28	9.61
16/7/09	740	740	620	620	12660	9580	15280	10660	8	-	-
21/7/09	6140	4780	7280	5660	7660	5900	10120	7800	14	123.84	16.34
23/7/09	6280	4760	6520	4900	7900	5860	10000	7460	14	-	-
28/7/09	5020	-	6840	-	8020	-	10820	-	11	-	-
4/8/09	5780	4320	8340	6320	10080	7580	11740	8940	12	264.89	31.84
6/8/09	5800	-	7640	-	8960	-	10180	-	12	-	-
11/8/09	6300	4840	6120	4640	7280	5400	8360	6220	11	-	-
13/8/09	5840	4400	5820	4340	7040	5280	8060	6000	-	-	-
18/8/09	5820	4420	5880	4340	7300	5360	7860	5880	18.5	-	-
20/8/09	5980	4320	5940	4280	7060	5180	8520	6040	17.5	-	-
25/8/09	5100	3960	6860	5240	8300	6340	9760	7380	15.5	-	-
27/8/09	5320	4040	7200	5400	9420	7020	10680	7780	14	-	-
1/9/09	13080	9780	12820	9580	12500	9340	33040	24520	0.3	-	-
8/9/09	10260	7700	13320	9920	16520	12200	19640	14440	13	-	-
10/9/09	8900	6000	12220	10180	15600	11740	18720	14040	9	-	-
15/9/09	2640	2620	3220	3080	16320	11920	22380	15800	11	-	-
17/9/09	8480	6620	8680	6660	11680	8860	12620	9460	13	-	-
22/9/09	10200	7420	9620	7120	12020	9000	14920	10820	14	-	-
24/9/09	9220	6680	9100	6560	11340	8140	13960	10000	15	-	-
1/10/09	8220	6300	11480	8600	13860	10260	18140	13440	6	-	-
6/10/09	9620	7300	10260	7900	11060	8360	13760	10300	15	-	-

	ANAEROBIC		ANOXIC		AEROBIC		MEMBRANES				
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS	TSS
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
9/10/09	8980	7120	11440	8880	13560	10440	16620	12700	12	-	-
14/10/09	13200	10820	13260	10320	14860	11060	16680	12460	6	-	-
16/10/09	10300	8040	9400	7280	11460	8860	13420	10380	-	-	-
21/10/09	9080	6580	8880	6440	9860	7180	11140	8060	14	-	-
23/10/09	7800	5980	8280	6360	9240	7000	10700	8020	14	-	-
30/10/09	1200	1080	10780	8000	9820	7360	11020	8100	11	-	-
4/11/09	3020	2440	6940	5260	6960	5260	6960	5260	11	-	-
6/11/09	1440	1140	9420	7100	8500	6420	9460	7140	11	-	-
11/11/09	6380	4960	9060	6960	7600	5900	9300	7280	12	319.1	43.8
13/11/09	8180	6380	10820	8400	7580	5940	10620	8260	8	-	-
18/11/09	4340	3300	6020	4480	5820	4400	6760	5120	9	-	-
20/11/09	6120	4920	6600	5200	6540	5180	8460	6580	9	-	-
27/11/09	6740	5392	7500	5500	8700	6700	10700	8240	11	-	-
1/12/09	8300	6300	8600	6580	9700	7440	11540	8620	10	-	-
3/12/09	7400	5720	7100	5680	8140	6200	10740	8260	10	-	-
10/12/09	4560	3500	5400	4250	5900	4484	7060	5400	8	-	-
17/12/09	5100	4050	5500	4150	6500	5050	10050	7800	6	-	-
29/12/09	4980	3800	5230	4020	5980	4530	9500	7230	7	-	-

	Composite Sample		Grab sample												Composite sample			
	Influent		Anaerobic			Anoxic			Aerobic			Membranes			Effluent			
	TN	NH_4^+	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	TN	NH_4^+	NO_3^-	NO_2^-
7/4	-	51.7	-	-	-	-	5.22	-	-	10.4	-	-	9.74	-	-	1.85	7.33	-
9/4	59.8	42.8	-	6.72	0.561	-	9.93	0.435	-	14.2	0.496	-	14.7	0.518	23.9	2.04	14.2	0.51
14/4	62.4	35.9	-	0.379	0.056	-	0.54	0.07	-	3.28	0.334	-	3.57	0.424	17.9	7.98	6.94	0.115
16/4	62.1	40.3	-	0.296	-	-	0.354	-	-	4.49	-	-	5.83	-	15.4	5.39	8.3	-
21/4	63.2	42.90	-	-	-	-	-	-	-	-	-	-	-	-	26	0.168	15.0	-
22/4	63.4	42.6	-	0.475	-	-	1.94	-	-	9.83	-	-	10.4	-	17.6	0.228	11.1	-
29/4	77	54.1	-	18.1	-	-	18	-	-	18	-	-	18	-	36.7	0.091	>18	0.035
30/4	-	-	-	6.79	-	-	14	-	-	23.1	-	-	18	-	-	-	-	-
4/5	63.3	47.8	27.1	0.406	-	11.7	3.98	-	0.406	13.4	-	0.34	13.8	-	19.8	0.1	13.8	0.013
5/5	-	-	-	0.329	0.032	-	2.86	0.256	-	11	0.142	-	9.78	0.303	-	-	-	-
7/5	74.4	48.50	28.3	0.479	-	11.8	0.68	-	0.448	11.3	-	0.47	9.53	-	12.5	0.097	12.5	-
11/5	-	-	-	0.391	-	-	1.58	-	-	7.84	-	-	8.05	-	-	-	-	-
12/5	92.7	44.20	-	0.242	-	-	1.02	-	-	8.6	-	-	9.75	-	15	0.11	10.9	-
14/5	116	52	22.8	0.245	0.037	12.7	1.5	0.128	-	10.8	0.228	-	10.9	0.244	15.30	0.14	12.90	-
19/5	89.0	56.5	-	0.2	-	-	1.97	-	-	11.7	-	-	11.4	-	18.90	0.11	14.00	-
21/5	112.0	62.9	25.6	0.276	0.075	16.9	0.245	0.067	0.693	9.53	0.386	0.91	5.91	0.487	23.00	0.20	17.10	0.07
26/5	93	57.60	-	0.273	-	-	1.77	-	-	19	-	-	18.6	-	20.4	0.1	15.5	-
28/5	68	45.40	30	0.444	0.039	12.6	0.651	0.071	0.227	9.66	0.24	0.25	9.16	0.323	15.4	0.1	11.6	0.0
4/6	57.5	45.1	-	1.07	-	-	0.59	-	-	8.43	-	-	9.09	-	15.0	0.14	10.00	0.03
9/6	-	-	-	0.51	-	-	2.95	-	-	13.00	-	-	13.10	-	-	-	-	-
11/6	88.1	51.7	28.7	0.39	0.04	14.3	1.88	0.24	0.34	13.10	0.16	0.35	12.40	0.26	12.3	0.19	8.75	0.05
16/6	109.0	69.7	-	-	-	-	3.98	-	-	11.20	-	-	11.70	-	17.5	0.14	16.30	0.02
19/6	149.0	99.0	29.7	0.57	0.06	15.5	0.41	0.03	0.43	6.05	0.16	0.50	6.79	0.24	17.4	0.19	11.30	0.05
25/6	101.0	65.2	29.0	0.35	0.04	11.2	0.36	0.03	0.36	6.37	0.23	0.41	5.24	0.31	23.3	0.18	15.60	0.04
3/7	78.2	56.7	33.1	0.607	0.037	18.2	0.351	0.026	0.299	12.8	0.376	0.56	12.2	0.641	15.9	0.215	10.6	0.035
7/7	83.1	46.6	-	0.38	-	-	0.443	-	-	5.75	-	-	5.14	-	18.6	0.147	11.2	-

	Composite Sample		Grab sample												Composite sample			
	Influent		Anaerobic			Anoxic			Aerobic			Membranes			Effluent			
	TN	NH_4^+	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	NH_4^+	NO_3^-	NO_2^-	TN	NH_4^+	NO_3^-	NO_2^-
10-7	68.6	44.7	27.9	0.467	0.035	12.1	3.07	0.286	0.288	12.7	0.287	0.27	12.6	0.347	15.6	0.142	11.4	0.027
14-7	71	53.6	-	0.49	-	-	0.385	-	-	3.07	-	-	2.93	-	21.2	0.097	14.3	-
16-7	68.4	51.9	52.8	0.444	0.079	51.8	0.466	0.068	0.498	26.1	0.802	0.45	25.5	1.13	21	0.105	13.6	0.031
21-7	88.8	87.4	-	0.54	-	-	0.508	-	-	11.1	-	-	10.7	-	20.2	0.68	14.4	0.278
23-7	74	65.4	15.6	0.088	0.128	15.1	0.308	0.031	0.121	9.76	0.265	0.17	9.61	0.403	15	0.141	7.78	0.020
28-7	85.5	56.3	-	0.329	-	-	1.11	-	-	7.9	-	-	8.26	-	14.8	0.063	10.2	0.013
4-8	96.9	60	-	0.37	-	-	0.283	-	-	7.49	-	-	7.6	-	14.80	0.100	9.58	-
6-8	85.4	71	23.4	0.27	0.03	11.4	4.58	0.352	0.229	14.7	0.392	0.21	15.5	0.428	18.1	0.178	12.8	0.03
11-8	73.3	53.8	-	8.39	-	-	4.41	-	-	14	-	-	15.1	-	22.9	0.139	17.3	-
13-8	81.7	75.2	15.7	4.28	0.34	13.2	2.02	0.382	0.118	12.8	0.228	0.12	13.4	0.104	15.6	0.123	10	0.022
18-8	77.6	80.2	-	2.45	-	-	0.602	-	-	8.42	-	-	8.11	-	13.3	0.093	7.78	0.021
20-8	95.7	74.6	16.84	10.7	0.256	16.28	6.75	0.34	0.104	19.6	0.213	0.09	19.8	0.159	14.7	0.140	10.6	0.026
25-8	77.8	53.2	-	0.445	-	-	0.491	-	-	1.83	-	-	1.12	-	16.1	0.155	11.5	-
27-8	102	74.2	35.8	0.499	0.04	17	4.77	0.692	0.166	18	0.715	0.2	17.8	0.788	20.7	0.090	17.8	0.017
1-9	130	88.6	-	0.442	-	-	0.388	-	-	0.278	-	-	0.686	-	36.5	1.71	0.23	-
8-9	123	73.2	-	0.468	0.087	-	0.392	0.055	-	0.456	0.064	-	0.289	0.023	14.0	12.50	0.43	0.08
10-9	122	80.8	28.7	0.401	0.051	17	0.333	0.051	3.02	0.435	0.034	2.730	0.335	0.024	8.5	0.23	4.21	0.03
15-9	75.2	65.0	49.5	0.402	0.091	48.4	0.398	0.097	6.26	7.09	1.39	5.500	4.50	1.49	24.9	14.30	3.96	0.17
17-9	83.3	63.0	17.3	0.252	0.028	13	0.238	0.031	0.181	3.45	1.01	0.353	2.55	1.24	15.7	0.18	10.90	0.02
22-9	78.2	66.0	-	0.45	-	-	0.319	-	-	9.96	-	-	8.21	-	16.9	0.124	8.53	0.01
24-9	75.1	46.1	13.9	0.243	0.028	15.3	0.266	0.034	0.478	7.67	1.08	0.306	6.19	1.37	11.8	0.447	8.40	0.05
29-9	103	63.8	-	0.354	-	-	0.401	-	-	0.376	-	-	0.388	-	21.7	1.91	1.06	0.11
1-10	93.6	49.2	41.5	0.368	0.102	32.1	0.366	0.12	1.98	0.318	0.102	1.93	0.363	0.079	34.7	1.3	0.629	0.207

	Composite Sample		Grab sample												Composite sample			
	Influent		Anaerobic			Anoxic			Aerobic			Membranes			Effluent			
	Nt	NH4	NH4	NO_3^-	NO_2^-	NH4	NO_3^-	NO_2^-	NH4	NO_3^-	NO_2^-	NH4	NO_3^-	NO_2^-	Nt	NH4	NO_3^-	NO_2^-
6/10	95.4	51.9	-	0.276	-	-	0.275	-	-	2.1	-	-	0.226	-	8.07	1.01	3.03	0.299
9/10	175	61.9	25.8	0.301	0.061	12.6	0.247	0.36	1.79	1.06	1.13	0.738	0.539	0.993	10.3	0.885	5.21	0.124
14/10	70.8	43.9	-	0.415	-	-	0.386	-	-	0.303	-	-	0.341	-	8.31	2.87	0.562	0.051
16/10	151	58.1	12.9	0.255	0.051	12.4	0.625	0.059	0.818	2.66	1.14	0.125	4.05	0.646	11	1.91	4.94	1.29
21/10	64	36.6	-	0.298	-	-	0.21	-	-	1.15	-	-	1.21	-	12.1	0.151	5.32	0.032
23/10	45	22.5	7.12	1.27	0.56	5.28	0.457	0.297	0.149	6.05	0.18	0.06	7.07	0.096	12	0.115	5.69	0.053
30/10	77.9	52.1	-	0.55	-	-	1.65	-	-	8.04	-	-	6.83	-	19.1	0.148	10.09	0.054
4/11	63.8	46.2	-	0.48	-	-	4.03	-	-	11.4	-	-	11.3	-	14.7	0.106	9.69	0.043
6/11	184	48.2	40.4	0.47	0.11	3.5	6.51	1.17	0.53	11	0.87	0.47	10.2	1.03	11.7	0.128	10.3	0.044
11/11	122	47.7	-	0.74	-	-	4.46	-	-	9.68	-	-	11.0	-	17.6	0.143	12.8	0.091
13/11	128	47.4	14.8	0.25	0.04	6.7	0.96	0.28	0.24	5.26	0.34	0.15	6.1	0.24	7.93	0.100	4.12	0.014
18/11	-	59.2	-	0.52	-	-	4.22	-	-	9.53	-	-	12.1	-	-	0.829	10.8	-
20/11	94.1	53.6	-	1.94	0.41	-	0.27	0.05	-	8.59	0.25	-	6.12	0.21	13.3	0.129	7.1	0.026
27/11	116	57.4	25.8	0.29	0.04	20.9	0.33	0.05	0.40	8.16	0.41	0.47	7.33	0.43	13.5	0.207	8.0	0.425
1/12	94.8	45.4	-	0.26	-	-	0.203	-	-	6.78	-	-	7.36	-	12.1	0.068	7.78	0.075
3/12	80.4	54.2	-	0.34	-	-	0.355	-	-	7.35	-	-	7.72	-	15.3	0.223	9.96	-
10/12	72.6	41.3	16.6	0.79	0.403	19.5	0.503	0.135	2.12	8.71	0.912	2.4	10.5	0.087	9.91	0.078	6.35	0.186
15/12	70.1	45.8	-	-	-	-	-	-	-	-	-	-	-	-	11.1	0.088	6.67	0.1
17/12	68	43.7	9.7	0.41	0.641	13.9	0.209	0.079	0.399	8.51	0.712	0.301	8.89	0.718	13.7	0.097	6.73	0.032
29/12	71	46.9	13.8	0.25	0.22	12.1	0.305	0.054	0.5	8.45	0.245	0.251	7.54	0.231	10.7	0.085	6.5	0.051