Enhanced Nutrients Removal in Membrane Bioreactor ENREM

PLANNING, CONSTRUCTION AND OPERATION FROM JANUARY 2004 TO JUNE 2007

Technical Report
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IMPORTANT NOTIFICATION ON REPORT

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EXTENSIVE PROJECT SUMMARY (LAYMAN REPORT)

Scope of project and objectives

The "Island Problem" in Berlin

In the peripheral areas around Berlin, approximately 33 000 people in isolated locations are not connected to the city's 9300 kilometre-long sewerage system, and still dispose of their household sewage into cesspits. This is not only expensive, inconvenient, and occasionally very unpleasant, but also poses considerable environmental risks. In particular older cesspits can develop leaks through which infectious effluent can seep unintentionally into the groundwater.

More service for customers

The management of the 240 million cubic metres of wastewater generated every year in Berlin is a high priority for the city administration and the Berliner Wasserbetriebe (BWB). However, the expenditure for the construction and operation of sewers and pump stations must be set against the volumes of wastewater to be handled in each case. Only approx. 1% of the population are still not connected to the central sewerage system for either technical or economic reasons, and BWB is interested in ways of providing these households with decentralised wastewater treatment at acceptable costs while nevertheless meeting high environmental standards.

Centralised - Decentralised?

In rural areas with lower population densities, it can be advantageous to provide decentralised or semi-centralised wastewater treatment. In the case of centralised alternatives it will be necessary to install long sewers – which is very expensive and involves considerable construction work. Other problems are also encountered with the long sewerage networks, such as odours and concrete corrosion. With decentralised wastewater treatment the water can be reintroduced directly into the local water cycle, so that there is no use to install a pump works.

Pilot project with state-of-the-art technology

The proposed solution involves a pressure sewer system combined with a membrane bioreactor (MBR plant).

Low-pressure sewer system

With the low-pressure sewer system, every household is fitted with a storage tank in which there is a grinding pump. When level in the storage tank reaches approx. 100L, the grinding pump feeds the wastewater through a pressure sewer to a local treatment plant.
The advantages of the low-pressure system are:

- An enclosed system, so that there is no smell nuisance
- Lower installation depths and smaller pipe diameters than with gravity dewatering, and therefore frequently also more cost-effective
- Ability to buffer peak demands on the system as a result of the storage containers (800L) in every household
- No inflow and infiltration (storm water or groundwater)

Membrane bioreactor process

In the MBR process, the sewage is first treated biologically by the activated sludge, when is then filtered out by a filtration membrane. The membrane ensures that all the biomass and particles are held back, and offers the following advantages:

- Complete disinfection: the limit values of the EU-Bathing water directive are already complied with by the effluent;
- Compact system: Installation of the complete MBR system in a freight container, and with 17 square metres area for 250 residents it is no larger that a pump station;
- Monitoring of the functions by remote control and alarm reports via a mobile telephone;
- Enclosed container plant can be more easily integrated in the landscape with the advantage over open ponds that there is no inconvenience due to odours or noise;
- By varying the biomass concentration in the biological system and the area of the membrane it is possible to cope with a greater range of intake pollutant load than with conventional systems with sedimentation.

The biological process involved

Since the year 2000, BWB and Veolia Water have been carrying out research into increased biological phosphorous elimination in membrane bioreactors even with longer bacteria residence times. They also developed post-denitrification without carbon dosing and thus were able to avoid one sludge recirculation cycle. A patent was taken out on this biological process, which saves space, energy, and chemicals. Without the need for chemical additives, more than 95% of carbon compounds can be removed, more than 99% of phosphates, and more than 90% of nitrogen. The result is an effluent quality which is better than the EU criteria for sensitive areas and bathing waters, and this represents an important contribution to the protection of surface waters.

Project phase 1: Design validation

Choosing a location for the demonstration plant

When selecting the locations for the demonstration plant, 20 settlements on the periphery of Berlin were considered, and Berlin-Margaretenhöhe was finally chosen. This settlement only has 250 residents, which is much smaller than the more economically-viable size of approx. 1000 residents which was originally targeted, but it did offer other advantages. A suitable piece of land was already available, so that the construction of the MBR-plant could proceed without delay. The distance to the central sewerage network was great enough for a decentralised solution to offer economic advantages. The outflow could be fed into an local surface waterbody so that there was an added ecological benefit, because this would improve the hydrological balance in the adjacent protected landscape area. The water authorities imposed particularly strict criteria on the outflow waters, appreciably above those for Berlin's large-scale sewage treatment plants, because the outflow was to be released into a sensitive brook in a protected landscape area.

Preparatory study

In order to determine the appropriate dimensions and operational parameters, a pilot plant was erected and operated for one year. This provided important results, on the basis of which planning decisions could be made:

- The intake in decentralised areas varies considerable. Overnight there is hardly any wastewater flow and during the daytime there are clear peaks.
- Due to low water consumption and the exclusion of rainwater, the sewage is more concentrated.

- The installation of a buffer tank from which the MBR-plant is fed offers considerable advantages. It is possible to ensure a steady flow to the membrane bioreactor, which not only makes it possible to operate with a lower membrane area, but also has a positive effect on the biological process.
- The original intention was to extract excess sludge at intervals, because this would mean that it was not necessary to construct a sludge container and would offer economic advantages for decentralised applications. However, it was found that this approach had a destabilising effect on the process of biological nitrogen elimination.
- Even without the addition of an external source of carbon, good denitrification rates of about 1 mgN/h/gVSS were achieved.
- In smaller MBR-plant attention must be paid to infestation with sludge worms (T. tubifex) and any necessary preventive measures should be adopted in good time.

Project phase 2: Construction and start-up

Plant construction

The international call for tenders for the construction of the MBR plant was awarded to the Germany company Martin Systems, which not only submitted the cheapest tender but also presented a very innovative proposal. All components of the plant including the pre-sieving were integrated in a compact container. The MBR plant was assembled in the company workshops within only 6-7 months and then delivered and installed at the demonstration location. On 1 March 2006, the MBR plant was started up.

Construction of the pressure sewer network
In all, some 2000 metres of pressure pipe were installed. When the plant was started up, some 30% of the residents were connected to the pressure sewer network. After a period of seven months, a level of 100% was reached, exceeding the predicted level of 80%.

Starting up and the first months of operation

It was found that the concentrations in the wastewater were higher than in the settlement areas which had previously been investigated (Tab.2). The concentrations measured indicate a water consumption of only 50-80 L per resident per day, which is considerably below the average consumption in Berlin.

Without all households connected up to the system, the volumes of wastewater in August 2006 exceeded the planned value of 10 m3/d. Not only were there variations in the flow of wastewater during the day, but there was also a clear pattern over the week. The flow of wastewater at the weekends was 18 m3/d, which is 50% higher than during the week, when most of the residents are not at home during the day.

The higher concentration of the sewage in combination with the larger volumes resulted in a nutrients load which was 100% above the design values. This gave rise to various problems, such as severe foaming in the membrane bioreactor, inadequate oxygen supply, and insufficient nutrients elimination. Beginning in December 2006, a part of the inflow was taken away by truck and the biological process was stabilised. Additional aerators were also installed in order to ensure the improved provision of oxygen for the process.

Project phase 3: Technical and economic evaluation

Results for stable operations

The MBR plant has been operating stably since April 2007. It has been possible to show that the level of purification is very high, even though the plant is still operating with a 25% overload on maximal design value. The membrane filtration ensures concentrations for the parameters E. coli and Enterococci which are below the limit of detection. More than 95% of the organic compounds was degraded, and 90%-95% of nitrogen was eliminated. The required limit values of 50 mg COD /L and 10 mg/L total nitrogen in the outflow could be met. The elimination of phosphorous was constant at above 99%, and was therefore also very high, although in this case the outflow values of 0.1-0.2 mg/L were slightly above the required quality limits. With regard to the high inflow concentration and the very low orthophosphate concentration (85%tile < 0.05 mgP-PO4/L) this seems to represent the refractory proportion which cannot be removed with a biological process.

The filtrate flow rate was 6-12 $L/m^2/h$ and the cross flow membrane aeration was approx. 1 $Nm^3/m^2/h$. Due to various factors including the hydraulics in the module and reactor, the cleaning strategy and the membrane material, the membrane filtration could only be operated at unsatisfactory levels for the long-term operations. The filtration technology was exchanged. It is recommended that the hydraulics are thoroughly inspected and that a high freeboard is provided for the biological system.

Cost evaluation

The semi-central sewerage system offers savings for customers with the piping from the settlement to an existing central sewerage system. The plot of land required for the MBR-plant corresponds to the area of a pump station. The savings for the construction of the sewerage network and pump station are approx. EUR 650 000. The entire small wastewater treatment plant costs only EUR 382 000, or approx. EUR 1500/p.e. A scale up to an MBR-plant for 1000 residents providing the same standards (with regard to target parameters, measuring technology and fittings) would give total costs of EUR 1 059 000 or specific costs of approx. EUR 1000 /p.e.

The operating costs are EUR 2.80/m^3, which is markedly higher than the city tariff for wastewater, and this does not include any specific amortisation for the investments. The costs are mainly attributable to the power consumption, the servicing contract and the analysis costs. There are considerable savings to be made here. For the small MBR plant, the costs for membrane replacement and cleaning are negligible.

A project with promise

The treatment plant was located in the settlement itself, with residents living only a few metres away, but nevertheless it was well received. Through the entire operating period of the MBR-plant there have not been any complaints about smells or noise.

Of course, the process itself is not one which can only be applied in Berlin. There are many areas in Germany and in other countries, in particular in central and eastern Europe, which are without connection to a central sewerage network for which a decentralised or semi-centralised strategy would be appropriate.

Main facts

- A membrane bioreactor (MBR) was installed for the decentralised treatment of domestic sewage and operated successfully.
- The wastewater system with low-pressure sewer, a buffer container and the MBR plant was evaluated positively by the project partners.
- The demonstration plant is designed for 250 residents and was constructed and installed in a freight container.
- There were no problems integrating the system in the existing settlement and it has been well accepted by the residents.
- The biological process for increased biological elimination of nutrients with post-denitrification without carbon dosing provides good results. Stable operations with inflow conditions in accordance with the design specifications provide treatment levels which are markedly better than those from Berlin's large-scale sewage treatment plants. Without any chemical additives, more than 95% of carbon compounds can be removed, more than 99% of phosphates, and more than 90% of nitrogen.
- The operation of the MBR-plant can be monitored remotely, which increases the reliability of the process and significantly reduces the costs for personnel.
- The specific investment and operating costs for 250 residents are still relatively high. Lower specific costs are anticipated with larger plants for up to 5,000 residents.

AUSFÜHRLICHE ZUSAMMENFASSUNG (LAYMAN BERICHT)

Projektumfang und Ziele

Das „Insel –Problem“ in Berlin

In den Randgebieten Berlins sind derzeit ca. 33000 Menschen, deren Bewohner durch ihre Insellage abseits des 9300 Kilometer langen Kanalnetzes ihr Abwasser bisher über eine abflusslose Sammelgrube entsorgen müssen. Eine ebenso kostspielige wie mit allerlei Unannehmlichkeiten und für die Umwelt mit erheblichen Risiken verbundene Angelegenheit. Denn besonders ältere Gruben könnten undicht sein und infektiöses Abwassers versickert unbeabsichtigt in den Untergrund.

Mehr Service für Kunden

Die Entsorgung der in Berlin jährlich anfallenden etwa 240 Millionen Kubikmeter Abwassers hat für die Stadt und die Berliner Wasserbetriebe absolute Priorität. Allerdings muss der Aufwand für Bau und Betrieb der Kanalisation und Pumpwerke dem zu entsorgenden Abwasservolumen gegen gerechnet werden. Nur ca. 1% der Bevölkerung ist bisher aus technischen oder wirtschaftlichen Gründen nicht an das zentrale Abwassersystem der Berliner Wasserbetriebe angeschlossen. Die Berliner Wasserbetriebe suchen daher nach Wegen Haushalten in gegenwärtig nicht abwassertechnisch erschlossenen Gebieten auch dezentrale Entsorgungsmöglichkeiten auf hohem ökologischem Niveau zu akzeptablen Kosten anzubieten.

Techniken: Zentral - Dezentral?

In ländlich strukturierten Gebieten mit niedriger Bevölkerungsdichte kann eine dezentrale oder semizentrale Abwasserentsorgung vorteilhaft sein. Bei zentralen Lösungen werden lange Kanalisationen notwendig, die sehr teuer und aufwendig gebaut werden müssen. In den langen Rohrnetzen entstehen weitere Probleme, wie Geruchsbelästigung und Betonkorrosion. Bei einer dezentralen Abwasserbehandlung wird das Wasser direkt wieder in den lokalen Wasserkreislauf eingebunden, und auf die Errichtung von Pumpwerken kann verzichtet werden.

Pilotprojekt mit neuester Technologie

Die erarbeitete Lösung sieht eine abwassertechnische Erschließung mittels Druckentwässerung kombiniert mit einem Membranbelebungsanlage (MBR-Anlage) vor.

Druckentwässerung

Bei der Druckentwässerung wird in jedem Haushalt ein Speichertank installiert, indem sich eine Schneidwerkspumpe befindet. Ist ein Füllstand von ca. 100L im Speicherbehälter erreicht, fördert die Schneidwerkpumpe das Abwasser über ein Druckrohrnetz zur Kläranlage.

Die Vorteile der Druckentwässerung sind:

- Geschlossenes System, daher keine Geruchsbelästigung
- Geringere Bautiefe und geringerer Rohrdurchmesser als bei Freispiegelentwässerung, daher häufig auch kostengünstiger

- Rückstauvermögen des Kanalnetzes bei kurzfristiger Anlagenüberlastung durch die Speicherbehälter (800L) in jedem Haushalt
- Kein Fremdwasser (Regen- oder Grundwasser)

Membranbelebungsverfahren

Beim Membranbelebungsverfahren wird ohne mechanische Reinigung das Abwasser biologisch gereinigt und dann mit einer Membranfiltration der belebte Schlamm abgetrennt. Die Membran sorgt dabei für einen vollständigen Biomasse- und Partikelrückhalt und es ergeben sich folgende Vorteile:

- Vollständige Desinfektion: die Grenzwerte der EU-Badegewässerrichtlinie werden bereits im Kläranlagenablauf erfüllt;
- Kompakte Bauweise: Einbau der kompletten MBR-Anlage in einen Frachtcontainer und mit 17 Quadratmeter Grundfläche für 250 Einwohner ist diese nicht größer als eine Pumpstation;
- Überwachung der Funktionen per Fernsteuerung und Alarmmeldung auf ein mobiles Telefon;
- Geschlossene Containeranlagen gliedern sich besser in das Landschaftsbild ein und bieten gegenüber offenen Becken den Vorteil, dass keine Geruchs- und keine Lärmbelästigung entstehen;
- Durch Variation der Biomassekonzentration im biologischen System und der eingesetzten Membranfläche kann ein größerer Bereich an Zulauffracht abgedeckt werden als bei konventionellen Systemen mit Sedimentation.

Angewandtes biologisches Verfahren

Seit dem Jahr 2000 forschten die Berliner Wasserbetriebe und Veolia Water, um die vermehrte biologische Phosphorelimination auch bei hohen Bakterienverweilzeiten im Membranbelebungsverfahren einzusetzen. Weiterhin entwickelten sie die Post-Denitrifikation ohne Kohlenstoffdosierung und sparten dadurch einen Schlammkreislauf ein. Dieses biologische Verfahren, das Platz, Energie und Chemikalien einspart, wurde patentiert. Ohne die Zugabe chemischer Hilfsmittel können Kohlenstoffverbindungen zu über 95%, Phosphat zu über 99% und Stickstoff zu über 90% entfernt werden. Dabei liegt die erreichte Ablaufqualität über den EU Kriterien für sensitive Gebiete und Badegewässer und somit wird ein wertvoller Beitrag zum Schutz der Gewässer geleistet.

Projektphase 1: Designvalidierung

Standortbestimmung der Demonstrationsanlage

Bei der Auswahl des Standortes der Demonstrationsanlage wurden 20 Siedlungen im Berliner Randgebiet verglichen und Berlin-Margaretenhöhe ausgewählt. Die Siedlung ist mit 250 Einwohnern zwar recht klein, ursprünglich war eher eine wirtschaftlichere Größe von ca. 1000 Einwohnern angestrebt, bot aber andere Vorteile. Der Bau der MBR-Anlage konnte schnell erfolgen, da ein passendes Grundstück vorhanden war. Die Distanz zum zentralen Kanalnetz war groß genug, so dass eine dezentrale Lösung wirtschaftliche Vorteile bot. Die Einleitung konnte in ein vorhandenes Oberflächengewässer erfolgen und erbringt einen ökologischen Mehrwert, da der Wasserhaushalt in einem nahen Landschaftsschutzgebiet aufgebessert wird. Von der Wasserbehörde wurden für die Einleitung extrem strenge Ablaufkriterien gefordert, die die Anforderungen Berliner Großklärwerke deutlich übertreffen, da es sich bei dem aufnehmenden Bach um ein sensibles Gewässer in einem geschützten Landschaftsgebiet handelt.

Vorbereitende Studie

Zur Bestimmung von Auslegungs- und Betriebsparametern wurde eine Pilotanlage errichtet und über den Zeitraum von einem Jahr betrieben. Damit konnten folgende wichtigen Ergebnisse erzielt werden und die richtigen Entscheidungen getroffen werden:

- Die Zulaufbelastung in dezentralen Gebieten unterliegt starken Schwankungen. In den Nachtstunden fällt kaum Wasser an und tagsüber kommt es zu deutlichen Belastungsspitzen.
- Durch den geringen Wasserverbrauch und das Fehlen von Regenwasser ist das Abwasser höher konzentriert.
- Die Installation eines Puffertanks, aus dem heraus die MBR-Anlage beschickt wird ist von großem Nutzen. Durch den Speicher kann das Membrankläranlage mit einem gleichmäßigem Zulauf beaufschlagt werden, was nicht nur in einer geringeren Membranfläche resultiert sondern sich auch positiv auf den biologischen Prozess auswirkt.
- Eine diskontinuierliche Überschussschlammentnahme wurde zunächst angestrebt, da in diesem Fall kein Überschussschlammbehälter gebaut werden muss und dies bei dezentralen Anwendungen ökonomisch vorteilhaft sein kann. Es zeigte sich aber, dass sich diese Fahrweise destabilisierend auf den Prozess der biologischen Stickstoffelimination auswirkt.
- Auch ohne die Zugabe einer externen Kohlenstoffquelle sind gute Denitrifikationsraten von etwa 1 mgN/h/goTS erreichbar.
- In kleinere MBR-Anlage muss es auf die Vermehrung von Tubifex Würmern geachtet werden und notfalls sollten diese frühzeitig bekämpft werden.

Projektphase 2: Bau und Inbetriebnahme

Anlagenbau

Der Bau der MBR-Anlage wurde europaweit ausgeschrieben. Den Zuschlag erhielt die Deutsche Firma Martin Systems, die nicht nur das günstigste Angebote unterbreitete, sondern auch ein sehr innovatives Konzept vorstellte. Hierbei wurden sämtliche Anlagenkomponenten inklusive der Vorsiebung in einen kompakten Container integriert. Die MBR-Anlage wurde in nur 6-7 Monaten in den Werkstätten der Firma montiert und dann zum Demonstrationsstandort geliefert und aufgestellt. Am 1. März 2006 wurde die MBR-Anlage in Betrieb genommen.

Bau des Kanalnetzes

Insgesamt wurden knapp 2000m Druchrohr verlegt. Zum Anlagenstart waren etwa 30% der Einwohner bereits an das Kanalnetz angeschlossen. Der Anschlussgrad erhöhte sich in den folgenden sieben Monaten auf 100% und übertraf damit die Prognose, die bei 80% lag.

Inbetriebnahme und erste Betriebsmonate

Es zeigte sich, dass das Abwasser noch höher konzentriert war als in den zuvor untersuchten Siedlungsgebieten (Tab.2). Die gemessenen Konzentrationen lassen auf einen Wasserverbrauch von nur 50-80 L pro Einwohner und Tag schließen, was deutlich unter dem Berliner Durchschnittsverbrauch liegt.

Durch den hohen Anschlussgrad lag die Abwassermenge ab August 2006 deutlich über dem Designwert von 10 m3. Es wurde nicht nur ein Tagesgang des Abwasseranfalls aufgezeichnet, sondern auch einen klaren Verlauf über die Woche. So ist der Abwasseranfall an den Wochenenden mit 18 m3 um 50% höher als unter der Woche. Diese Charakteristik ergibt sich dadurch, dass die Bewohner an Werktagen tagsüber nicht zu Hause sind.

Durch die höhere Konzentration und Menge des Abwassers resultierte eine Nährstofffracht, die 100% über dem Designwerten lag. Daraus ergaben sich viele Probleme wie z.B. starkes Schäumen der MBR-Anlage, unzureichende Sauerstoffversorgung und Nährstoffelimination. Seit Dezember 2006 wird ein Teilstrom des Abwassers abgefahren und der biologische Prozess stabilisierte sich. Weiterhin wurden zusätzliche Belüfter installiert, um eine bessere Sauerstoffversorgung des Prozesses zu gewährleisten.

Projektphase 3 : Technische und ökonomische Auswertung

Ergebnisse beim stabilen Betrieb

Seit April 2007 konnte ein stabiler Betrieb der MBR-Anlage realisiert werden. Es konnte gezeigt werden, dass trotz einer immer noch vorhandenen 25%tigen Überlastung der MBR-Anlage eine sehr hohe Reinigungsleistung erbracht wird. Die Membranfiltration gewährleistet für die Parameter E. coli und Enterokokken Konzentrationen unter der Nachweisgrenze. Organische Verbindungen werden zu mehr als 95% abgebaut und Stickstoff zu 90%-95% eliminiert. Die geforderten Grenzwerte von 50 mg/L CSB und 10 mg/L gesamt Stickstoff im Ablauf können realisiert werden. Die Elimination von Phosphor war mit konstant über 99% ebenfalls sehr hoch, allerdings lagen die Ablaufwerte mit 0,1-0,2 mg/L geringfügig über der geforderten Qualität. Bezogen auf die hohe Zulaufkonzentration und die sehr geringe ortho-Phosphatkonzentration (85%tile < 0.05mgP-PO_4/L) ist diese Konzentration als der refraktäre Anteil zu betrachten, der nicht mehr entfernbar ist.

Der Filtratfluss lag zwischen 6-12 L/m²/h und die Crossflow-Belüftung betrug ca. 1°Nm³/m²/h. Langfristig konnte die Membranfiltration aufgrund mehrerer Faktoren wie z.B. Hydraulik im Modul und Reaktor, Reinigungskonzept und Membranmaterial, nur auf einem unbefriedigen Niveau betrieben werden. Die Filtrationtechnologie wurde ersetzt. Als Empfehlung gilt, dass eine Überprüfung der Hydraulik und ein hohes Freibord für das biologische System vorgesehen werden sollte.

Kostenauswertung

Für die semizentrale Entwässerung von Kunden ergeben sich Einsparungen in der Überleitung aus dem Siedlungsgebiet zu einem existierenden zentralen Entwässerungsnetz. Die Grundstücksfläche für die MBR-Anlage entspricht der Fläche für eine Pumpstation. Eingespart wurden im Netzbau und Pumpwerk Kosten von ca. 650.000°€. Die gesamte Kleinkläranlage kostete nur 382.000 €, das entspricht ca. 1500 €/EW. Die Evaluierung für einen Scale up einer MBR-Anlage für 1000 EW mit den gleichen Standards (bezüglich Reinigungszielen, Messtechnik und Ausstattung) ergab Gesamtkosten von 1.059.000 € oder spezifischen Kosten von ca. 1000 €/p.e.

Die Betriebskosten liegen mit 2,80€/m³ deutlich über dem Tarif für Schmutzwasser und enthalten noch keine spezifischen Abschreibungen für die Investitionskosten. Die Kosten ergeben sich im Wesentlichen durch den Energieverbrauch, den Wartungsvertrag und die Analysenkosten. Dabei sind deutlich Einsparungen zu erzielen. Vernachlässigbar bei diesen kleinen MBR-Anlagen sind die Membranersatzkosten und die Reinigungskosten.

Projekt mit Zukunft

Die Kläranlage befindet sich direkt in der Siedlung. Die nächsten Häuser von Anwohnern sind nur wenige Meter entfernt. Die MBR-Anlage wird dennoch sehr gut angenommen. In der gesamten Betriebszeit der MBR-Anlage gab es keine Beschwerden bezüglich Geruch oder Lärm.

Das entwickelte Verfahren muss selbstverständlich nicht auf Berlin begrenzt bleiben. In Deutschland, aber auch über die Grenzen hinaus, vor allem in Mittel- und Osteuropa, gibt es viele Gebiete ohne zentrale Abwasserentsorgung, wo ein dezentrales oder semizentrales Konzept sinnvoll ist.

Fazit

- Es wurde eine Membranbelebungsanlage (MBR) zur dezentralen Behandlung häuslicher Abwässer erfolgreich aufgebaut und betrieben.
- Das gesammte Abwasserkonzept mit der Druckwasserentwässerung, einem Pufferbehälter und der MBR-Anlage wurde von den Projektpartnern positiv bewertet.
- Die Demonstrationanlage ist für 250 Einwohner angelegt und wurde in einem Frachtcontainer gebaut und geliefert.
- Die Eingliederung in die vorhandene Siedlung erfolgte problemlos und die Akzeptanz in der Bevölkerung ist sehr gut.
- Das angewandte biologische Verfahren zur vermehrten biologischen Nährstoffelimination mit Post-Denitrifikation ohne Kohlenstoffdosierung hat gute Ergebnisse gezeigt. Bei stabilem Betrieb unter Auslegungs-Frachtbedingungen wurde eine Reinigungsleistung erreicht, die deutlich über dem Standard Berliner Großklärwerke liegt. Ohne die Zugabe chemischer Hilfsmittel können Kohlenstoffverbindungen zu über 95%, Phosphat zu über 99% und Stickstoff zu über 90% entfernt werden.
- Der Betrieb der MBR-Anlage konnte per Fernsteuerung überwacht werden, was die Zuverlässigkeit des Verfahrens erhöhte und den Aufwand für das Personal deutlich verringerte.
- Die spezifischen Investitions- und Betriebskosten sind für 250 Einwohner noch relativ hoch. Niedrigere spezifische Kosten werden für größere Anlagen bis 5,000 Einwohner erwartet.

CONTENT

GLOSSARY

AE	Aerobic reactor
AN	Anaerobic reactor
AOX	absorbable organic halogen
AX	Anoxic reactor
AST	Activated Sludge Treatment
BSP	Bench-Scale Plant
CAS	Conventional activated sludge
CIP	Cleaning In Place (currative cleaning)
DIN	Deutsches Institut für Normung e.V.
EBPR	Enhanced Biological Phosphorus Removal
GAO	Glycogene Accumulating Organisms
ICP	Inductive coupled plasma
IMF	Immersed Membrane Filtration
HRT	Hydraulic Retention Time
MR	Membrane reactor
MBR	Membrane Bioreactor
N	Nitrogen
P	Phosphor
PAO	Polyphosphate Accumulating Organisms
PR	Proteins
PS	Polysaccharides
PP	Pilot Plant
SRT	Sludge Retention Time (= “sludge age”)
T	Temperature
TMP	Transmembrane Pressare
TS	Totale Solids
VFA	Volatile Fatty Acid
WWTP	Wastewater Treatment Plant

FIGURES

TABLES

INTRODUCTION

There is a worldwide requirement of treating the wastewaters in order to alleviate and avoid the pollution of water bodies and the phenomenon of eutrophication. Fact is also that in EU many bathing waters do not comply with the “EU Bathing Water Directive”. Improvement of existing wastewater treatment systems, together with construction of new plants is therefore of paramount importance. The development of novel efficient and cost-effective processes is relevant if we consider the increasing discharge criteria to be matched by treated effluents.

Future stringent phosphorus regulations together with the availability of innovative membrane processes are the bases for this project. In contrast to conventional activated sludge plants, the technology of enhanced biological phosphorus removal (EBPR) is not proven yet for membrane bioreactor (MBR). Current practice of P-removal in MBRs is the addition of coagulants in a co-precipitation mode. This project focussed on developing EBPR in MBR processes and optimising the biological treatment

This 3-year project aims at undertaking the first full-scale assessment of an innovative treatment process. This combines enhanced biological phosphorus and nitrogen removal with post-denitrification together with a membrane bioreactor, and should lead to improved removal of nutrients and pollutants compared with the treatment performance of conventional plants. A successful completion of the project would open the utilisation of this process to other applications in Germany, Europe or worldwide.

A demonstration plant was designed according to this innovative process, with a capacity of 250 p.e. This plant was built in a remote and so far unsewered area around Berlin, in parallel with the sewer deserving the population of the local area to supply the plant. The effluent is characteristic of a decentralised area, i.e. it does not contain any industrial wastewater neither storm water. The goal of the ENREM-Project is to demonstrate the technical feasibility and reliability of the novel treatment process at a commercial scale capacity.

After commissioning and start-up, this plant was then operated continuously over 1.5 year, treating the collected sewage to a quality meeting the EU criteria for sensitive area and bathing water. The operation of the system was assessed and optimized in order to identify the best operation conditions to achieve the required discharge criteria at least operation cost and to detect any issue related to full-scale implementation. The performances of the biological system, such as the kinetic rates were closely monitored and assessed, both through measurements on-site but also in the laboratory in standard batch tests. The performance of the membrane filtration system was also thoroughly controlled, especially in view of fouling and clogging problems, in order to insure reliable and continuous operation of the demonstration plant.

I. BACKGROUND OF STUDY AND PROCESS SELECTION

The technology selected for the ENREM demonstration plant is the wastewater treatment process of membrane activated sludge, commonly referred to as membrane bioreactor (MBR), designed for enhanced biological elimination of phosphorus and nitrogen. The MBR technology consists in the combination of an activated sludge system together with a micro- or ultra-filtration step to achieve the physical separation of the treated effluent from the mixed liquor. The membrane filtration ensures complete removal of suspended solids and colloids, together with pathogens.

Over the last decades, since the first demonstration of membrane filtration systems of low pressure submerged module, in Japan in the early 90's, the MBR technology went through a quick development and application pace. The first European MBR plant for municipal wastewater was built in 1998 (in Porlock, UK, 3,800 p.e.). In 2004, the largest MBR plant worldwide was commissioned to serve a population of 80,000 p.e. (in Kaarst, Germany).

Meanwhile, the technology was adapted to different technical conditions, and many products are now available on the market for the different application sizes. In particular, two types of submerged module designs are proposed with polymeric membranes: the flat-sheet membrane modules, and the hollow fiber membrane modules. A non-exhaustive list of European producers is given below for the sizes corresponding to decentralised and semi-central applications:

- 4 to 50 p.e. (decentralised treatment): Busse, Huber, Martin System, MallBeton, etc
- 50 to 500 p.e. (containerised-like turn-key plants for semi-central treatment): Kubota, Huber, A3 Water Solutions, Puron, etc
- 500 to 5,000 p.e. (with standardised filtration units for semi-central treatment): Kubota, Zenon, Mitsubishi, Memcor, Huber, Puron, A3 Water Solutions etc

The main advantages of the MBR technology, compared with the conventional activated sludge (CAS) technology, are:

- outstanding quality of treated effluent: the membrane insures a particle- and pathogen-free effluent, complying with unrestricted irrigation and bathing water criteria;
- stable treatment performance in time, with greater robustness to load variation (daily or seasonal), and no risk of sludge bulking or sludge lost in the clarifier; and
- compactness: no needs of large-footprint clarifiers, sludge concentration 3 to 4 folds higher than conventional activated sludge process, possibly no need of primary sedimentation. The overall footprint of an MBR plant is considered to be twice as small as this of a CAS technology.

For semi-central sanitation systems up to 10,000 p.e., the technology of membrane bioreactor can offer the further following advantages in comparison with other processes:

- broad operational window (sludge age 10 to > 100d, sludge concentration 6 - 18 g/L, etc), adaptable to sometimes unpredictable population growth of remote areas
- reliable and excellent quality in time without degradation of treatment performance over years
- possibility of remote control with on-line detection of process disturbances
- containerisation of entire plant (up to 2,000p.e.) or the filtration units (up to 10,000p.e.) with modularity of filtration system, therefore flexibility of plant volume increase

- the MBR plant should not entail the usual inconveniences of wastewater treatment plants to the local neighbourhood, namely odour and noise emissions, or increased truck traffic.

The main drawback of the membrane bioreactor technology still remains the capital and operation costs due to use of the high-tech membrane filtration aggregates, and depending from both membrane fouling and effective module lifespan. This is also a “high-tech system” which requires qualified and committed staff, clear operational guidelines, and quick reaction in case of any process or system disturbance.

Figure 1 compares recent capital cost of MBR plants with capital costs of CAS plants and wetlands. It shows that the capital costs of the MBR technology have become competitive with other conventional processes, which however do not achieve a similar degree of treatment.

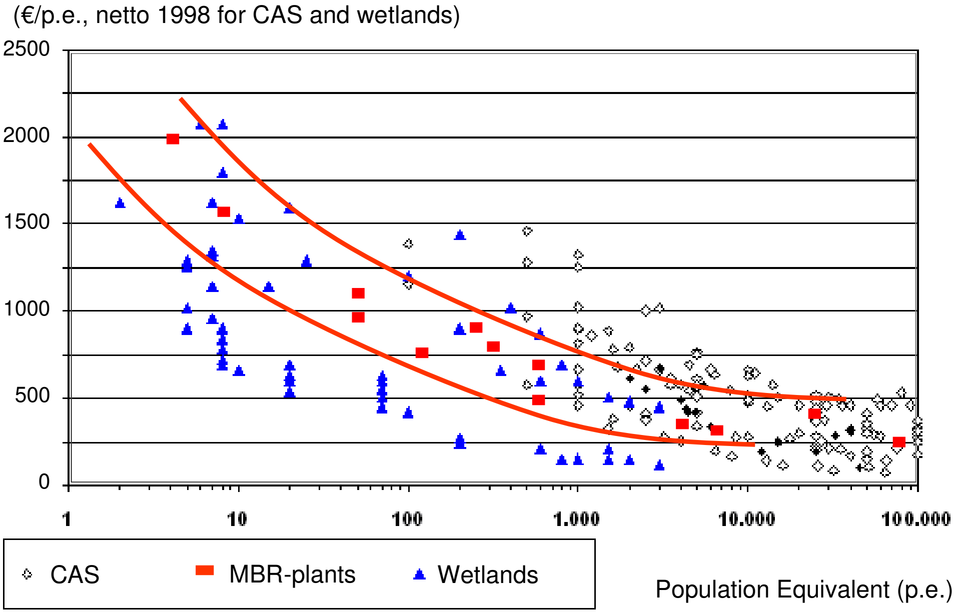


Figure 1 Capital costs of MBR plants, CAS plants and wetlands (Lesjean, 2005, adapted from Reicherter, 1999)

Similarly, the continuous efforts of the MBR systems suppliers to reduce the operation costs led to minimised energy, labour and chemical requirements. As example, the total plant energy needs of MBR systems, initially greater than 1.5 kWh/m^3, has reached now 0.9 kWh/m^3 in recent large municipal applications (> 10.000 p.e.), with the objective to optimise this value down to 0.75 kWh/m^3. We have however to bear in mind that this remains much greater than the energy requirement of a CAS plant (0.1-0.2 kWh/m^3), even when combined with tertiary filtration (0.3-0.6 kW/m^3), as provided by Gnirss et al. (2001). These results from the needs of important membrane aeration rates required to run the submerged filtration system under relatively stable hydraulic conditions. It is obvious that a small WWTP will have higher specific energy demand than a large WWTP, due to low energy efficiency of small aggregates and fix energy requirements (PLC, light, heating / cooling etc). The energy requirement of containerized MBR plants reported during the project preparation was 7.7, 5 and 3 kWh/m^3 respectively for capacities of 300, 500 and 1000 p.e. (source: A3 water solutions). This high energy requirement impacts significantly on the net present values (NPV) of decentral containerised MBR plants, which are consequently higher than central CAS systems.

II. DEMONSTRATION SCHEME AND PLANT DESCRIPTION

Municipal waste waters handling can be divided into three steps: the first part is the collection, the second one is the transport and the third one is the treatment. The investment costs for collection and transportation are usually up to 80% based on the total investment costs. The aim of ENREM was not only to focus on the process for wastewater treatment but to optimise all three steps in terms of operation in order to perform an integrated cost assessment.

The demonstration scheme was built as a low-pressure sewer system without storm water collection according to the results of the site evaluation (Annex I). Instead of erecting a pumping station and a pressure main up to the central sewer, a decentralised MBR plant was constructed to fulfil the high quality requirements (Annex II). The MBR plant facility included a storage tank, a pre-treatment step, the biological reactors, three membrane reactors, and a control and an acquisition system as described below. The plant is designed to treat 100% of the incoming flow, without any possibility of bypass or emergency overflow, and to comply with the required nutrients elimination grade as long as the temperature remains greater than 12°C.

A public tender process for the sewer and the MBR plant were conducted by the Berliner Wasserbetriebe. According to the tender process the sewer was constructed by the company Tepe, the household pumping stations were delivered by Jung Pumpen and the MBR-plant was constructed by Martin Systems.

II.1. DESCRIPTION OF THE DISTRICT OF MARGARETENHÖHE

The district of Margaretenhöhe is located in the north east of Berlin and has a surface area of approximately 24 hectares, for an average of about 250 residents (some houses are used only during summer period). The district, which does not include any shop, restaurant or industry, hosts only one bear local, and is surrounded by gardening parcels which do not need to be connected to the sewer. The WWTP effluent is discharged in the "Margaretengraben" creek (within 200m), which often dries out in summer and lies in the catchment area of the river Panke, under the responsibility of the Berlin Senate. The protected landscape area requires special infrastructure, as negotiated between Berliner Wasserbetriebe and the local administration: the periphery of the MBR-plant was replanted with bushes and a wear with built up on the creek to retain the treated water in summer.

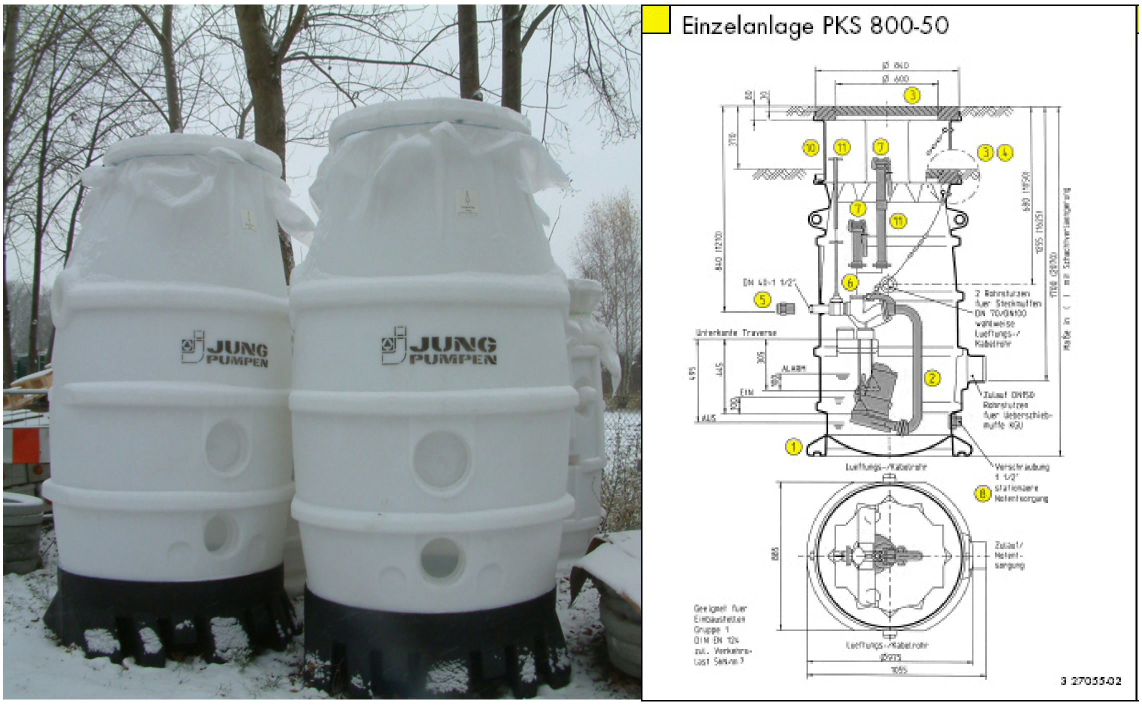
Picture 1 Satellite view and sketch of the district of Margaretenhöhe (Google-Earth)

II.2. LOW-PRESSURE SEWER

The raw wastewater is first collected in household buffer tanks equipped with grinding pumps. The majority of the inhabitants (99%) were provided a 750 litres capacity tank and little larger housing were equipped with a 1200 litres capacity tank. Once the level in the buffer tanks reaches 100 litres, the 1.9 kW grinding pump (7mm) evacuate the wastewater within 30 seconds under about 0.5 bar in the low-pressure sewer system. It was chosen to evacuate the wastewater very fast in order to avoid unpleasant odours by the inhabitants and also because wastewater are infectious and must be as fast as possible evacuated. In case of disturbance and failure no work at the customers must be done during the night or the weekend due to the storage capacity, which enables at least 48h reaction time. The total storage capacity of the household buffer tanks is estimated as follows:

- Operation volume: about 10 m^3 (HRT ~ 2 -6h depending on instant flow)
- Emergency volume: about 60 m^3

The raw wastewater is the transported from the customer in the low-pressure drainage system. The diameters of pipes are DN 40, 50 and 60 with respectively 57m, 1810m and 18m of installed length. As the sewer is discharged under water level of the buffer tank, it was decided not to construct the high pressure air stations which are usually built with these kinds of systems to flush on a daily basis and prevent from odour release at the discharge point. The other advantage renouncing the air flushing is the avoidance of extreme peak flows which would enter the buffer reactor at each flushing event. Separated protection pipes and waterproof electronic panels are installed at each household for power supply. The storage capacity of the sewer network (always full) is estimated to be of about 4m^3, with a mean residence time of 1-6h (depending on instant flow).



Picture 2 House buffer tanks and pumps installed at each house

II.3. INCOMING VALVE, BUFFER TANK AND PRE-TREATMENT

The pre-treatment system included the following steps (see Figure 2):

1. Automatic valve between low-pressure sewer and buffer tank
2. Buffer tank (~10m^3, effective 2 - 9 m^3;buffer + acts as sand trap, HRT ~ 3 -12h)
3. 2 Raw water pumps (7mm grinding pumps, equal to house pumps, see Picture 2)
4. Fine screen drum (1mm punch hole screen, 600L pit)

No sand grit was foreseen, as the wastewater is storm water-free, and due to the presence of the buffer tank and the fine screen. No fat trap was installed as the area is devoid of industry or restaurant.

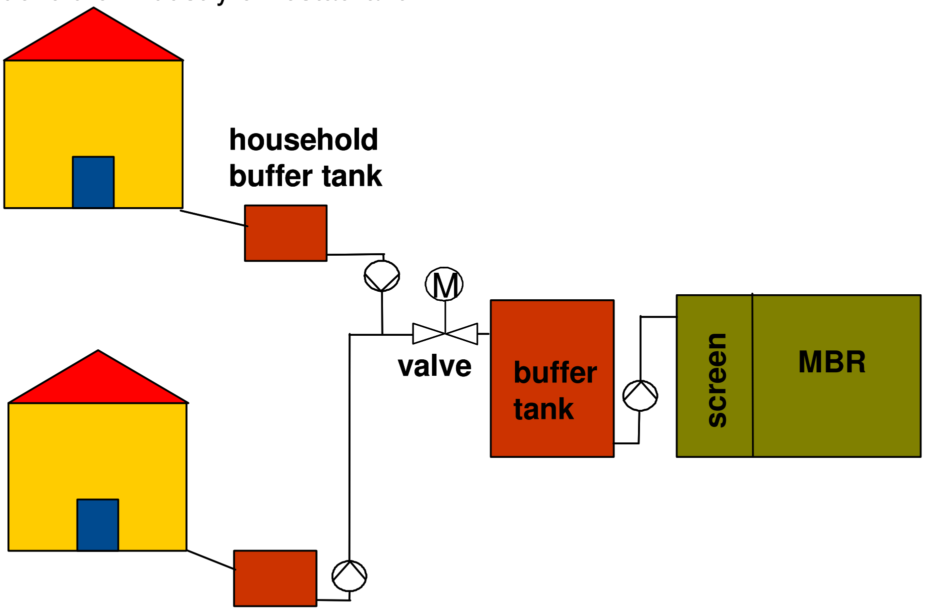
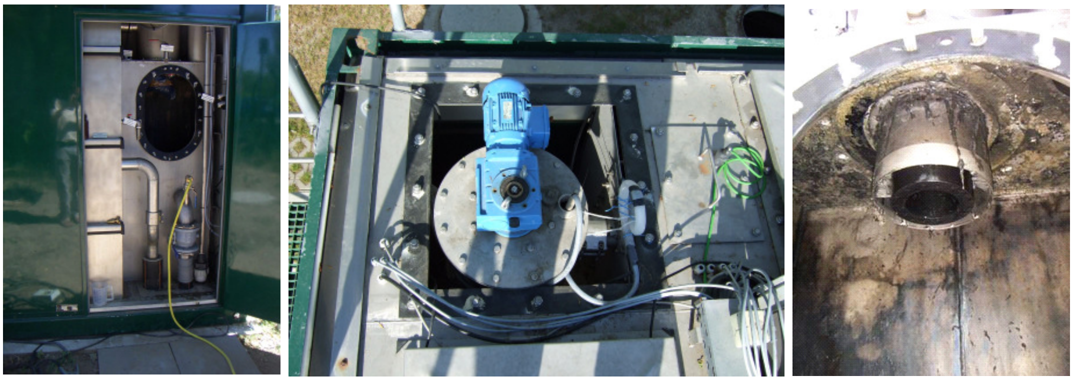


Figure 2 Flow scheme of Network, Valve and Pre-treatment system

The screen drum (Picture 3) was supplied by Martin Systems and set up directly in the Container. The raw water pumps are operated according to the water level in anoxic tank AX2. The raw water filled the vertical screen drum up to a certain level and the raw water flows through the screen. The grits are scrapped off the screen with an external nylon brush (vertical sieve with rotating brushes), and expelled out off the drum into the 600L pit. After one months (design-value) the pit must be emptied in the excess sludge tank by opening a manual valve. For redundancy a motor and a brush are in stock to ensure repair work within 2 hours.



Picture 3 Pre-treatment in container, raw water pit and sieve

The long total hydraulic retention time in the household storage tanks, in the pressure main and in the buffer tank (total of 6h to 24h), as well as the double steps of grinding pumps, and the cleaning of the grits by the wastewater, are considered to be positive for the biological processes, as they optimise the presence of readily biodegradable organic matter.

II.4. DESIGN HYPOTHESES

The design of the biological process was based on the experience gathered during

1. the R&D project IMF performed by the same partners (2000-2003) [Gnirss et al., 2003, Adam, 2004; Lesjean et al., 2005]
2. the preliminary pilot study performed on the decentralised site of Grünau (2004-2005) [Vocks et al., 2005a]

The pilot study in Grünau (750 e.p. with gravity flow) enabled to validate the final design and operation criteria presented below, with a pilot unit of 300 L/d, and in a representative and remote area of east Berlin. The main outcomes of the study were:

- The selected design and operation criteria are OK for quality targets

A buffer tank with max. 12h HRT is sufficient for load equalisation with a flow profile typical of a decentral area (according to simulations performed to estimate the minimum buffer tank size to avoid both overflow and dry out of the tank in extreme profile conditions [Villwock, 2005].

- Regular sludge extraction with sludge storage is most appropriate sludge management strategy [Vocks et al., 2007a]

In addition to this verification, a campaign of wastewater characterisation was performed on the representative site of Ransdorf with low-pressure sewer (East-Berlin, 500 p.e.), in order to estimate the wastewater amount and quality that will be collected by the new wastewater scheme of Margaretenhöhe [Villwock, 2005].

II.4.1. Design hypotheses: wastewater amount

This was derived from the local drinking water consumption (50 L/e.p.), taking account potential addition due to the utilisation of wells and rain water, but also some lost due to gardening.

The hypotheses of connection rate, as observed in other decentralised areas of Berlin were:

- 30% at start
- 80% after 12 months
- Close to 90% at long term

In addition, it was considered that the local drinking water consumption would slowly increase up to about 100 L/e.p., increasing by two fold the hydraulic load of the plant (ultimately up to 24m^3/d), but not the pollution load for a given connection rate.

II.4.2. Design hypotheses: wastewater composition

Table 1 shows the wastewater quality which was selected from the measurement campaigns performed in Rahnsdorf.

This is a highly concentrated municipal wastewater (due to low water consumption). In order to estimate the nitrogen peak load, it was determined that the 85%-tile concentration would be 131 mgTN/L, lowered to 120 mgTN/L after max. 12h-buffer tank. This later value was taken as peak-load to achieve nitrification and denitrification with temperature above 12°C.

Table 1 Design wastewater composition (50%-tile concentrations)

Parameter	Concentration
BOD5	493 mg/L
COD	986 mg/L
TS	356 mg/L
TKN	108 mg/L
TP	15 mg/L
VFA	94 mg/L

II.4.3. Design hypotheses: wastewater load

Table 2 presents the projected evolution of key design and operation parameters in time taking into account the estimations of connection rate and water consumption. It shows that the unit should be designed to cope both in terms of purification and filtration performances with ranges of 4-24 m^3/d and 0.46-1.47 kg/m^3/d. The design included therefore the adaptation of operation parameters in the range 6-12 g/L and 15-35d SRT.

Table 2 project of key design and operation parameters in time

	Connection rate	Water consump.	Through-flow	COD-load	TSbio	SRT
First months	30%	50L/d	4 m^3/d	0.46 kg/m^3/d	6 g/L	35 d
Year 1	**80%**	**50L/d**	**10 m3/d**	**1.23 kg/m^3/d**	**12 g/L**	**25 d**
Long-term	100%	100L/d	24 m^3/d	1.47 kg/m^3/d	12 g/L	15 d

Table 3 present for each pollution parameter the range of 50%-tile daily volume load that should be handled by the unit (corresponding to min-max flow). This highlights the challenge of the project: to design advanced biological nutrients removal with a broad nitrogen load range of 0.05 kg/m^3/d up to 0.15 kg/m^3/d (ratio 1 to 3!).

Table 3 50%-tile daily volume load at min and max flows

Parameter	Concentration	50%-tile Daily Volume Load (@ **min flow of 4m^3/d**)	50%-tile Daily Volume Load (@ **max flow of 10m^3/d**)
BOD5	493 mg/L	0.25 kg/m^3/d	0.62 kg/m^3/d
COD	986 mg/L	0.49 kg/m^3/d	**1.23 kg/m^3/d**
TS	356 mg/L	0.18 kg/m^3/d	0.45 kg/m^3/d
TKN	108 mg/L	**0.05 kg/m^3/d**	0.14 kg/m^3/d (peak **0.15**)
TP	15 mg/L	0.009 kg/m^3/d	0.019 kg/m^3/d
VFA	94 mg/L	0.005 kg/m^3/d	0.012 kg/m^3/d

In addition to the impact on the biological process, we shall insist, for such a single-lane plant, on the difficulty of the equipment selection to cope with the very broad range of operation conditions. The estimation of total aeration requirement for the biology can be taken as example: neglecting the O2 carry-over from membrane reactor and considering the load increase with time, together with the α-factor decrease, as well as a temperature range of 10-27°C, the total aeration requirement can be calculated in the range as broad as 2.9 - 29 Nm^3/h, knowing that this should be achieved with only one single blower only!

II.5. BIOLOGICAL REACTORS

The dimension of the MBR pilot plant is about 10 m^3 (15 up to 30h HRT) and consists of a 2.5m deep rectangular shaped tank which is divided in 1 anaerobic reactor, 2 aerobic reactors, 1 de-aeration zone and 2 anoxic reactors. Collection channels before and after the three membrane units distribute the flow equally. The configuration of the reactors is given in Figure 3 and the size of the reactors is given in Table 4. The biological reactors were requested to suit the full design capacity and the filtration unit should have redundancy due to cleaning and/or maintenance.

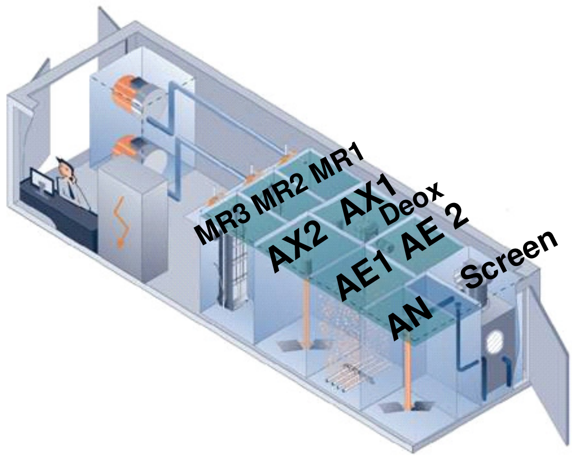


Figure 3 Reactor configuration

Zone	Volume
Anaerobic	0.73 m^3
Aerobic	2x 1.96 m^3
Deox	> 0.040 m^3
Anoxic	2x 1.8 m^3
Membrane	3x 0.6 m^3
Total	~ 10 m^3

Table 4 Reactor sizes

The ENREM process combining EBPR and post-denitrification without carbon source addition was selected. The previous demonstration project IMF performed by the same partners (Lesjean et al., 2004) could demonstrate that this process could achieve advanced biological phosphorus and nitrogen removal with only 2 recirculation pumps instead of 3 in conventional processes, saving energy and equipment. The drawback is a larger anoxic volume (+ 50%) due to lower denitrification rates, which is generally not an issue for small units[1]. Centrifuge pumps were used as filtrate pumps and volumetric pumps are implemented for all other internal flows. The flow scheme is given in Figure 4.

Two air blowers each with a capacity of 2x 60 Nm^3/h set up in parallel sustained the air requirement of the biological and membrane units (each one in redundancy for the other). The two air blowers are encapsulated to avoid noise emission. An air conditioning system is required for the cooling of the dry area inside the container, especially because of the heat of the blowers. Two Envicon aerators of a diameter of 327 mm are installed in each aerobic reactor. The requirement for the maintenance protocol was to remove the aerators without emptying the tank. This can be easily done by removing the whole aeration pipe together with the diffusers. Each anaerobic and anoxic reactor includes a plate-mixer.

[1] In addition, in the present case with concentrated wastewater, high HRT / Volume is required, so volume is not so much limiting.

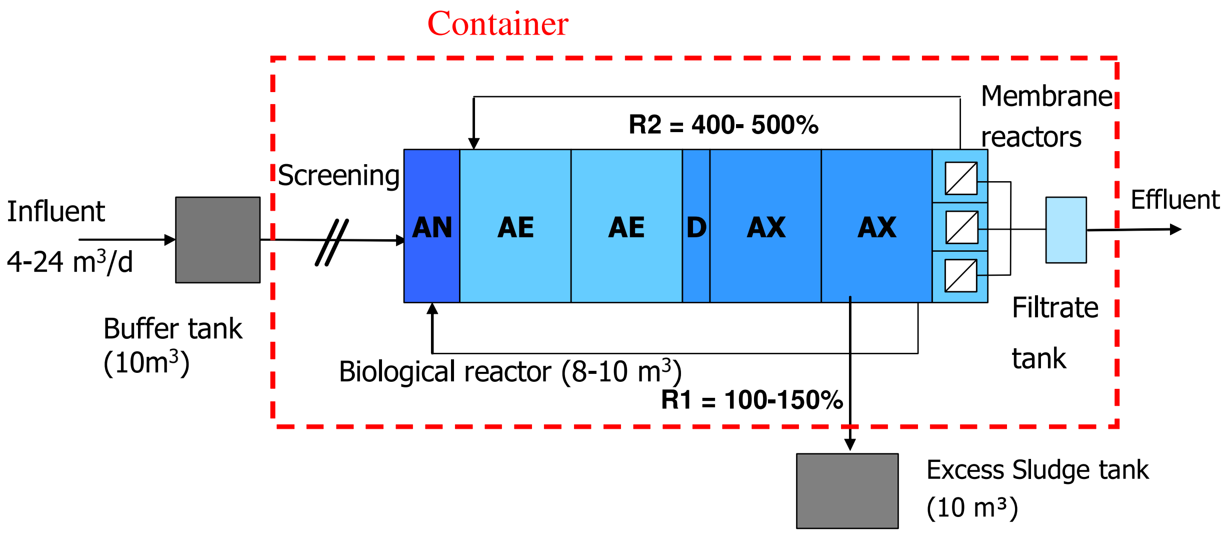


Figure 4 Flow scheme of the ENREM membrane bioreactor

II.6. FILTRATION SYSTEM AND MEMBRANE REACTORS

The membrane reactor had to be designed as small as possible (not more than 10% of biological reactor) but at least two parallel units. The third membrane zone is foreseen for the increase in flow capacity up to 24 m³/d which means to increase the flux from usual 6 L/m²h to 10 L/m²h for all three membrane units. Another specification of the filtration system is that the filtration should not be completely off-line for longer than 5h (in case of cleaning etc). Martin Systems equipped each filtration vessel with two triple deck immersed flat sheet membrane modules as shown in Picture 5 (pore size app. 0.037 µm, and membrane area of 37.5m^2 for each module). The clear water permeability at 20°C of the new modules was measured between 800 and 1000 L/h.m^2.bar.

The membrane reactors are fed by sludge originating from the last anoxic reactor AX2 (Figure 4). The recycle rate of sludge concentrate from the membrane back to the first aerated reactor can be in the range of 400-700% related to inflow. This recycle rate results theoretically to a sludge thickening of 1.1-1.3 fold in the membrane vessel compared to the sludge inlet concentration.
The strategies implemented to control fouling are adapted from the recommendations provided by Martin Systems. The standard recommendations include the following:

1. *Membrane aeration:* Air scouring with ~0.6-1 Nm^3/h/m² through membrane aerators located at the bottom of the module. Ascending bi-phasic fluid sweeps up the membranes, and creates turbulent conditions that improves matter transfer and reduces solid or gel accumulation at the surface of the membrane.
2. *Relaxation cycle*. The membrane modules are operated with e.g. 10 filtration and 2 min relaxation time.
3. *Curative cleaning, or cleaning-in-place (CIP).* When the transmembrane pressure (TMP) reaches 250-300 mbar, extended curative cleanings are undertaken with hydrogen peroxide, acid or alkaline solutions.

ENREM aims to develop a process adapted to decentralised areas, therefore minimising the maintenance operation, and the use and handle of chemicals on site. It was therefore decided to operate the filtration system with very conservative filtration conditions below 10 L/m²h. Also hydrogen peroxide (H_2O_2) was used for the CIPs. Chlorine was avoided as this chemical is not well accepted in the German water business due to the production of by-products such as AOX.

The data of the membrane and the filtration cycle are showed in Table 5. The productivity rate results from the situation that the operating flux is not given during the relaxation time and the starting period of the filtration pump.

Picture 4 Martin Systems Membrane Modules

Type	**-**	**Ultrafiltration / Flatsheet**
Material	**-**	**Polyether sulfone (PES)**
Pore diameter	**nm**	**37 (UF)**
Membrane area	**m²**	**37.5 (per line / triple deck)**
Specific air demand	**Nm³/m²/h**	**0.6 – 1.0**
TMP max.	**mbar**	**300**
Operating instant flux	**L/m²/h**	**5 – 15**
Filtration time	**sec**	**700 – 999**
Relaxation time	**sec**	**100 – 143**
Productivity rate	**%**	**~ 85**
Operating net flux	**L/m²/h**	**4 – 13**

Table 5 Details of membrane and filtration cycle parameter.

II.7. Control and Acquisition System

The process control is realised as schematically shown in Figure 5 with a PLC (programmable logic controller) and a separated SCADA system (supervisory control and data acquisition) which is located on an industrial PC. In case of PC breakdown an autonomous process control is guaranteed through the PLC in combination with an operating panel. PC remote control through an ISDN connection and alarm forwarding per SMS allows appropriate remote monitoring.

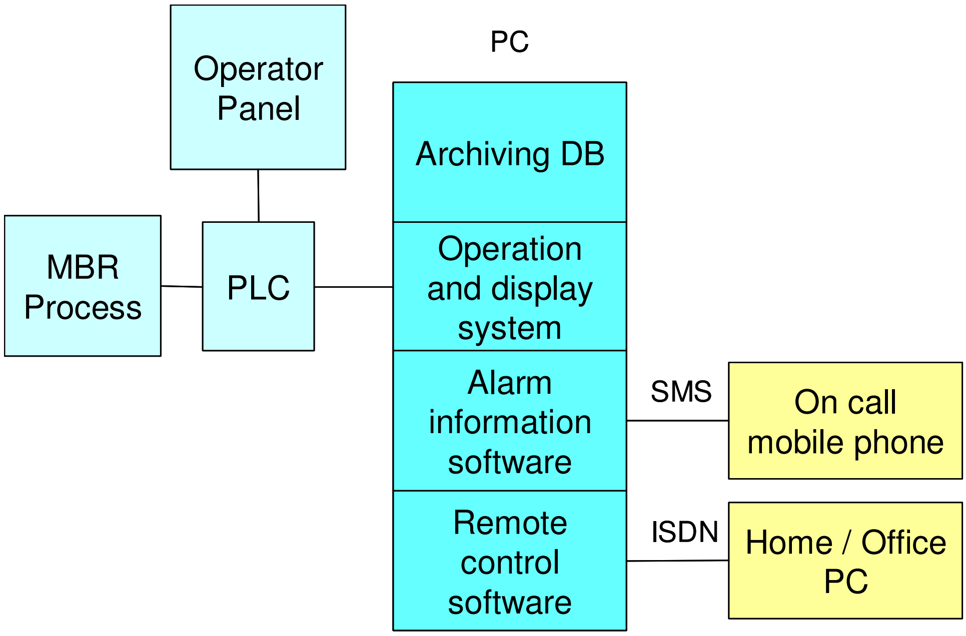


Figure 5 Process control System, Data acquisition and Remote control

The biological unit was equipped with the following electronic metering devices (Detailed flow scheme provided in Annex III):

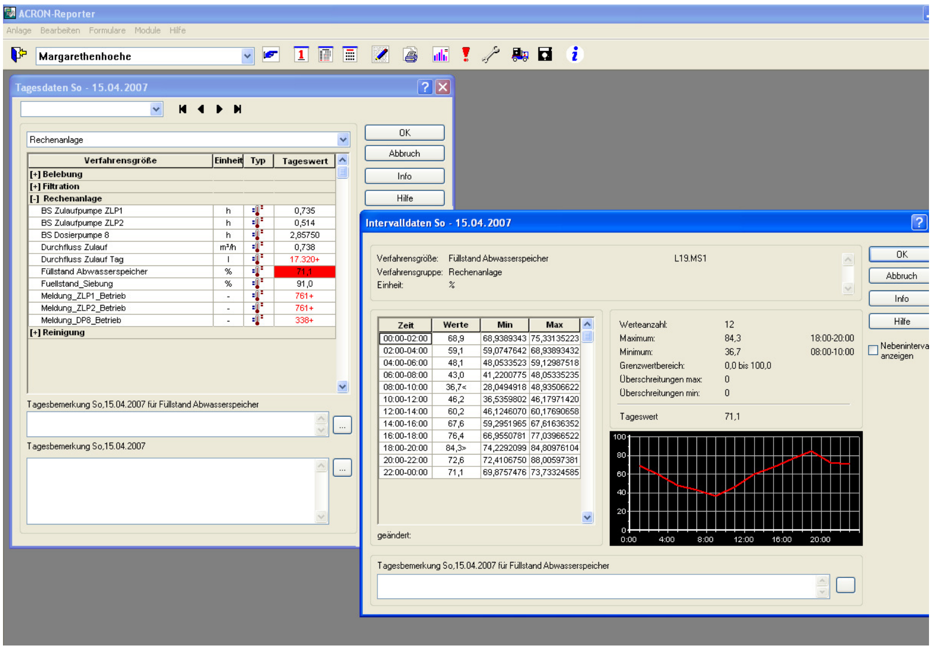
1. 2x DO and temperature probes (E+H)
2. Redox potential probe (E+H)
3. 2 Electromagnetic air flowmeters (E+H)
4. 2 Electromagnetic flowmeters for sludge recycling (E+H)
5. 3 Electromagnetic flowmeters for filtrate pumps (ABB)
6. Pressure sensor for water level in AX2, excess sludge tank and buffer tank (E+H)

Specific parameters related to membrane filtration, such as trans-membrane pressure, filtration/backwash flow, membrane sludge feeding flow, membrane vessel temperature were recorded by the central acquisition system.

Two turbidity meters (one in AX2) (E+H), NO_3 -analyser (Hach Lange, Stamosens CN750) and one PO_4 -analyser (Hach Lange, StamoLys CA 71 PH) in the effluent of the MBR plant, installed in series, completed the supervision facility. All these parameters were collected on-line by the acquisition software ACRON (Picture 5) visualised on the control screen, and archived in daily files. The excess sludge is withdrawn automatically from AX2 several times per day.

Two control systems were required to ensure high effluent quality:

1. *Feed water control*. The throughflow of the reactor is driven by the membrane unit. This is set according to the height in the buffer tank (min / mean / max flow for different height domains). In order to warranty a continuous raw water feeding and a constant volume load (important condition for the biological mechanisms and for reliable interpretations), the water level in the tank must be controlled at a given depth in AX2. PID parameters should be adjusted to limit the variations of feed water flow and to prevent from reaching low and high safety water levels when (re)starting the pilot units.
2. *DO control*. The DO level must be controlled in the last aerobic reactor to 0.5 mg/L to limit oxygen transfer in the anoxic zone. But in order to minimize air supply a PID control acting on the blower engine power should be always foreseen. The air flow rate of the other aerobic zone can be adjusted with manual flow meter to ensure appropriate DO levels of < 2 mg/L in each zone.



Picture 5 ACRON monitoring system.

II.8. VEOLIALINK DATA ACQUISITION SYSTEM

On the top of the standard ACRON monitoring system, Anjou Recherche has installed on site the software VeoliaLink, which is the specific system of Veolia for data acquisition of membrane processes. The particularity of the VeoliaLink software is that it does not record data at a given frequency (typically every minute or every five minutes), but that it records a set of calculated filtration parameters for each filtration cycle (typically every 10 minutes). The compile database is therefore optimised: the size is minimal as it does not include any redundant information, and at the same time it includes all relevant information without any lost. A system of alarm can be also easily implemented on selected parameters indicators of the filtration behavior.

A prototype version of the VeoliaLink software was available for hollow fiber systems (with backwash), but not for flat sheet membrane processes. Anjou Recherche adapted therefore VeoliaLink and installed a prototype version on the PC of the demonstration plant. After installation, some further days were required to adapt the overall settings and the interface to the local requirements of the demonstration plant.

The prototype software worked for several weeks but could not be used over the entire period of the project as it caused computer break-doyn. Although Anjou Recherche provided a permanent support to the local team to improve the software and install a stable version, no solution could be found for long term usage. The architecture or performances of the local PC is thought to be the cause of the problem, as VeoliaLink was installed successfully on other MBR units. In 2008, the commercial version of VeoliaLink, which should be more stable than the prototype, will be available and Anjou Recherche will install it on the demonstration plant.

II.9. ANALYTICAL METHODS

Supervision according to the Senate of Berlin

For monitoring the performances of the MBR-plant the water authority requires 24-h samples of substrate (COD and BOD), nitrogen (TN, nitrate, org N) and phosphorus (TP and PO4-P) in influent and effluent. Samples were taken with automatic sampling analysers once a week in the effluent of the buffer tank or effluent of the screen and the effluent of the MBR plant. Grab samples are taken for E. coli, Enterococcus and Coliphages directly in the effluent of one of the two membrane reactors. Metals and AOX are measured according to the requirements of the water authority every second months (6 times a year). All the analyses were done according to Standard Methods (DIN) in the certificated Laboratory of the Berliner Wasserbetriebe. All metals are determined by ICP, but mercury with AAS. The detection limits are Cd <3, Cr <5, Cu <10, Ni <10, Pb 15, Hg <0.2µg/L.

Mixed liquor concentration

To control the sludge concentration in the unit while adjusting excess sludge removal and solid retention time (SRT), mixed liquor suspended solids (TS) were taken at least once a week as grab sample in the aerobic and/or anoxic zones, and in the membrane reactor. Analytical protocol was either done according to DIN or on site with a quick test (Microwave): A 600 ml beaker is dried in a mircowave oven at 800W for 2 min. After cooling in an exsiccator it is weighted for the first time. Then, 50 ml sludge sample are filled in the beaker and cooked in the microwave oven at 200 W for 20 min. Afterwards it is dried at 800W for 10 min and placed in the exsiccator for cooling. Finally it is weighted for the second time. The TS concentration can be calculated with the difference of the two measured weights.

P/TS and N/TS

For the measurements of the P content in the sludge, 9ml sludge and 1ml sulphuric acid (97%) were cooked for 1h at 100℃. Afterwards the sample was diluted 1/100 and potassium hydroxide was dosed to a pH above 2. The TP concentration was measured with cuvette test kit LCK 350 (Hach-Lange).

A Kjeldal decomposition was conducted for the measurement of the N content in the sludge. 10ml of sludge were cooked with 20 ml of sulphuric acid and one Kjedal oxidation pill until the mixture had a light green colour. The pH was adjusted between 5 and 7 with potassium hydroxide afterwards. After a dilution of 1/100 the TN was measured with Hach-Lange cuvette test kit LCK 238.

Buffer tank investigation

Five measurements of a profile over a day (4h-samples) were carried out. The samples of the daily profile in the influent and effluent of the buffer tank were analysed for TN, Ammonia, P-fractions and COD with Hach Lange kits.

Analyses for profile measurements

Anions (NO_3-N, NO_2-N, PO_4-P) were measured on a Dionex DX 100 ion chromatograph with an IonPac AS 4a column. NH_4-N was determined on a Dionex DX 100 ion chromatograph with an IonPac CS12a column. Hach Lange cuvette test kits LCK 338 and LCK 238 were used for total nitrogen (TN) determination, LCK 349 and LCK 350 were used for total phosphorus (TP) determination. COD was also determined with Hach Lange cuvette test kits (LCK 314, 514)

Spatial concentration profiles

Weekly measurements were conducted for the observation of EBPR dynamics and the calculation of operational nitrification (NR_O) and denitrification rates (DNR_O) within the plant. Spatial concentration profiles were determined from filtered grab samples taken from each zone including the effluent of the screen and the permeate. Kinetic rates were calculated in each reactor with the respective contact times.

Intensive measuring campaign

In April and May 2007 when stable operation was reached 5 weeks of intensive measuring were conducted. 24 h mixed samples of the effluent of the screen and the permeate were collected on 5 to 6 days per week. Samples were analysed for TN, NH_4-N, TP, COD, Alkalinity, Fe^{3+}, hardness and VFA concentration (all with Hach Lange cuvette test kits).

Batch tests

For the determination of P-release, P-uptake, nitrification- and denitrification rates, standard batch tests were conducted at 20°C on a weekly basis. Sludge from the second anoxic zone was filled in a 1L stirred batch reactor, spiked with sodium acetate and flushed with N_2 for 1h to simulate the anaerobic zone. Afterwards ammonium chloride was dosed and the sludge was aerated until P uptake was almost completed. In order to avoid nitrate limitation sodium nitrate was spike at the start of the anoxic phase during which the reactor was continuously flushed with N_2.

Surfactants

In general surfactants also known as tensides are agents which lower the surface tension or the interfacial tension in between two liquids. Tensides are not stable and it is necessary that all samples are getting analyzed within one day in order to determine reliable outcome. In addition samples should be transported in glass bottles. Anionic, cationic and nonionic tensides are measured with Hach Lange cuvette test kits LCK 332, LCK 331 and LCK 333, respectively.

III. PLANT OPERATION

III.1. TRIALS PROGRAM AND OPERATION CONDITIONS

Continuous operation of the MBR plant started in March 2006 with seeding of sludge from a large WWTP with EBPR. From March 2006 to June 2007 four trial periods can be described. After start up- and stabilisation phase (Period 1, 2 month) the main operation problems were fixed up and steady state conditions were reached with design load conditions (Period 2, 4 months). After 100% connection rate was reached in August 2006 and all summer house residents were present, high inflow caused unsteady state conditions and permanent overloading resulting in the lost of the good performances in terms of nutrients removal (Period 3, 7 months). Trouble shooting led to a management strategy: effective measures were taken to reach stable operation conditions and satisfying performances (Period 4, 3 months). The most important operation parameters are given for each period in Table 6.
The sludge return and recycle ratios were set up at 100-150% from the anoxic to the anaerobic reactor (R1) and 400% from the membrane reactor to the aerobic zone (R2). The recycle rate leads to a contact time of 45-60min in the fully mixed anaerobic reactor and a sludge mass in the anaerobic reactor of only 5.5 % of total sludge in the MBR plant. Usually, at least 10% are required for sufficient EBPR performance. The volume ratio between anoxic and aerobic zone was 55:45. A larger anoxic volume is necessary because no carbon source is dosed and lower denitrification velocities are expected. During the trials, the pH-values were usualy between 7.2 and 7.9 throughout the reactors, the redox value in the second anoxic zone was between -500 and +100 mV.

Table 6 Average operational parameters of the biological system

Parameter **Period**		**1**	**2**	**3**	**4**
Time		**1.3.06-30.4.06***	**1.5.06-31.08.06**	**1.9.06-31.3.07***	**1.4.07-30.6.07**
Net flow	L/h	220 (80 – 500)	430 (270 – 740)	500 (260 – 730)	450 (360 – 580)
Biological reactor volume (Vax + Vae + Vm)	m^3	7.95	8.361	8.361	7.95
Volume ratio V_{ax} : V_{ae+m} (Resulting mass ratio M_{ax}:M_{ae+m})	%	55:45			
Total retention time	h	37.5	20.8	17.9	18.3
Total contact time	h	7.5	3.76	3.17	3.44
Sludge age	d	40 - 50	22 - 30	undefined	25 - 30
Sludge concentration	gTS/L	2 - 11	8 - 14	6 - 15	13 - 16
Mass organic load (based on V_{ax} + V_{ae} + V_m)	kgCOD/ kgTS.d	0.15	0.2	0.28	0.1
Volume organic load (based on V_{ax} + V_{ae} + V_m)	kgCOD/ m^3.d	0.67	2.09	2.19	1.52
Air flow	Nm^3/h	10 (3 – 27)	35 (25 – 54)	28 (13 – 54)	48 (31 – 57)
DO (AE1 / AE2)	mg/L	2.4 / 2.1	0.9 / 0.9	2.2 / 1.1	0.9 / 2.1

* TS in reactor not stable during this period, wastewater trucked away since Dec 2006

III.2. Evolution of Inflow

The sewer area of Margaretenhöhe contains approx. 250 persons in 90 households, whereas 20% of the households are inhabited only during the summer period. Due to ongoing construction work the connection rate increased from 30% at plant commissioning up to approx. 100 % within 8 month (Figure 6). The speed and completion of the connection rate went much beyond the design estimation (only 90% connection rate expected after 1 year).

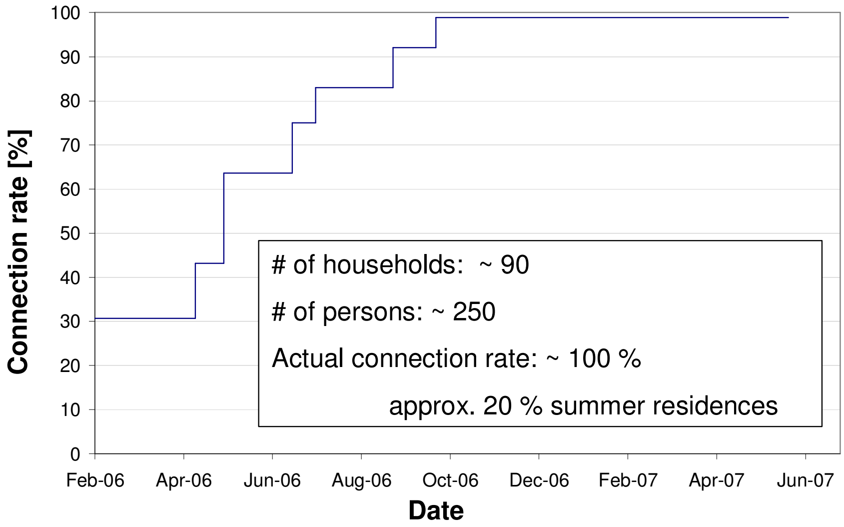


Figure 6 Households connection rate over time

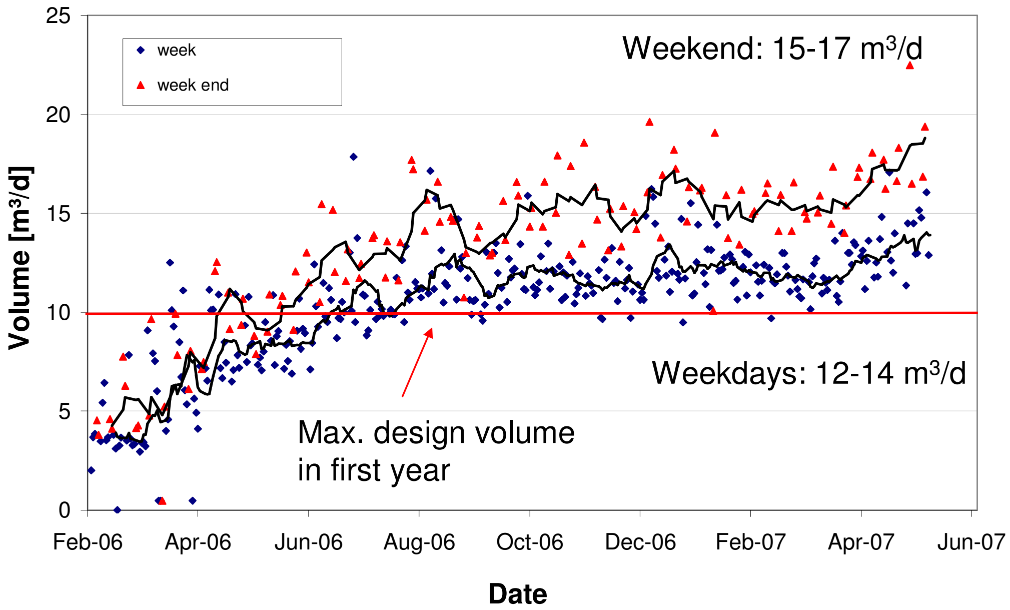


Figure 7 Daily inflow to the MBR plant over time

The daily inflow to the MBR plant is shown in Figure 7, separated in weekday and weekend inflow. The plant operation started with around 4 m^3/d and the expected max. inflow of 10 m^3/d for the first year was already reached in June 2006. Due to the completion of the connection works there was an average inflow at 12 m^3/d on weekdays and 15 m^3/d on weekends during winter season. The increasing of inflow in spring mainly relates to summer occupation of some parcels.

Single heavy discharges up to 20 m³/d and more were observed at irregular intervals. It is assumed that illegal discharges from old tight septic tanks (during connection works) and storm water tanks (some septic tanks were converted into storm water tanks) are responsible for these events. The occurrence of infiltration water can be excluded because there is often no inflow during night hours, no air sewer flushing and no relation between inflow peaks and heavy storm water events.

III.3. PERFORMANCE OF BUFFER TANK

III.3.1. Hydraulic performance

The hydraulic flow pattern during a week varies strongly. Especially during weekends high inflow rates with maximum inflow 24 m³/d were monitored. The effect of the buffer tank on the equalisation of the wastewater inflow is shown in Figure 8. Nearly the whole amount of the water appeared between 5 am and 11 pm and no water comes during the night. While the hourly average inflow varies in a wide range between 0 and > 2.5 m³/h, the outflow is relatively stable between 0.5 and 0.7 m³/h in average. With the concept of the buffer tank a constant inflow is provided even during the night hours and ensures good conditions for the sensitive biological process.

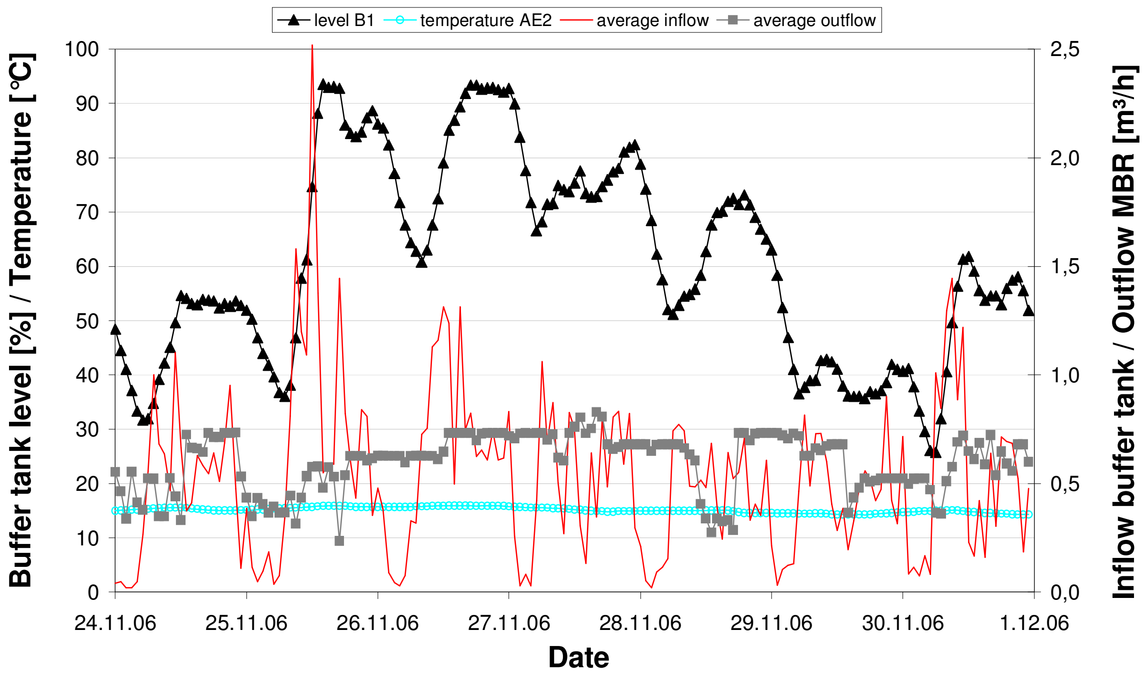


Figure 8 Hydraulic profile of the inflow of the buffer tank and outflow of MBR plant

Statistical distribution of the inflow was evaluated on the basis of 15min-data for the period from July to December 2006 and is shown in Figure 9. The mean value of inflow is 0.51m³/h but a difference of inflow between < 0.05 m³/h (20%) and < 1.0 m³/h (85%) is measured every day. Due to this daily profile pattern, and according to the German DWA guidelines, small WWTPs (<50 p.e.) have to be built with 100% more reactor volume when not equipped with a buffer tank. In the present project, the presence of the buffer tank has several advantages. First, the plant equipment (pumps, blowers) does not need to cope with an extreme wide range of operation (max. 85%-frequency of 1.0 m^3/h instead of max. 100% frequency of 7.6 m^3/h). In addition, a smaller biological reactor can be built (even pollution load), less membrane surface can be installed and less redundancy is required. Operational costs, such as energy, membrane replacement and cleaning costs are reduced as well.

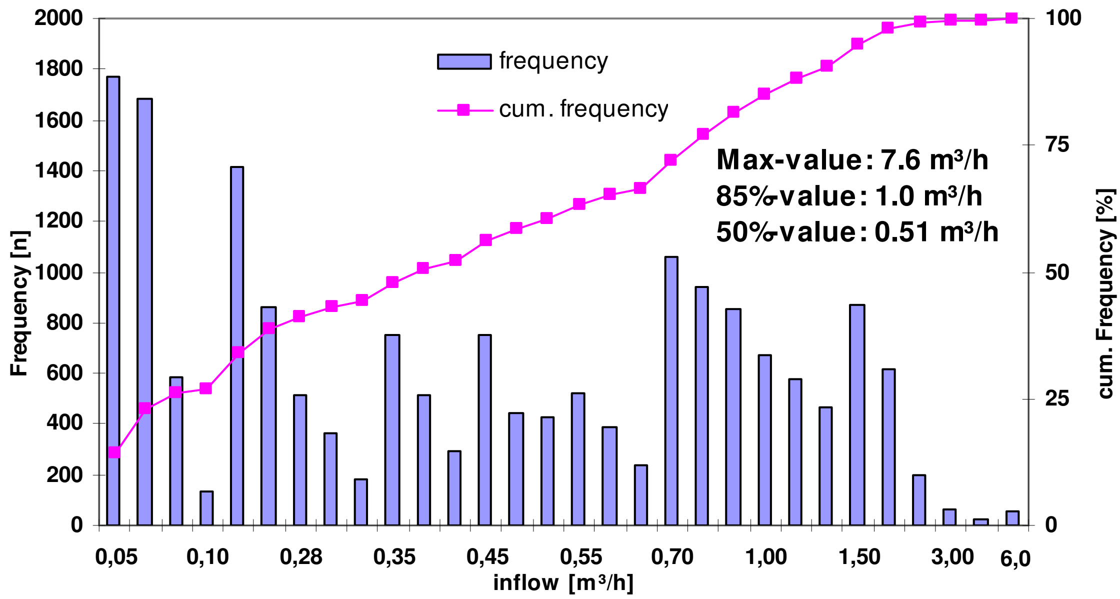


Figure 9 Frequency of the daily inflow for the period from 1.7. – 31.12.06

III.3.2. Equalisation of concentration peaks

The effect of the buffer tank on the equalisation of the concentration peaks is shown in Figure 10. The in- and effluent concentration over one day in 2h-samples is shown. It is apparent that the concentration peaks are very well buffered. Though the wastewater is already homogenized and mixed in the individual tanks of each household for at least 12 hours, the COD concentration, total phosphorus and total nitrogen rise up during the day to 2000 mgCOD/L, 28 mgP/L and 250 mgN/L, respectively. In example the ammonia concentration lies between 50 and 185 mgNH_4-N/L but the effluent concentration is relatively stable with 100 mgNH_4-N/L. Concentrations in the buffer tank show that this retention time can reduce average peak load up to 25% and therefore verify the simulation results obtained with the pre-study (Villwock, 2005). These results show that the buffer tank acted well to level out the pollution peaks, warranty constant flow through the plant (i.e. constant retention time in each reactor), and therefore ensures good nutrients removal performances.

Influent concentrations over the period of the project are given and discussed in detail as average removal performance (24h-samples) and biological kinetics data (grap samples) in chapter IV.1 and VII.1, respectively.

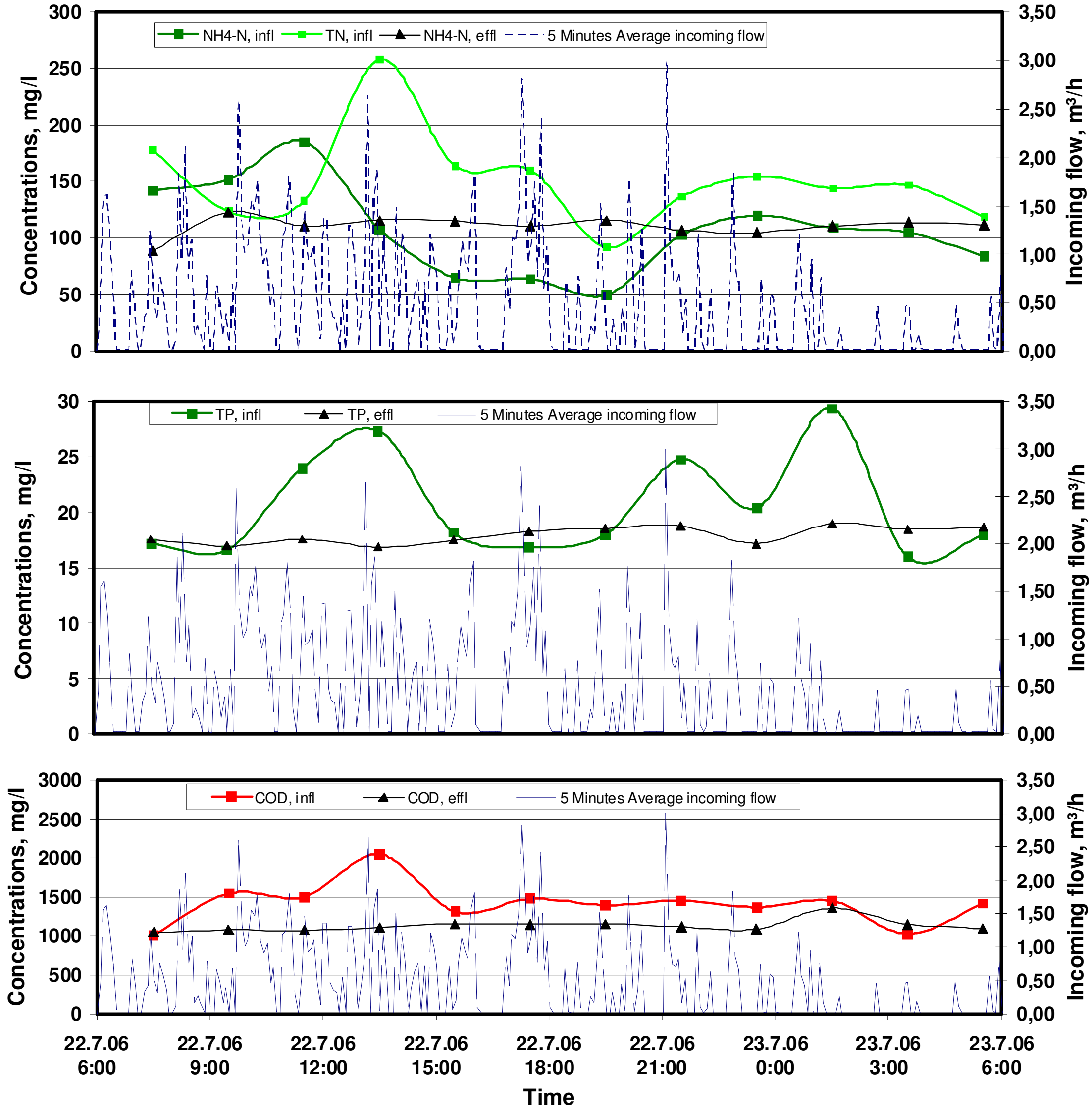


Figure 10 Concentration profile of the in- and effluent of the buffer tank

III.4. OPERATIONAL PHASE AND EVOLUTION OF TOTAL SOLID CONCENTRATION

The evolution of the total solids (TS)[2] concentration and the solid retention time (SRT) is shown in Figure 11. In the first period (1.3.06-30.4.06, start up) the TS concentration dropped from 6 g/L at commissioning below 4 g/L due to dilution and settings optimisation. The target operating range of 6-8 g/L was reached in April with an initial SRT of 50 days. Due to the increasing load the target operating range was set to 10 – 12 g/L. In this 2nd period (1.5.06-31.8.06) the plant was running nearly under design load with a SRT of 22-25 days. Because of several operational problems such as permanent overloading, foaming, module clogging and bad hydraulics (sludge distribution), resulting in uncontrolled sludge withdrawal (foam overflow, sludge backflow to sieve), the 3rd period (1.9.06-31.3.07) was identified non-representative of stable operation. The TS concentration decreased below 7 g/L, with undefined SRT. By turn of the year most of the operational problems could be solved (see III.6). Because of increasing hydraulic and nutrients load (see III.2 and III.6.3) it was decided to increase TS concentration in the

2 In Berlin, TS (g/L) ~ MLSS (g/L) + 1 g/L

biological system to 14 – 16 g/L and stable conditions could be reached in the 4th period (1.4.07-30.6.07) with a SRT of 25 days. Volatile suspended solids (VSS) were stable between 70% and 80% of TS. The growth yield was 0.36 gTS/gCOD determined in a 4 week intensive measuring campaign (see III.5)

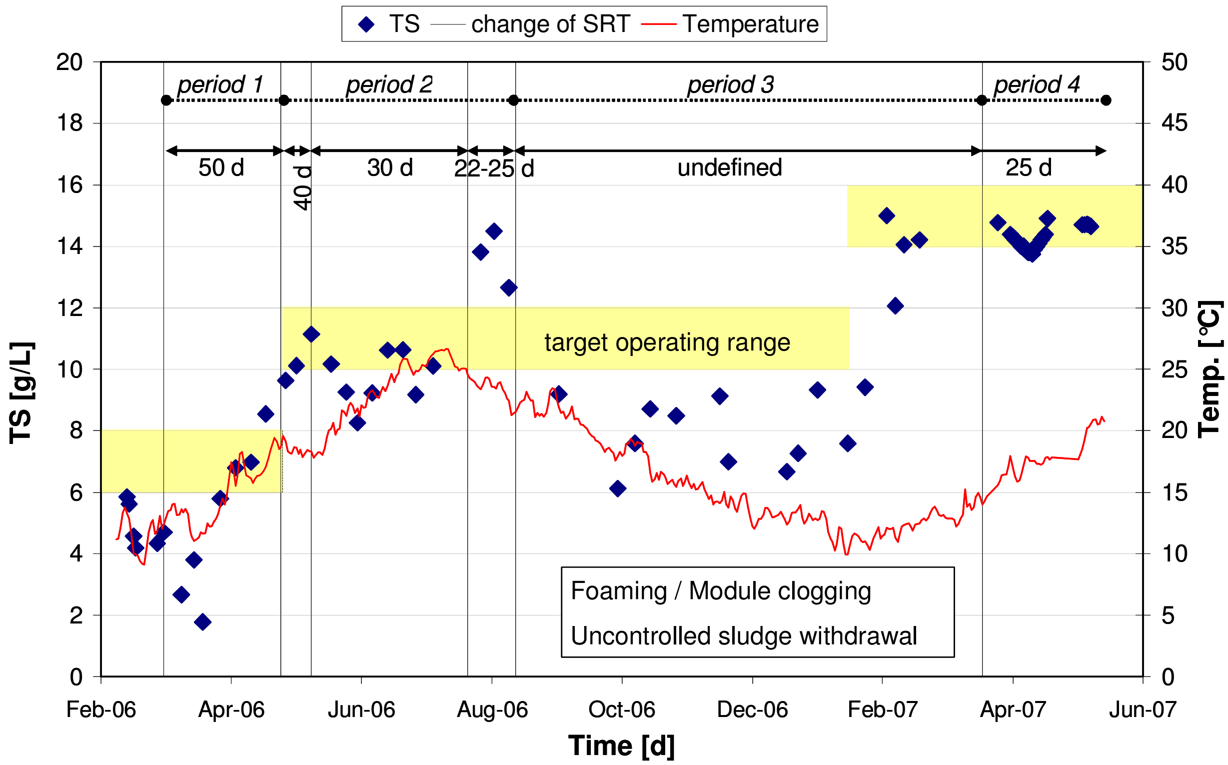


Figure 11 TS concentration (measured in AX2), Temperature and SRT over time

III.5. INTENSIVE MEASURING CAMPAIGN

In the months April and May 2007, when stable operation was reached 5 weeks of intensive measuring were conducted. During that phase, the sludge age was stable at 25d and the TS concentration between 14 g/L and 15 g/L. Table 8 and

Table **9** are showing the mean operational parameters during that period. Excess sludge removal was about 360L/d withdrawn from AX2. Figure 16 and Figure 17 summarize the volumetric load during that period. Balances for sludge, nitrogen and phosphorus were conducted with the collected data. Some results during this period are presented in Figure 20 and Figure 23.

Table 7 Loading conditions (50 %-tile) during steady state conditions (April-May 2007)

	Unit	Measured load	Max design load
COD	(kg/m³/d)	1.4	1.23
Nitrogen	(kg/m³/d)	0.18	0.14
Phosphorus	(kg/m³/d)	0.024	0.019

Table 8 Mean operational parameters

	Unit	
TS in AX2	g/L	14-15
VFA influent	mg/L	205-285
Acetate dosing	L/d	2.5 (33%, not from 21.4. till 26.4.)
pH	-	7.6 - 8
Temperature	°C	15-19

Table 9 Reactor volumes und hydraulic contact times for a throughput of 10m³ d^{-1} of the demonstration plant.

	Volume (L)	HCT (min)
AN	717	42
AE1	1882	42
AE2	1882	42
DG	154	3
AX1	1784	40
AX2	1837	41
MR1*	400**	11
total	8656	221

* MR1=MR2=MR3
** 711L minus app. 300L displaced volume by a membrane module.

III.6. OPERATION OF MECHANICAL & ELECTRICAL SYSTEM AND TROUBLE-SHOOTING

III.6.1. Sieving

The Martin Systems screen drum achieved efficient and reliable screening performances. The sieve ran successfully without manual intervention. The automatic sieve cleaning with a rotating brush worked well and no blockage occurred. It has to keep in mind that both the grinding pumps at the households and in the buffer tank hackle the solids to pieces smaller than 7 mm. There was no brush change necessary during the first 15 month.

However, the manual screening tank emptying was necessary more often than expected (see II.3). At present the emptying takes place every 2 weeks, that means 10 minutes work and 600 L inflow to the excess sludge tank which represents the excess sludge volume of 2 days. Tests must be done to check whether an emptying every 3 or 4 weeks would be possible. Some mechanical modifications were required to enable the “siphon effect” which entrains the particles out of the grit chamber: the piping was enlarged, and a “full swing” manual valve was built in instead of the initial “wheel valve”. Accidentally, by opening this valve the “siphon effect” was so strong that half of the anaerobic zone was sucked out. Because no level control was installed in anaerobic zone this was not recognised till January 2007.

III.6.2. Mixed liquor hydraulic distribution

Except for the two recirculation pumps, the hydraulic distribution of the mixed liquor throughout the unit occurs per gravity. The overall hydraulic head between top and bottom water level was however by construction of few centimetres only. This caused severe perturbation of the mixed liquor flow in the second semester of 2006, especially when foaming occurred (see also II.6.5). Hydraulic problems were particularly observed at the following locations:

- Deaeration pot: due to the narrow diameter, the foam accumulated and prevented the flowing of the mixed liquor. The water level rose in the two aerobic zones, and in the anaerobic zone. Ultimately, the water level of the anaerobic zone reached the height of the sieve drum; the sludge introduced in the drum and blocked the sieve. Two mechanical modifications improved this: the elevation of the sieve drum to the maximum possible (+ 24cm) and the permanent flushing of the deaeration pot with mixed liquor. This is only done if scum is present.
- The distribution channel to the membrane reactors: due to low hydraulic height, a bad distribution occurred, resulting occasionally in a thickening of the sludge up to > 40 g/L in one of the reactors (see Picture 6). The elevation of the 3 membrane reactor inlets with small cylinders (about 6cm), as well as the permanent aeration of the channel (to avoid sedimentation) solved this trouble in December 2007.
- The collection channel from the membrane reactors: foam tended to accumulate, rising the water level in the membrane reactor and inducing a bad distribution of the fluid between the reactors. Alternative spraying of permeate could solve the problem. This solution was not required when only one membrane reactor was in operation. Alternatively, a weir at the outlet of the membrane reactor could partly prevent carry over of the foam in to the collection channel.

III.6.3. Nutrients overload reduction

In order to overcome the scenario of permanent heavy overloads (see V.1) and loss of EBPR and post-denitrification due to the recycling of too much nitrate to the anaerobic zone, the following measures were taken:

- The load was reduced by diverting a portion of incoming flow and storing it in the excess sludge tank. It was then trucked away twice a week (from November 2006 onwards).
- The TS concentration in the anoxic reactors was elevated to 14-15g/L to have more biomass in the system. Since the oxygen transfer is strongly influenced by the TS concentration the amount of aerators were doubled to four in each aerobic reactor. This way, complete nitrification was possible in the aerobic reactors (from December 2006 onwards).
- To sustain the recovery of the EBPR and post-denitrification processes, acetate was dosed into the anaerobic zone for a time period of 4 months (February- May 2007). This reduced the competition of the pre-denitrification process in the anaerobic zone and ensured the availability of fatty acids for the P release.

All these actions finally helped to recover the EPBR process and to reduce the nitrogen effluent concentration below the targeted limit. In the last three months of the reported period, the plant was operated stable and showed very good biological performance.

III.6.4. Module clogging

In summer 2006, severe module clogging was observed. This could be accounted for by:

- The few events of reactor thickening due to bad mixed liquor distribution, fostered by foam events
- Bad hydraulics in the reactors themselves (airlift perturbed by small free volume under the aerators)

These problems caused shut-downs of single filtration lines, lower filtration performances and a higher cleaning effort (see chapter VII.2). In December 2007, the plant constructor installed an additional feet to the membrane module to improve the hydraulic. Following this measure and the elevation of the water level in the distribution channel, severe module clogging was not observed anymore.

Picture 6 Reactor thickening and module clogging

III.6.5. Foaming

Foaming is reported to occur in MBR-plants. An overboard of 50 cm was therefore designed to contain ordinary fouling events. From September 2006 onwards a second severe operational issue aroused in addition to the trouble related to permanent overloading. Heavy foaming and foam accumulation occurred in the plant. The foam was build up in the aerated reactors (AE1,AE2 and MR) but was found in the whole plant. Foaming was that heavy that it was flooding the plant and thereby destroying the stirrer engines. Furthermore it was clogging the channel for biomass recirculation leading to bad biomass distribution in the membrane reactors. The foam reached also the board of the plant and overflowed outside of the reactor. This reduced the biomass concentration in the biological reactor. Due to the weak hydraulics in the plant, the accumulation of foam could also lead to a backflow of sludge into the screen, creating screen clogging and stopping the feeding of the unit.

To overcome the problem of heavy foaming different strategies had to be tested. Antifoaming (Anti Schaum 2020) was dosed manually for several weeks. This did not have a permanent effect. The positive impact of this dosage was in the range of minutes to hours. A dosage of activated carbon did not help at all to reduce foaming.

Polymers which are used in the MBR technology for flux enhancing shall also reduce foaming. Hence, Nalco MPE 50 was dosed to 3 ppm, but this also did not improve the situation.

A study was conducted on surfactants. It could be shown, that the surfactants influent concentration in Margaretenhöhe was up to 3 times higher than in the conventional large WWTP in Berlin (see IV.3). Therefore it was assumed that the foaming may result from this high amount of surfactants. However, since April no foaming occurred and tensides concentration still is in the same range. As the foam decreased with increased TS, it is believed that higher sludge concentrations improved the biodegradability / adsorption of the tensides.

Four actions finally controlled the foaming:

1. TS increase (impact on surfactants ? impact on bubble size through higher viscosity ?)
2. Avoidance of too small bubbles: with higher air flow rates and resulting bigger bubbles, the foaming could be reduced significantly.
3. Mechanical foam destruction in the degassing zone: since the foam is formed in the aerobic tanks, it accumulates in the degassing zone and blocks it. A small pump was installed to circle the sludge in the degassing zone and thereby destroy the foam.
4. Constant and moderate volumetric load: since trouble shooting led to stable operation conditions (no sludge loss in anaerobic zone, trucking away waste water, etc.) the mixed liquor suspended solids are stabilised, and no events of extreme organic loading peaks or long-term overloading occurred.

To the authors opinion the last one is the most important issue and the afore-mentioned reasons played only a minor role. Since May 2007 the automatic oxygen control regime is in operation causing no trouble (see Chapter III.6.6) and the pump in the deox pot for foam destruction is not in operation.

III.6.6. Air supply

The aim was to supply only the amount of air required for carbon removal and full nitrification without wasting energy and avoiding oxygen carry over in the anoxic zone. Therefore, set points for DO-concentration were < 2 mg/L in AE1 and 0.5 mg/L in AE2. Automatic operation of the DO regulation was only possible for some hours during a day, as will be explained later in Chapter III.6.7. The "Hand-mode" which was the mode most implemented led to the optimization problem presented in Figure 12: on one hand air flow is low due to bad nitrification and low TS concentration and DO concentration raises up to 4-6 mg/L. But as TS concentration increases and a very high F/M-load reaches the MBR plant (F/M-Load >0.18 kgCOD/kgTS.d and > 0.2 kgTN/kgTS.d) air flow rate increased above 50 Nm^3/h. However, high air flow rate was not sufficient to achieve DO-concentration above 0.1 mg/L. If we calculate a theoretical air demand of 58 Nm^3/h (T= 25°C) we have to assume that the α-value drops down to 0.3 when TS reached 16-17 g/L. These dramatic changes in α-value are already reported in Günder (2000) and Krause et al. (2007). The consequence would be that the maximum treatment load was reached in the biological system in terms of oxygen transfer.

Initially each aeration system was equipped with two plate diffusers, and it was suspected that these were working above their normal operation range when the blower was at its maximum capacity of 50-60 Nm^3/h. This could cause the production of larger bubbles, therefore less efficient in terms of oxygen transfer. In order to eliminate this possible reason, each aeration reactor was equipped with additional two plate diffusers.

The limit of oxygen transfer capacity will be further investigated in summer time, as well as the impact of other parameters such as high surfactant concentrations (see IV.3).

DO concentrations in the membrane reactors were evaluated during the intensive measuring campaign. The concentrations were between 3 and 6 mg/L without nitrification, and between 1 and 3 mg/L when residual nitrification occurred in the membrane reactor (in case of nitrogen overloading).

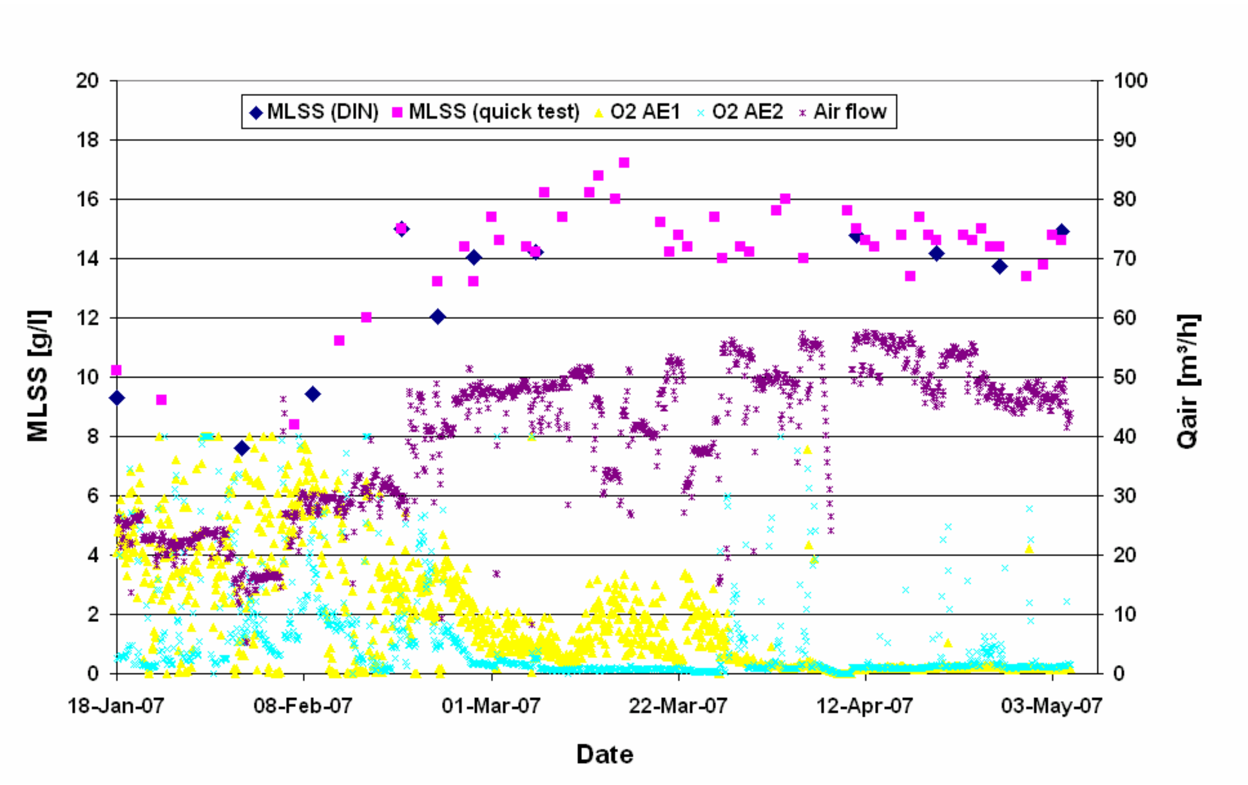


Figure 12: DO concentration, TS concentration and air flow rate over time

III.6.7. Automation

PROCESS CONTROL AND REMOTE MONITORING

Good experiences were made with the plant remote control. The advantages of the installed system are:

- Fast alarm response
- Flexible dial-in (persons, locations)
- Weekend remote control and parameter adjusting
- Security through passwords, call-back and limited session time

However, a constantly running PC is essential for the remote and alarm function as well as data acquisition. PC problems happened once in a while which caused losses of data and prevented the forwarding of alarm signals and remote monitoring. To date, the industrial PC remains still highly unreliable.

FEED WATER REGULATION

The regulation of the influent pumps and the filtrate pumps was mainly dependent on the water level in the buffer tank. A 3 step open loop control was implemented where 3 different pumping and pause periods can be preset at each pump group. Switch off constraints (over-, under filling of the plant) are given by the water level in the reactor AX2. The installed feeding pumps with a minimal discharge of 6 m³/h made the use of frequency inverters for PID control difficult. The given regulation requires continuous manual pumping settings (for both pump groups) and causes - depending on the settings – influent breaks of varying periods which should have been avoided (see Figure 13). Also the breaks could be reduced down to about 15min every 2h (which was considered, due to the contact time in the anaerobic zone of at least 30min, to have minor impact on the EBPR mechanisms), the regular influent breaks caused huge drops of oxygen demand in the aerated reactors, and therefore impacted severely the oxygen regulation in the two reactors.

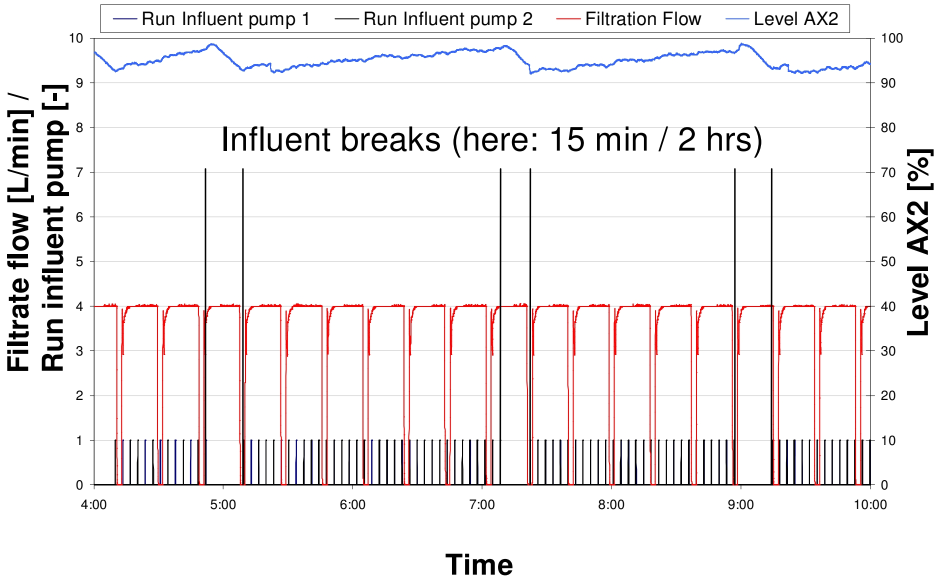


Figure 13 Influent and effluent regulation

DO REGULATION

DO regulation and control was disturbed by (1) lack of sustainable PID settings, (2) lack of reliability of DO sensors, and (3) sludge flotation and foaming with either very low or high air flow rates during the continuous operation. The problems with the DO sensors are shown in Figure 14: The set point for the DO concentration in AE2 was set to 1.0 mg/L. Because of the increasing of the DO concentration in AE2 the aeration flow was automatically set to its minimum (6 Nm³/h). Afterwards the DO sensor still showed increasing values although the DO concentration measured by a mobile sensor fall down to values of around 0.4 mg/L.

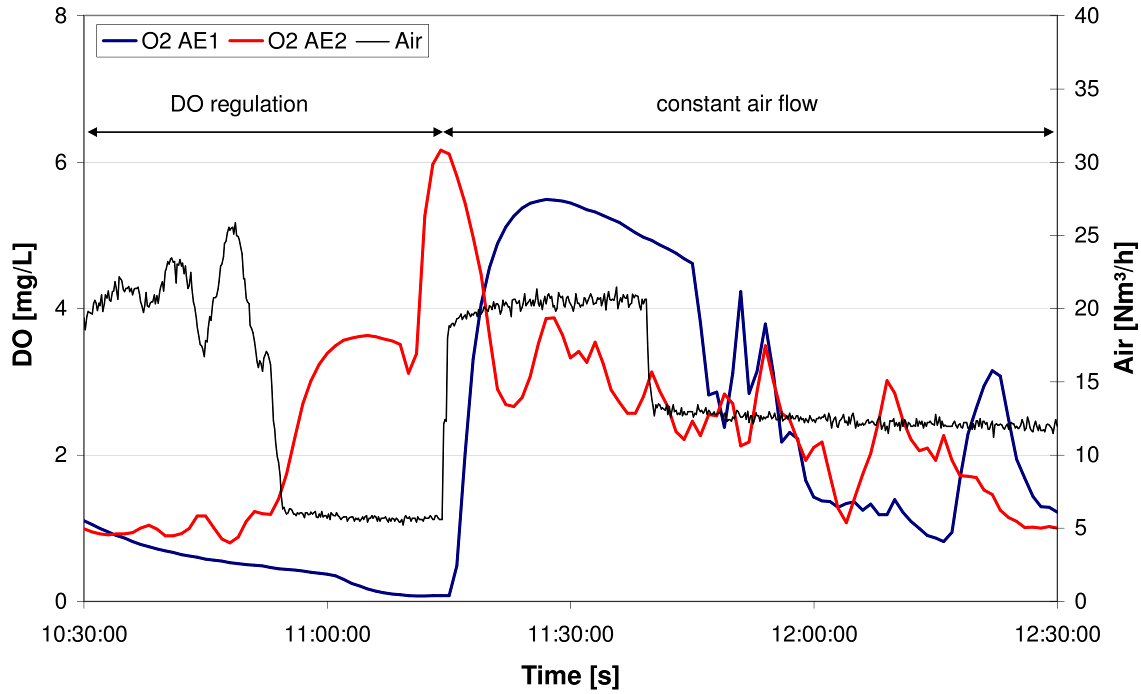


Figure 14 DO regulation

Frequently undertaken comparison measurements often showed different absolute values and dynamics for the installed sensors compared to mobile sensors and parallel tested sensors of other manufacturers. In the face of the foaming problem at lower blower rates too, the DO control was cut off.

The reliability of the DO sensor is still under investigation, the set points for airflow regulation are fixed now, however flotation is still a problem and automatic airflow was not in operation without supervision till May. The "manual mode" was therefore the only reliable alternative to operate the system. At this time of the project, it is not possible to conclude whether automation of such a small WWTP is reliable and cost effective.

SLUDGE REGULATION

The sludge return and recycle ratio from the anoxic to the anaerobic reactor (R1) was fixed and only once in a while manually changed depending on significant changes of the plant inflow. The range was set between 100% and 150% of the daily inflow. The recycle ratio from the membrane reactor to the aerobic zone (R2) was automatically adjusted in accordance to the flow rate of the filtration pumps and was set to 400%.

III.6.8. Instrumentation and on-line analysers

It was decided to equip the demonstration plant with much more instrumentation and on-line analysers than what would be required for a commercial unit. The intention was to facilitate the evaluation but also to identify which devices would be helpful for routine operation. Most of the equipment was provided by the German company Endress + Hauser. The implementation and maintenance of these equipments were very time consuming and costly. At the time of the redaction, the following evaluation can be done on the different equipments:

- Oxygen sensors (1 per aerobic zone, about € 2,000 each): Quite unstable in the first months, they finally enabled to control the aeration level through a PID and are recommended for future installations. For good results, the probes have to hang free in the middle of the reactor and 50 cm below water level.
- Nitrate analyser (about € 5,000): Reliable, easy and low-cost maintenance and would enable on-line monitoring and control of a crucial parameter for the biology. Recommended even for container installations.
- Phosphate analyser (about € 15,000): threshold value of 0.01 mgP-PO_4/L and precision value of 0.05 mgP-PO_4/L, but require regular maintenance (change of piping + chemicals, about € 1,000 per year). Recommended only for plants above 5,000 p.e. or for control of metal salt or carbon addition when strict values are required at grab-sample level.
- Sludge concentration probe (about € 5,000, low maintenance): was intended to help remote plant monitoring and excess sludge control. However the signal appeared not being reliable even with weekly calibration. Probes from other suppliers may be appropriate.
- Turbidity probe (about € 5,000, low maintenance): was planned in permeate for monitoring of membrane integrity. It was however poorly mounted by Martin Systems (not enough water depth in front of the sensor) and the calibration of real absolute value was not possible. It was however monitored that the relative value reacted quickly when the water was slightly turbid. It is not recommended for commercial units, unless strict requirements of disinfection are specified (water reuse, bathing water guidelines). Alternatively, microbiological measurements at start-up and at regular interval may also provide evidence of the system integrity. A cartridge filter with pressure sensor (for hollow fiber systems, can be installed on backwash circuit as supplementary protection) may be also a good indicator of system integrity.

- Redox probe measured in anoxic zones (about € 2,000, low maintenance): Not recommended at this stage as the signal drifts much, rendering the interpretation or utilisation difficult.
- pH probe (about € 2,000, low maintenance): Not recommended for hard water, as the pH appeared to be stable without requirement of pH control. Weekly manual measurement may be sufficient.
- Electromagnetic air flow meters (about € 6,000 each, no maintenance): were built on the biology and membrane aeration lines. They were reliable and useful for the evaluation but may not be required for commercial applications, although the information is advantageous for diagnosis and trouble-shooting.
- Electromagnetic sludge flow meters (about € 6,000 each, no maintenance): were built on each sludge recirculation loop. Would be always recommended for setting and/or control of the sludge recirculation rates (crucial parameters for the biological performances)

III.6.9. Impact on neighbourhood and local environment

The plant and the storage tanks are very well encapsulated, so the emissions of noise and odour could be reduced to the minimum. Since commissioning there was no single complaint about odour and noise, though the next neighbours are only 20 m away (see Figure 7).

The plant was extremely well accepted by the local residents, as proven by the unusual score of next to 100% of connection rate few months only after commissioning. This high acceptance was also certainly related to the communication activities that were regularly organised with the inhabitants (information days, day of opening doors etc).

To be mentioned yet that a total of 3 burglaries or intrusions happened within the first 12 months. Hence, the entrance door had to be reinforced and a video observation was installed.

According to the recommendations of the "Bezirksamt" (local council), the treated water had to be discharged in the local creek with the intention to sustain a natural wetland right ahead of the creek during summer time. A first evaluation of this measure was performed at the end of the second summer after commissioning (in September 2007, see Annex IV). A positive impact on the vegetation was noted: for the first time since many years water was present in the creek, and the surrounding vegetation was luxuriant. Later investigations may demonstrate also the positive impact on the fauna through this improved habitat of animal species.

Picture 7 Environment of the MBR plant

IV. AVERAGE REMOVAL PERFORMANCE

This section presents the results of the weekly analysis performed on 24h-sample of influent and treated water by the accredited laboratory of Berliner Wasserbetriebe.

IV.1. AVERAGE SUBSTRATE & NUTRIENT REMOVAL

The average value (24h-samples) of the substrate and nutrients concentration are calculated for the four representative periods and given in Table 10. The influent COD-concentration varied between 850 and 2000 mg/L. For all periods effluent concentrations of COD were below 50 mg/L and removal rate was about 96%. No further COD reduction is expected for the Berlin wastewater, rich in natural refractory humic substances (here about 4% of COD in wastewater). During steady state conditions (periods 2 and 4), nitrogen removal is very high with 88%, but nitrogen concentrations below 10 mgTN/L can not be reached due to the very high nitrogen load, leading therefore to incomplete denitrification. An increase of denitrification volume would be necessary. The refractory nitrogen fraction amounts to about 2% of the mass present in wastewater. EBPR shows very satisfactory results and an effluent phosphorus concentration of 0.2 mgTP/L can be reached without chemicals (99% elimination, about 0.5 to 1% of entering phosphorus load being assimilated as refractory fraction).

Table 10 Average influent and effluent concentration of the MBR-plant for the four representative periods (24h-samples)

Parameter	COD	SS	TN	NH_4-N	orgN	NO_3-N	TP	o-PO_4-P
Units	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Influent (min - max)	1265 (851 - 2000)	356 (130 - 770)	124 (90 - 144)	98 (70 - 117)	25 (19 - 37)	-	22 (13 - 28)	14 (8.7 - 17)
	Period 1 1.March - 30.April 2006							
Filtrate	48.7	0.6	24.8	5.3	2.1	16.9	1.5	1.4
(Elimination)	(96%)	(100%)	(80%)	(95%)			(93%)	
	Period 2 1.Mai - 31.August 2006							
	47.1	0.8	15	0.2	2.5	12.2	0.77	0.65
	(96%)	(100%)	(88%)	(100%)			(97%)	
	Period 3 1.October 2006 - 31.March 2007							
	47.5	1.2	27.8	6.1	2.6	19.4	7.7	6.68
	(96%)	(100%)	(78%)	(94%)			(65%)	
	Period 4 1. April - 30. June 2007							
	46.4	1.3	16.7	0.13	2.9	13.6	0.2	0.074
	(96%)	(100%)	(87%)	(100%)			(99%)	

IV.2. METALS AND TRACE ORGANICS

The metal concentrations were measured 9 times over the 15 months of operation according to the protocol of the water authority. Influent concentration of chrome, nickel, mercury, lead and cadmium lie below the detection limit, given in Chapter II.8. Copper, used for drinking water systems and heating installation, influent concentration ranged between 170 and 260 mg/L. The average effluent concentration is 10 mg/L and the elimination rate is 95%. Twice Chrome in influent was > 6 µg/L, which is due to individual illegal waste management, but the effluent concentrations were always < 6 µg/L. AOX concentration in the influent ranged between 69 and 86 µg/L, and was reduced down to 24 to 41 µg/L in the effluent, with an average concentration of 30 µg/L, and a mean elimination rate of 64 %. Many studies already assumed that high AOX concentrations are produced in households with cleaning detergents.

Table 11 Comparison of Metal concentrations of the decentralised MBR-plant and large WWTP (1 Mio p.e.)

2006/2007	**Influent**						
Parameter	**Cr**	**Cu**	**Ni**	**Hg**	**Pb**	**Cd**	**AOX**
Unit	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
Minimum	2.5	170	5	0.1	7.5	1.5	69
Maximum	7.8	260	5	0.1	7.5	1.5	98
Average	**3.5**	**221**	**5**	**0.1**	**7.5**	**1.5**	**86**
WWTP Berlin-Wassmannsdorf	5.5	300	7	0.9	10	1.5	
	Effluent						
Minimum	2.5	5	5	0.1	7.5	0.5	24
Maximum	2.5	23	5	0.8*	7.5	0.5	41
Average	**2.5**	**10**	**5**	**0.1**	**7.5**	**0.5**	**30**
WWTP Berlin-Wassmannsdorf	2.5	18	5	0.1	7.5	0.5	

*outliner

IV.3. SURFACTANTS

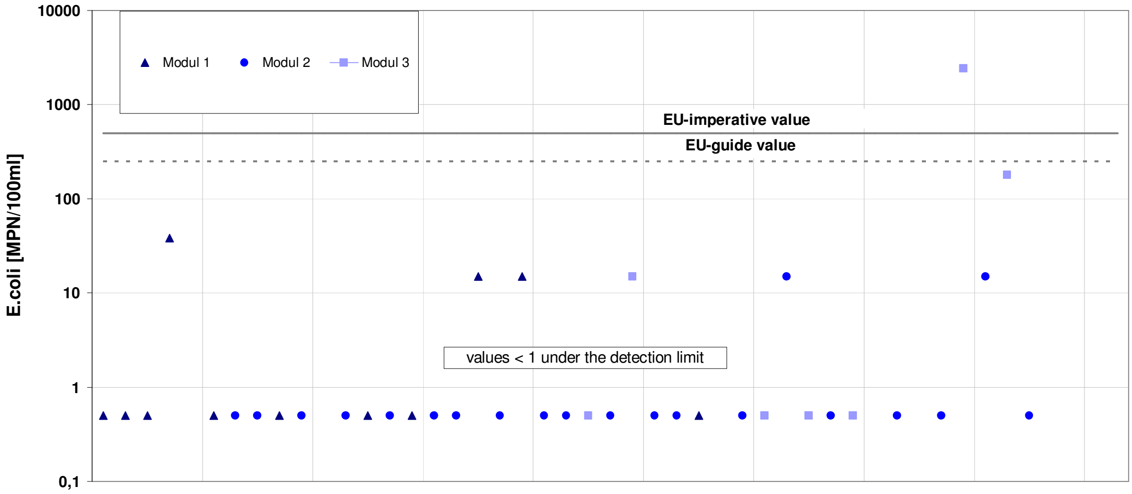
Surfactants are classified into anionic, cationic and nonionic tensides and have their influence on oxygen transfer efficiency and foam build up. All tensides are biodegradable and not persistent for a long time. Tenside concentrations were measured with Hach Lange tests kits. Influent concentrations of anionic, cationic and nonionic lie with 41, 0.8 and 6.6, respectively above concentrations measured in the large WWTP. In comparison, influent concentrations of the large conventional WWTP Berlin-Wassmanssdorf for anionic, cationic and nonionic lie with 4-12, 0.4 and 2 three times lower than the values for the decentralised small WWTP (Table 12). It is important to mention that the DIN-methods - conducted for the large WWTP- leads to lower values than the Hach-Lange test kits used for the monitoring in the ENREM project. Effluent concentrations for the CAS-plant for anionic, cationic and nonionic are 0.5, 0.2 and 0.2 mg/L. Elimination of anionic and non-ionic tensides in biological processes occurred above 99% wand 96%. Adsorption on activated sludge plays a mayor role in MBR and CAS, but also some retention / adsorption on the membrane was measured (see difference between “MR2” and “filtrate”. Especially for cationic tensides elimination rate of 63% could be increased up to rate of 75%. This may have some influence on fouling.

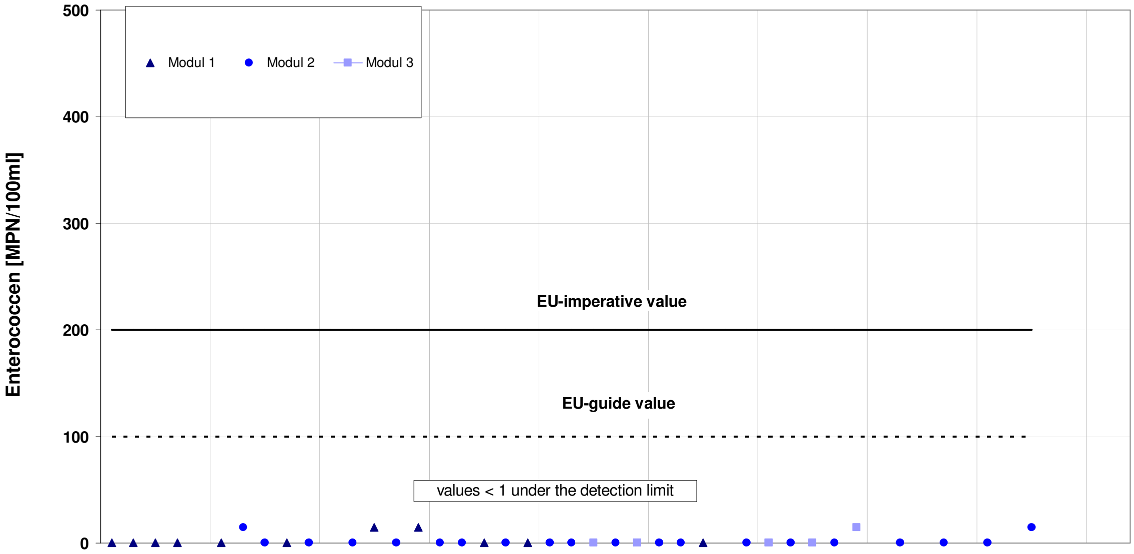
Table 12 Comparison of Tenside concentration (Grap samples)

	unit	anionic	cationic	nonionic
influent	[mg/l] (min, max)	41.2 (21.1 – 85.0)	0.8 (0.36 – 2.15)	6.6 (3.6 – 30.7)
	n<u>o</u> of samples	19	17	18
MR2	[mg/l]	1.3 (0.9 – 1.8)	0.3 (0.23 – 0.57)	1.4 (0.82 – 2.31)
	elimination [%]	97	63	86
	n<u>o</u> of samples	5	5	7
filtrate	[mg/l] (min, max)	0.5 (0.4 – 0.8)	0.2 (0.10 – 0.57)	0.4 (3.55 – 30.7)
	elimination [%]	99	75.2	96
	n<u>o</u> of samples	8	8	8

IV.4. DESINFECTION RESULTS

Every month two grab samples were analysed for E.coli, Enterococcus and coliphages. The results over time are presented in Figure 15. During the trials no disinfection of the membrane (no CIP cleaning with chlorine!) was carried out. All samples showed that bacteria and viruses were eliminated down to the detection limit. Therefore, the imperative values and even the guide values of the new EU-bathing water directive for the aforementioned bacteriological parameters could be matched over the trials period of one year. Coliphage - as a surrogate organism for enterovirus - were completely eliminated with the ultrafiltration membrane of 37 nm. As these organisms are generally very well adsorbed by solids, their almost complete elimination is expected due to the separation of the solids. The two high values of E.coli may be due to recontamination after the membrane, but no clear statement can be given, as the modules went out of operation in April, and replaced by another technology of filtration system (see VII.4).





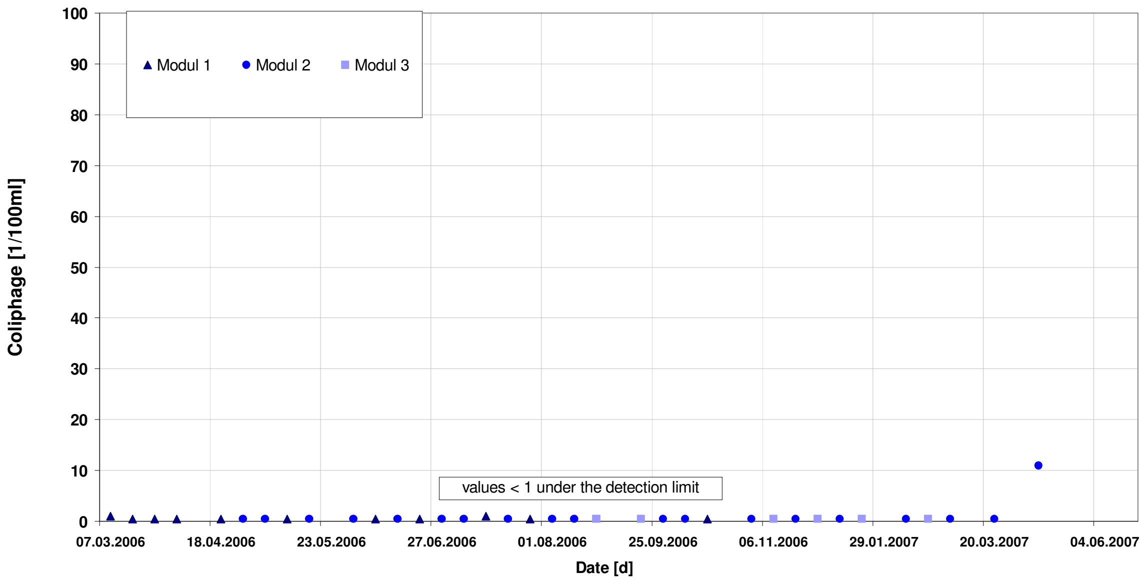


Figure 15 Effluent concentration of E.coli, Enterococcen and Coliphage over time

V. PERFORMANCE OF THE PROCESS FOR ENHANCED BIOLOGICAL NUTRIENTS REMOVAL

This section presents the results of the detailed analysis of the process, performed with grap-samples.

V.1. NUTRIENTS INFLUENT CHARACTERISATION

Although the buffer tank reduced the main concentration peaks in raw wastewater the influent concentrations for the biological system varied still in a wide range (Table 13), especially during the first six month of operation when the households were being connected (see Figure 6). This was due to illegal discharges such as storm water and the contents of old septic tanks. Afterwards, the influent concentrations varied in a lower range (see V.2.1, V.2.2 and V.2.3) but were still on a high level. As can be seen in Table 13 the median influent concentrations for all parameters were at least 30% over the design values. From the median concentrations of 1300 mg/ COD, 155 mg/L TN and 21 mg/L TP a water consumption in the network area of around 80 L/d person can be assumed, which is quite a low amount.

Parameter	**COD in**	**NH_4-N**	**TN**	**PO_4-P**	**TP**	**Org. Acids**
Unit	mg/L	mgN/L	mgN/L	mgP/L	mgP/L	mg/L
Min	746	79.5	105	5.3	11.7	150
Max	2755	188.6	200	25.2	47	294
Median	1296	109	155	15	21	265
Design	986		108		15	95

Table 13 Regular grab samples at the effluent of the screen

In addition, due to the high connection rate of nearly 100% of households, the amount of wastewater reaching the plant was also over the design value (see Figure 7). In combination with the higher influent concentrations, this led to a significant overload of the biological system. The Figure 16 and Figure 17 show that the volumetric load for phosphorus and nitrogen exceeded the maximum design load from the month of May onwards. In November the load reached its culmination when the plant was overloaded by 100% for both parameters. Afterwards the load was reduced by collecting a part of the inflow in the excess sludge tank and trucking away on a regular basis (see III.6.3). Still, the plant handled +30/50% of the max. design nutrients load, especially on weekends.

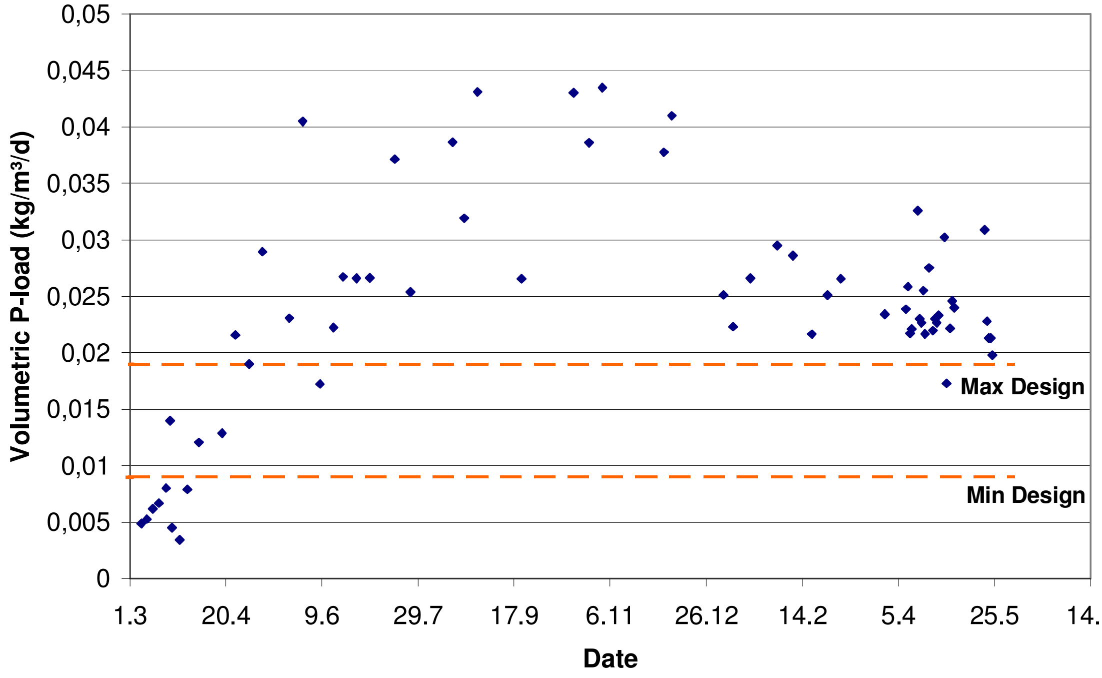


Figure 16 Evolution of the volumetric phosphorus load

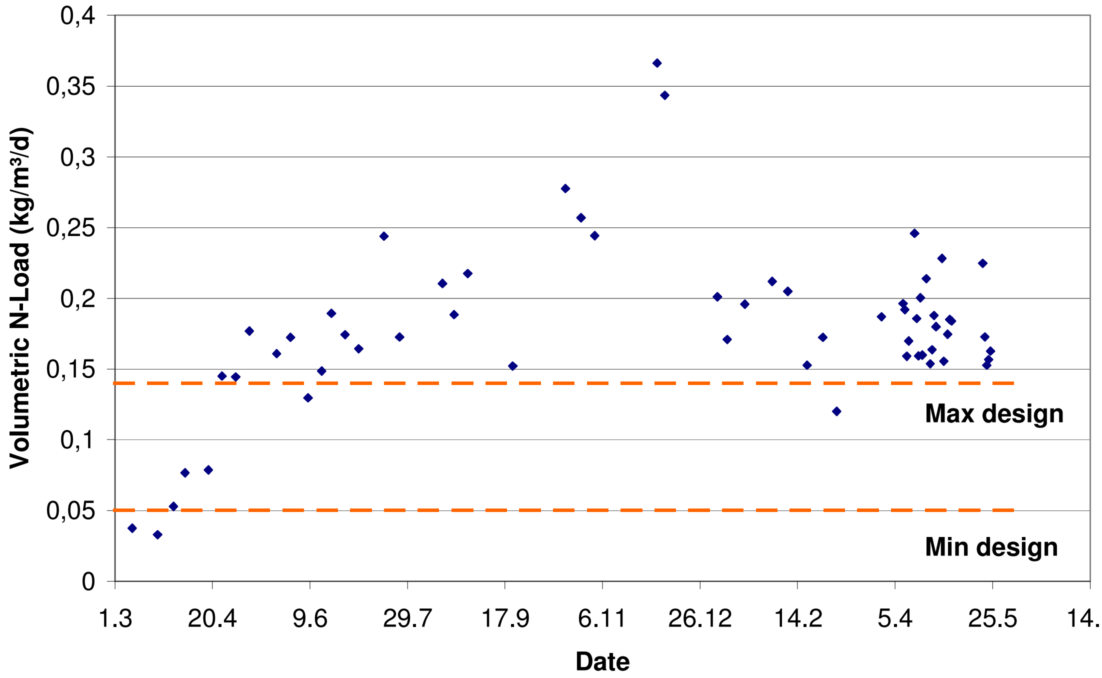


Figure 17 Evolution of the volumetric nitrogen load

V.2. PERFORMANCE OF THE BIOLOGICAL NUTRIENTS REMOVAL PROCESS

V.2.1. COD Elimination

The COD elimination was very stable during the whole operational time, and remained over 95% (Figure 18). The given target of 50mg/L COD was fulfilled most of the time, also during very heavy overloaded periods. Two occasions can be pointed out, where the effluent concentration was around 60 mg/L. The first one is right after the start up of the plant in March 2006. Here the TS concentration was low and the operational conditions were very unstable. A second reason can be mentioned: the membranes were new and unfouled. This is also the case at the second occasion in April 2007. At this time, new membrane modules were built in, and the first measured COD effluent concentration was clearly higher than before, without any additional stress for the biology. Hence, it can be concluded that unfouled membranes retain less COD than fouled ones. But the retention rose quickly and one week after the change of membranes, it was on the same level as before.
Furthermore, since the condition of the membrane influences the COD elimination it is remarkable that the change from ultra filtration membranes with a pore size of 35 nm to micro filtration membranes (200nm pore diameter) finally did not lowered the COD elimination.

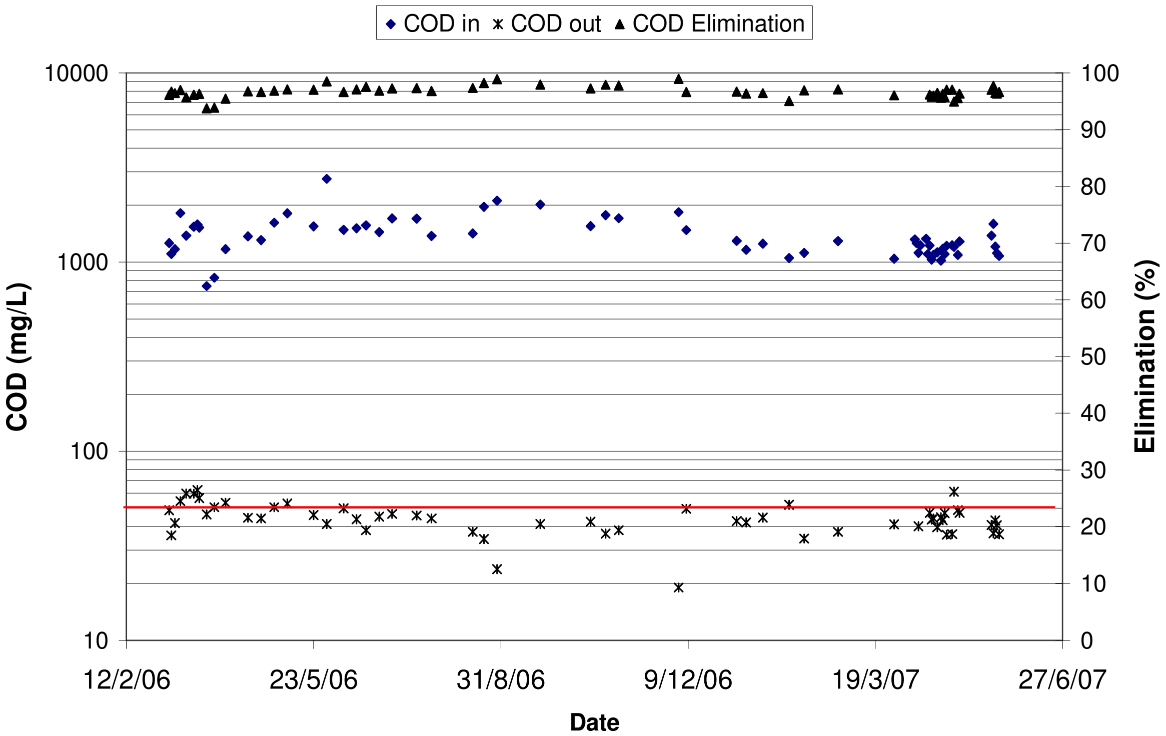


Figure 18 Time evolution of COD influent and effluent concentrations

V.2.2. Nitrogen elimination

Time evolution

The evolution of the nitrogen in- and outflow concentrations is given in Figure 19. It began with a relatively low N-elimination of 65% but rose constantly and reached 95% in June 2006. Here the target of 10 mgTN/L was fulfilled under design load conditions. Afterwards the elimination rate went down again for a short period, when constructions on the plant were carried out and the process was operated under unsteady conditions. A fast recovery followed. From July 2006 onwards the plant was constantly heavily overloaded and the operation was very unstable (see III.6). In this period N-elimination was not satisfying with only 70% to 90%. In the colder winter month also nitrification was not always completed and up to 12 mg/L NH_4-N were monitored in the effluent. Due to load reduction, TS increase and temporary supplement of carbon source in the anaerobic reactor (see III.6.3) N-elimination recovered in April 2007 and was afterwards most of the time around 95% with effluent concentrations below 10 mgTN/L.

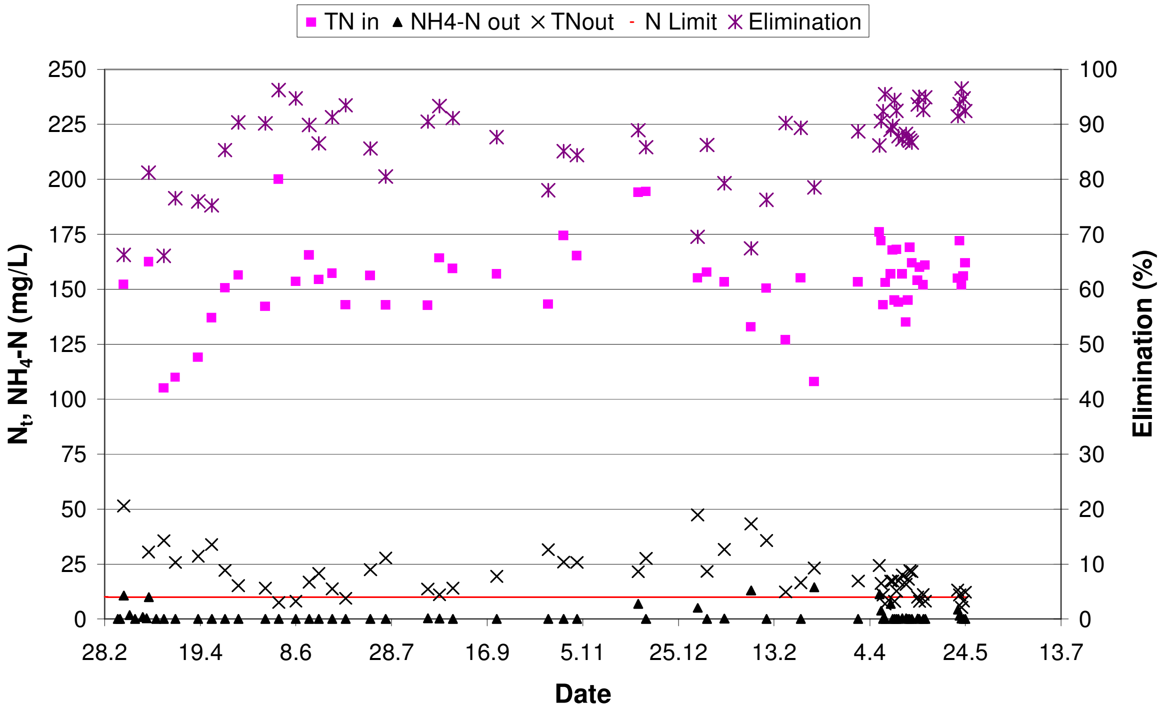


Figure 19 Time evolution of nitrogen elimination

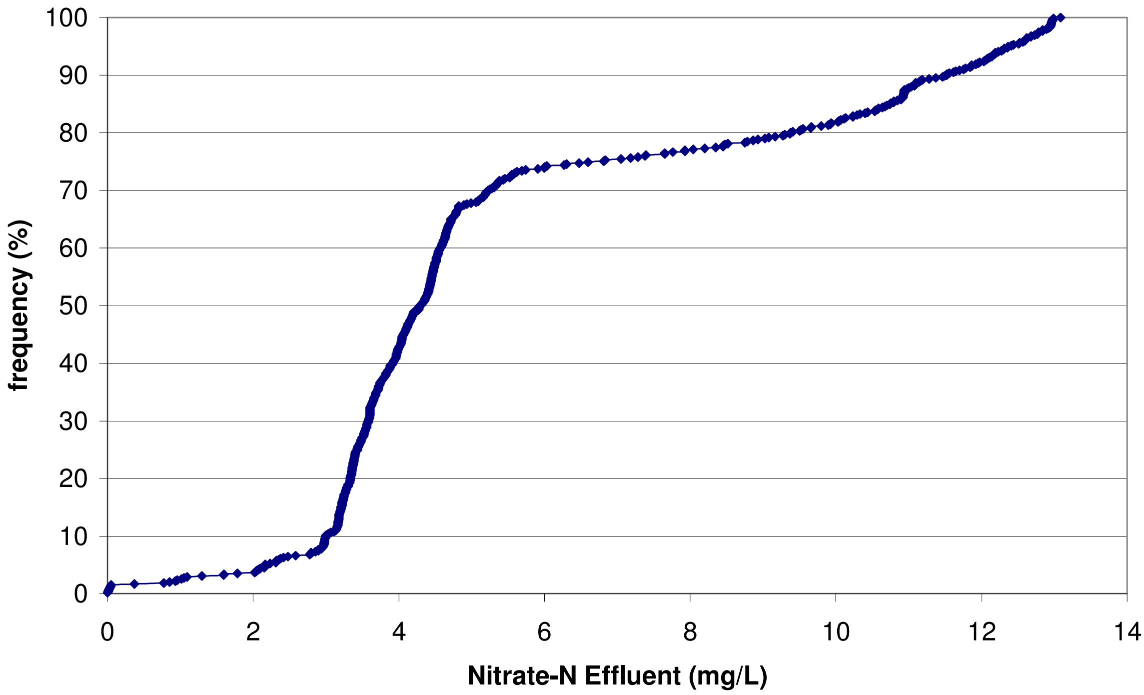


Figure 20 Frequency distribution of the nitrate effluent concentration (in Apr.-May 2007)

The good performance of the process, under low overload conditions, is underlined by the nitrate effluent concentration online data, monitored during the steady state conditions with moderate overloading (0.18 kgN/m^3/d, see Table 5). Figure 20 shows that in 85% of the time the nitrate effluent concentration is below 10 mg/L. Considering the high TN influent concentrations of app. 155 mg/L this means over 90% TN elimination.

On some occasions low nitrate concentrations was monitored in the effluent (< 3 mgN-NO_3/L 10% of time). This shows the high potential of the process: with the right load almost the whole nitrogen can be eliminated, excluding the refractory and soluble organic nitrogen fraction of about 3 mgTN/L (typically 2% of initial concentration).

Nitrification Rates

Most measured nitrification rates are scattered between 1 and 3 mgN/gVSS/h. In AE2 the rate is often limited by the ammonium concentration since most of the ammonium is nitrified already in the first aerobic reactor under normal operation conditions. A clear correlation to the temperature can not be seen (Figure 21). Other parameters such as sludge load and more importantly the oxygen concentration seem to have higher impact influence the nitrification. Due to a lack of reliable data for the dissolved oxygen concentration this can not be proven here.

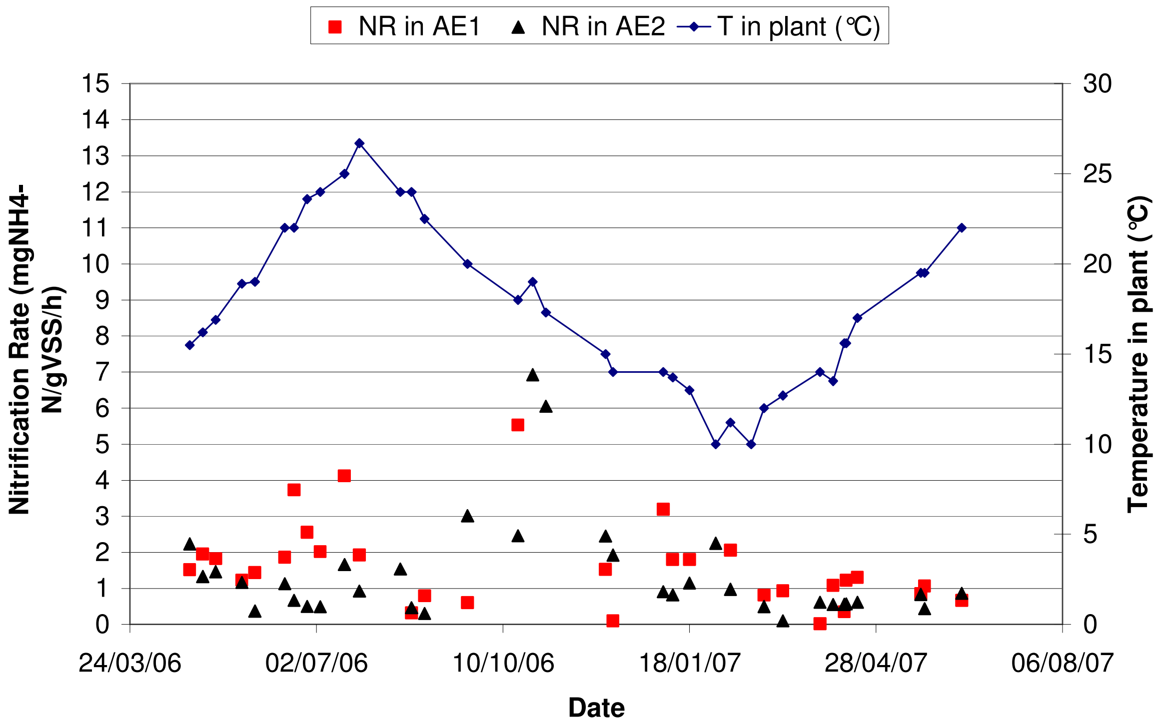


Figure 21 Time evolution of nitrification rates in AE1 and AE2 and the temperature in the plant

The denitrification performance and evolution is discussed in chapter VI.

V.2.3. Phosphorus elimination

Time evolution

The plant was inoculated with sludge from the WWTP Berlin-Schönerlinde, which operates with EBPR. Therefore P-elimination was already above 99%, without any chemical addition, right from the start (see Figure 22). Two instabilities of the P-elimination occurred in April and July 2007 due to plant construction activities. In September 2006 the P effluent concentration started to elevate constantly. In December 2006 P-elimination was as low as 40% with effluent concentrations above 10 mgTP/L. The next chapter provides information on the way this progressive degradation occurs, and lists the measures which were taken to recover the EBPR process. From March 2007 onwards the P-elimination was very constant above 99% with ortho-PO_4-P effluent concentrations below the detection limit and TP between 0.1 and 0.2 mg/L (about 0.5-1% TP in wastewater can be considered as refractory soluble and organic phosphorus fraction). This result, obtained without addition of metal salt for co-precipitation, is very satisfying considering the high inflow concentration of 21 mgTP/L in average and the phosphorus load above the maximal design load during this period (with 0.024kgTP/m^3/d). The initial effluent quality target of 0.1 mgTP/L is close to be reached, and would have certainly be matched should the wastewater have contained the expected design concentration of 15mgTP/L.

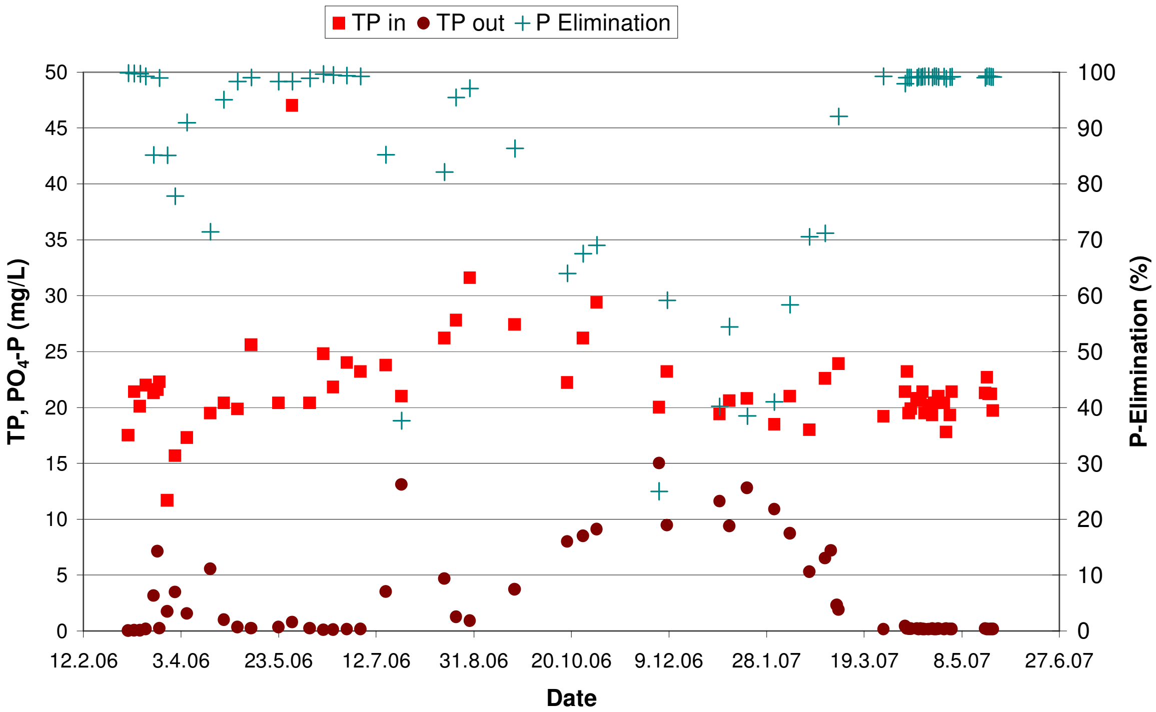


Figure 22 Time evolution of P-elimination

The data recorded by the online ortho-P sensor are strengthening the positive results for the biological P-elimination. The data shown in Figure 23 are monitored during the stable operation period from march 2007 onwards. It is apparent that 95% of the values were below 0.05 mg/L o-PO_4-P and 100% were below 0.09 mg/L. This shows the excellent stability and performance of the biological P removal, although the plant was still overloaded in that phase.

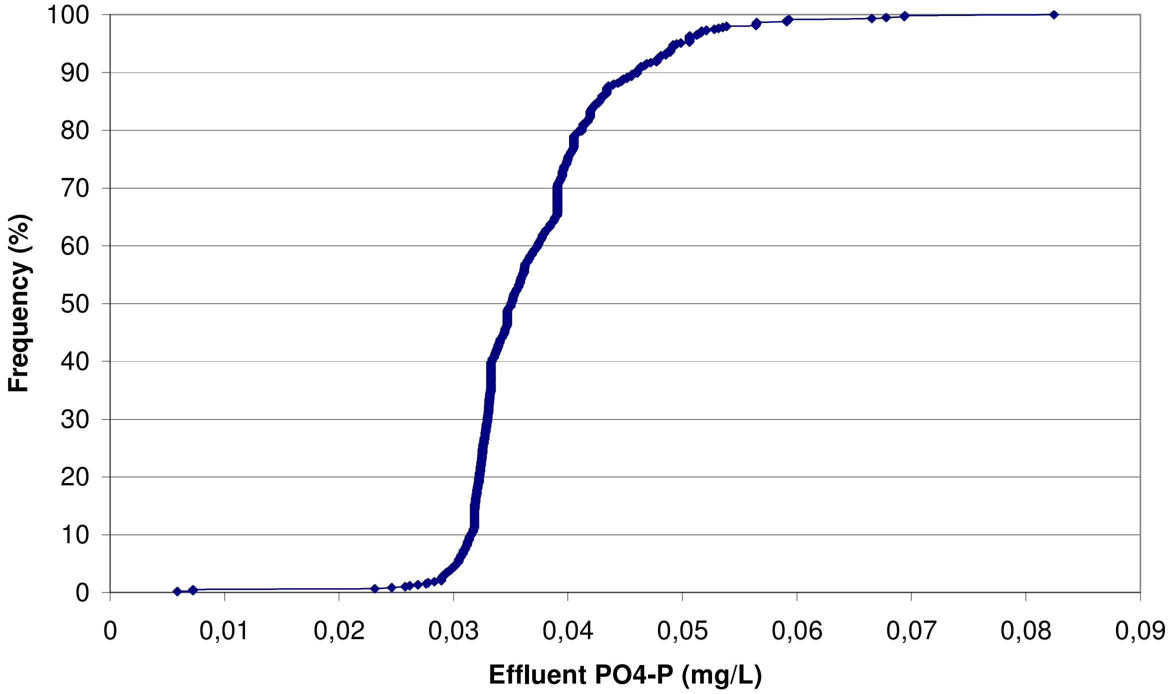


Figure 23 Frequency distribution for o-PO_4-P effluent concentration (in Apr.-May 2007)

Phosphorus bio-kinetics

The evolution of the phosphorus release rates (PRR) and phosphorus uptake rates (PUR) can be explained according to the total P elimination. Figure 24 shows rising PRRs and also enhancing PURs in the first month of operation. This can be explained by slowly rising P influent concentrations and rising TS concentrations. From August 2006 onwards the P-release is inhibited by a too high nitrate recirculation due to an overloaded plant (see next chapter). The P-uptake in AE1 is turn into a P release which is quoted with positive values in the figure. This can be due to:

- High organic P load in the influent, which is transferred into o-PO4-P in the aerobic zone and hence measured as a P-rise in the profiles
- High organic load and short anaerobic contact times due to a high plant throughput can lead to VFAs present in the aerobic zone leading to p-release
- Low oxygen concentrations in AE1 due to high organic load.

In this period some P-uptake still occurred in AE2. In January and February 2007 (red circle in Figure 24) the Bio-P finally broke down completely, no P-release and no uptake was measured anymore in the plant. In this period also the post-denitrification was inhibited (see VI). Due to the action taken (see III.6.3) the PRRs and PURs recovered from march 2007 onwards. Here in most cases the PUR in AE2 is smaller than in AE1. This is according to other EBPR studies. The more phosphorus is taken up already by the microorganism, the slower is the PUR.

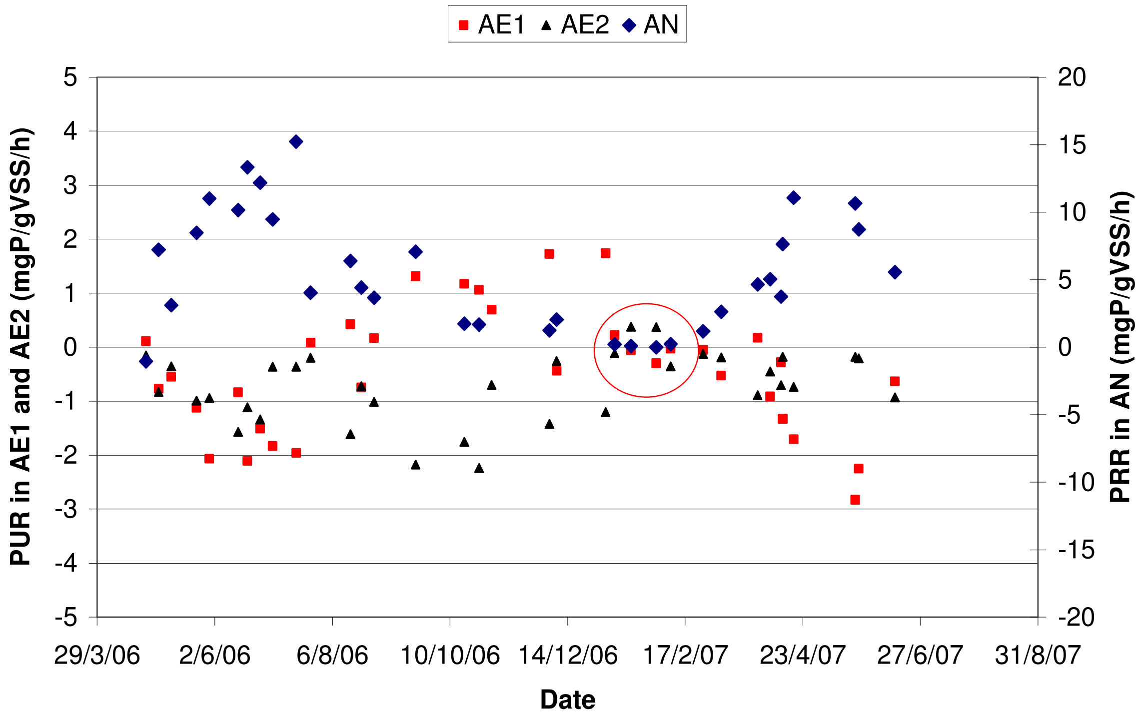


Figure 24 Course of PRR and PUR in the demonstration plant

V.2.4. Spatial nutrients profiles in the process

Concentration profiles for ammonium, nitrate, nitrite and phosphate were conducted on a weekly basis to monitor the biological performance of the system. A total sum of 60 profiles was measured. This led to a numerous amount of data which helped for a better monitoring and understanding of the new process, as well as the identification of trouble shooting measures when required. Out of these set of data two profiles are shown exemplarily.

The first one, presented in Figure 25, was recorded during moderate overload conditions. The ammonium influent concentration of 121 mgN-NH_4/L is reduced due to the two recycle streams. Nitrification occurs in the aerobic reactors and is completed in the second aerobic reactor. Nitrate is built up to an amount of 17 mgN-NO_3/L. In the anoxic zones nitrate is degraded down to 5 mg/L with a denitrification rate of 1.2 mgN/h/gVSS. This is remarkable since no external carbon is dosed. A more detailed discussion concerning the denitrification is made in VI. No nitrite is build up during the whole process, which is an evidence of the very good performance of the biological N removal. The TN effluent concentration is at 9 mgTN/L, below the target of 10 mgTN/L.

TP influent concentration is at 23 mg/L. Phosphate shows the typical release in the anaerobic zone, in this case to an amount of 40 mg/L o-PO_4-P. Phosphate uptake is performed in the aerobic and anoxic reactors down to concentrations below the detection limit. The TP effluent concentration is at 0.18 mg/L and only slightly above the limit.

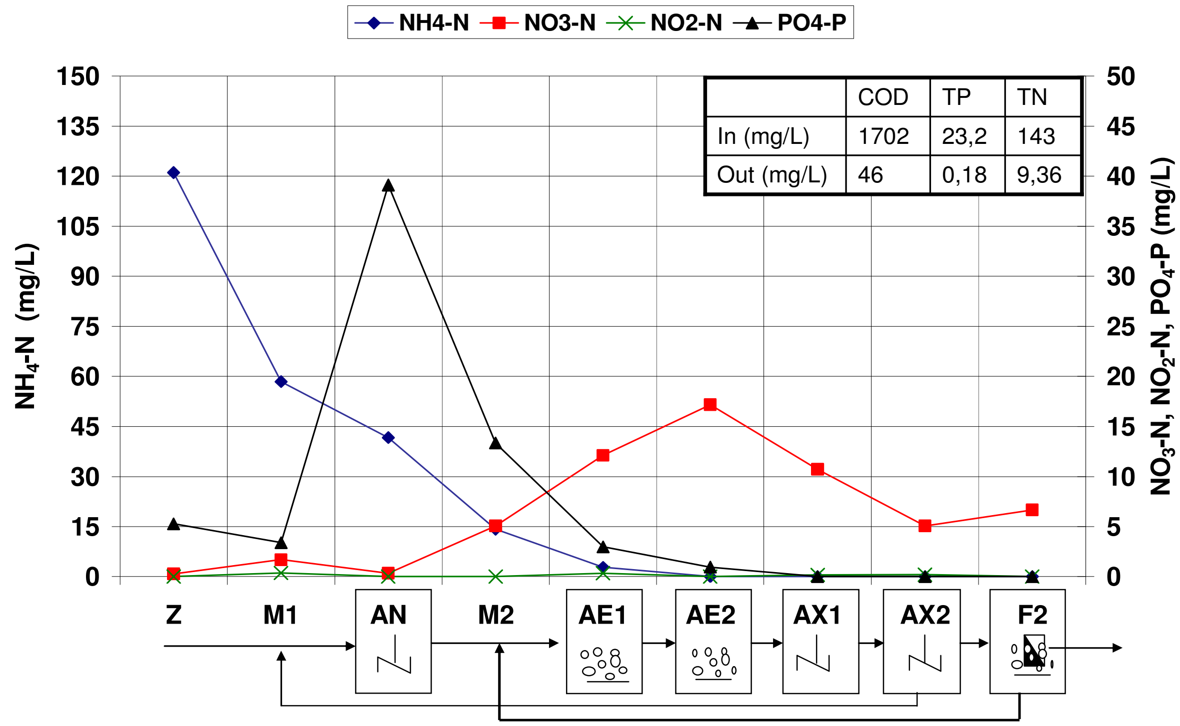
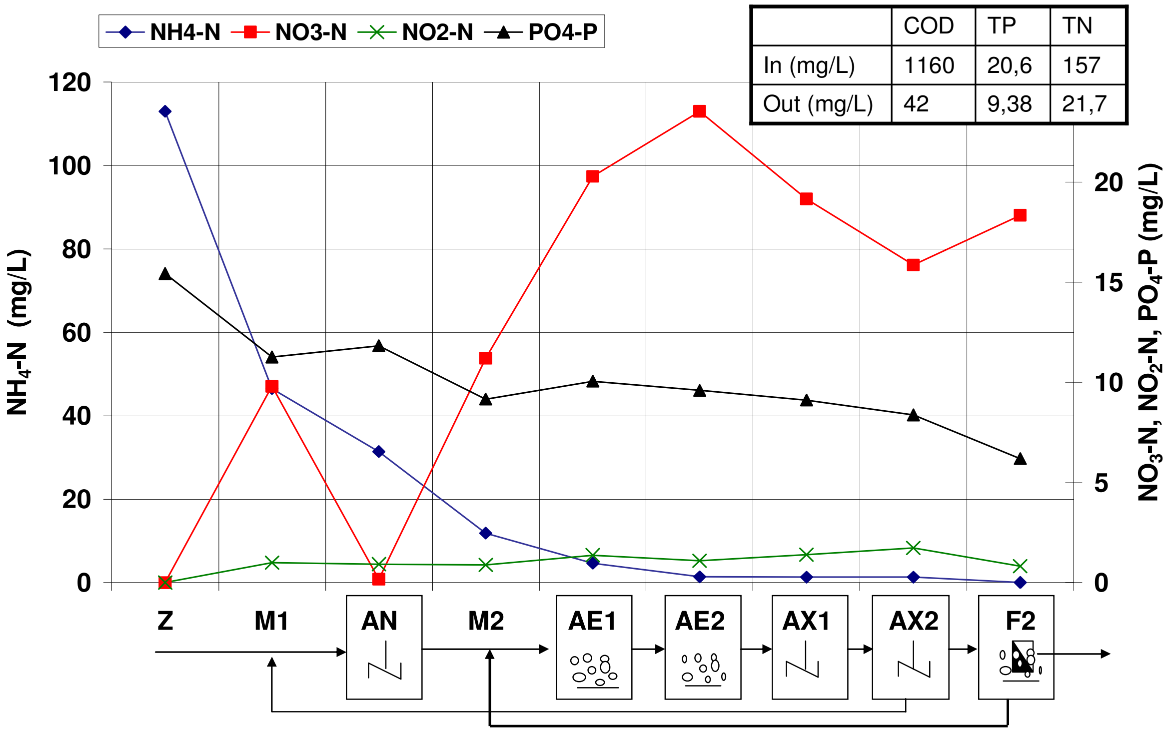


Figure 25 Concentration profiles for ammonium, nitrate, nitrite and phosphate during good conditions (4/7/2006)

The second profile was recorded early January 2007 after 5 months of heavy overload conditions. Figure 26 shows that ammonium is not completely nitrified in the aerobic reactor (mainly due to oxygen limitation and low temperature in the reactors). In this case 2 mgN- NH_4/L reached the membrane reactor and were finally nitrified there. Additionally the build up of up to 2 mg/L nitrite was observed, which indicates that the nitrogen elimination was overwhelmed. An amount of 23 mgN-NO_3/L was built up in the aerobic reactors. Since also the dentrification rate suffered during that phase (in this profile ~0.8 mgN/h/gVSS) and due to the relatively low TS content of 7 g/L, 16 mg/L NO_3-N were recycled from the second anoxic zone to the anaerobic reactor. The high amount of recycled nitrate harmed the EBPR process. The incoming VFAs were not anymore used for the P release and the accompanying build up of storage compounds but mostly for (pre-)denitrification. Hence, also only a small amount of phosphate is taken up in the plant and 9.38 mg/L TP were measured in the permeate.



	COD	TP	TN
In (mg/L)	1160	20,6	157
Out (mg/L)	42	9,38	21,7

Figure 26 Concentration profiles for ammonium, nitrate, nitrite and phosphate during overloaded conditions (9/1/2007)

V.2.5. N + P Mass balance

Nitrogen mass balance

During the intensive measuring period an average amount of 1.68 kg/d TN reached the plant. In average 8.5% of this nitrogen was measured in the filtrate and 31.5% were removed with the excess sludge. N/TS concentration was at 10%. Hence about 60% of the nitrogen mass was removed by the denitrification processes (pre-denitrification, post-denitrification and possibly residual simultaneous denitrification in the aerobic reactors). Compared to the IMF-project where 20-27% of nitrogen were removed with post-denitrification and about 25% with simultaneous denitrification (if SRT>25 days), 40-50% must be assumed to be removed with excess sludge (based on 8% N/TS). As already discussed in Gnirss et al. 2003, N/TS-values are much higher than known for conventional WWTP with N/TS of 5%

Phosphorus mass balance

The evolution of the total solids (TS) concentration is explained in chapter III.4. Volatile suspended solids (VSS) were stable between 70% and 80% of TS. The phosphorus content in the sludge (P/TS) was around 4% in the beginning. In June 2006 with rising load, the P/TS concentration reached 5%. Hence, in order not to disturb the EBPR process, the sludge age was reduced from 30d to 25d. The P/TS concentration dropped down to 4%. In the period of undefined sludge wastage, P/TS was as low as 2%. This shows, that a lot more sludge was extracted than it was intended to, but also, that the EPBR process was unstable and unreliable in that period (see V.2.3). After recovery of good biological performances, the P/TS concentration came back again to 4-4.5%. P/TS appears therefore as in important parameter to monitor on a regular basis to operate the system. It should be kept as high as possible, but should not exceed 5% (on typical domestic wastewater).

The measured P/TS concentration was around 4.2% which matches well the theoretical value of approximately 4%, calculated from the P mass balance. This shows that no phosphorus is precipitating and accumulating in dead volumes of the reactor. All phosphorus is taken up and removed with the excess sludge.

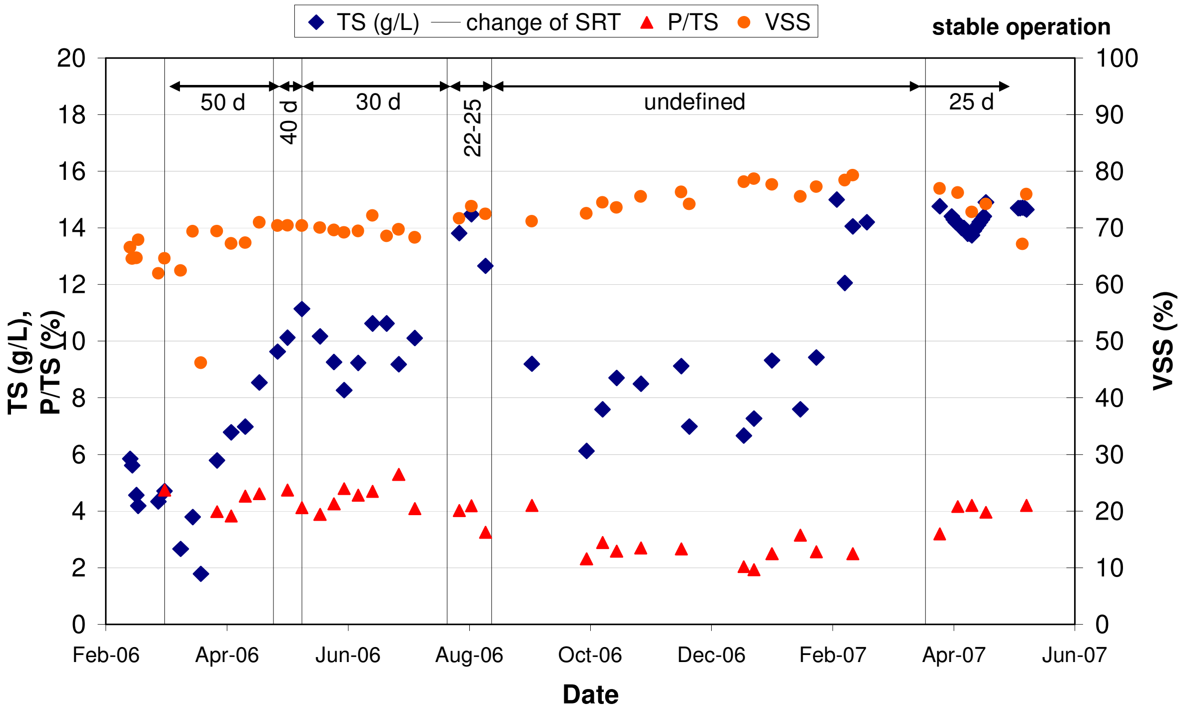


Figure 27 Course of TS, VSS and P/TS concentrations (measured in AX2)

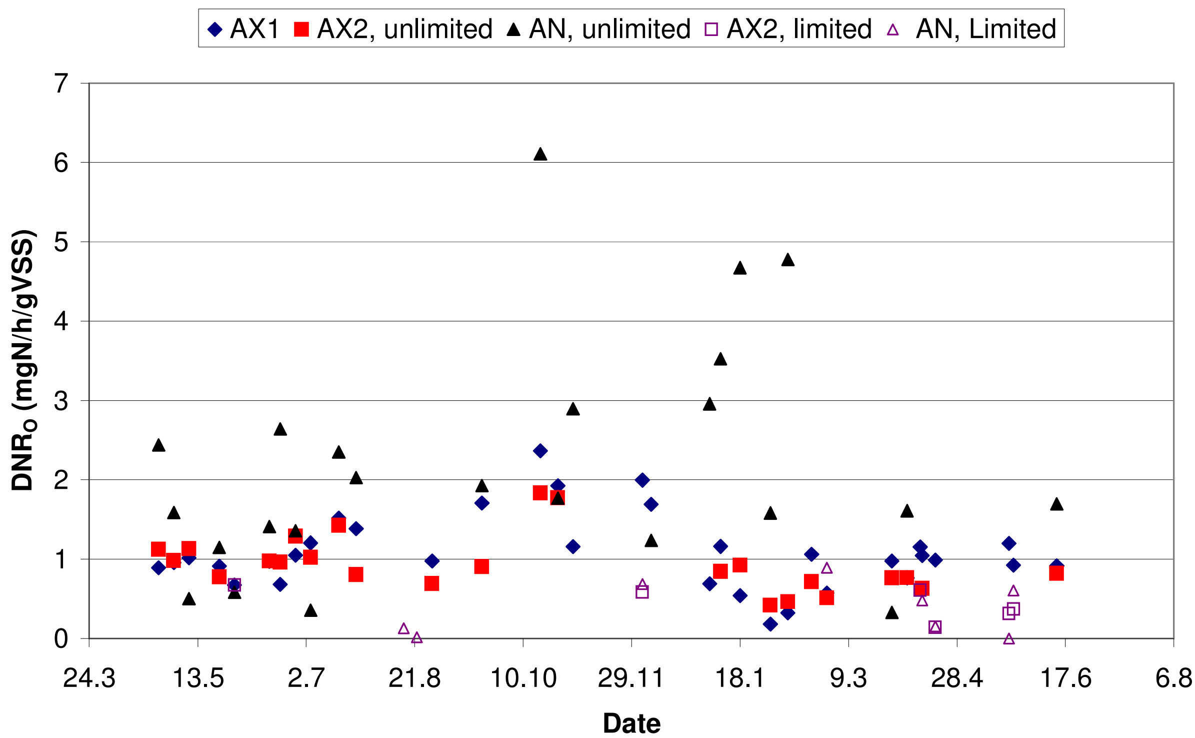
VI. INVESTIGATIONS ON THE ENHANCED POST-DENITRIFICATION

VI.1. EVOLUTION OF OPERATIONAL DENITRIFICATION RATES (DNR_O)

Denitrification rates recorded in the demonstration plant with profile measurements are further called operational denitrification rates (DNR_O, or DNR). Figure 28 shows the course of the DNR_O over more than one year of operation. The denitrification rates measured in the anaerobic zone are calculated with the mixing concentration from the recycle stream and the influent. DNR values are indicated as "limited" (light data point) when the nitrate concentration was below 0.15 mgN/L in the considered reactor, as the semi reaction constant of denitrification Ks is usually taken between 0.1 and 0.15 mgN/L.

Three periods can be observed:

1. March 2006 – September 2006: DNR in AX1 and AX2 was in the range 0.7-1.7 mgN/h/gVSS. DNR in AX1 increased as the load increased. As nitrate was still present in AX2 and recirculated to AN, DNR between 0.5 and 2.5 mgN/h/gVSS were monitored in the anaerobic zone.
2. October 2006 – February 2007: After several months of permanent and significant nitrogen overloading and high level of recycling in the anaerobic zone, the DNR in the anaerobic zone increased up to 6 mgN/h/gVSS while the DNR in AX 1 and 2 dropped down to 0.5 mgN/h/gVSS, about endogenous denitrification rate). This showed that the "anaerobic" was actually anoxic, and the "pre-denitrifiers" could develop and take advantage on the "post-denitrifiers".
3. March 2007 – June 2007: The process recovered. DNR in AX1 and AX2 was in the range of 0.7-1.2 and 0.6-0.8 mgN/h/gVSS respectively. As nitrate recirculation to the anaerobic zone was lower, the DNR in AN was very often limited (values



below 0.6 mgN/h/gVSS) and in any case always below 1.7 mgN/h/gVSS).

Figure 28 Time evolution of denitrification rates measured in the demonstration plant, the light data points were limited by the nitrate concentration

Since no carbon is dosed to the anoxic zone the DNR_O of 0.6–1.7 mgN/h/gVSS is still a high range. Traditionally an endogenous DNR of around 0.5 mgN/h/gVSS would be expected for a post-denitrification. These higher rates were first observed in the IMF project (Lesjean et al., 2003, Vocks et al., 2005), and were further investigated in the ENREM project.

VI.2. INFLUENCES ON THE DNR (POST-DENITRIFICATION)

Load

In Figure 29 the DNRs under undisturbed conditions, i.e. no oxygen carry over and no too high nitrate recirculation in the anaerobic zone, are plotted against the COD sludge load. It is apparent that higher sludge loads lead to higher DNRs. This is remarkable since the anoxic denitrification is the last treatment step in the ENREM process. This is a first indicator for a storage compound used as carbon source for the post-denitrification (see VI.3).

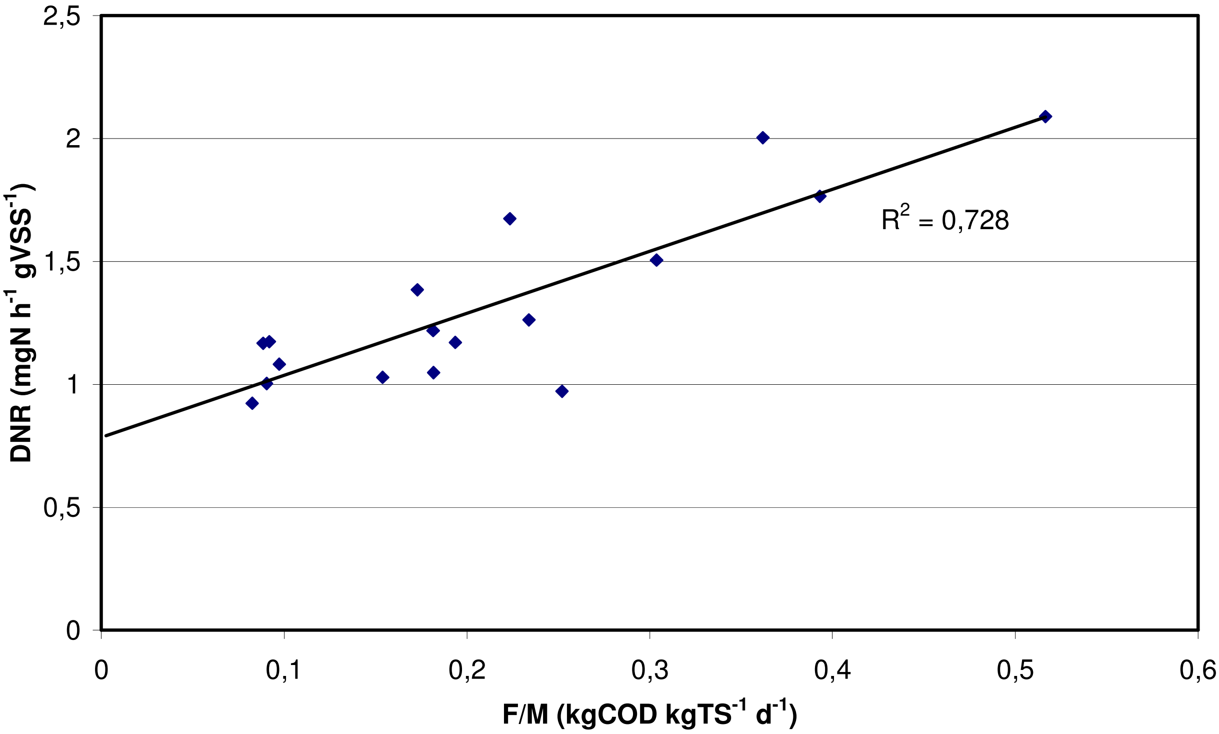


Figure 29 Influence of the COD sludge load on the DNR in the demonstration plant

Temperature

During the operation of the demonstration plant temperatures between 10°C and 27°C occurred in the biology. Figure 30 demonstrates that no clear influence of the temperature on the denitrification could be observed. Other influences like sludge load are more important. The DNR_O which were limited due to heavy nitrate recirculation in the anaerobic zone are not plotted in the figure.

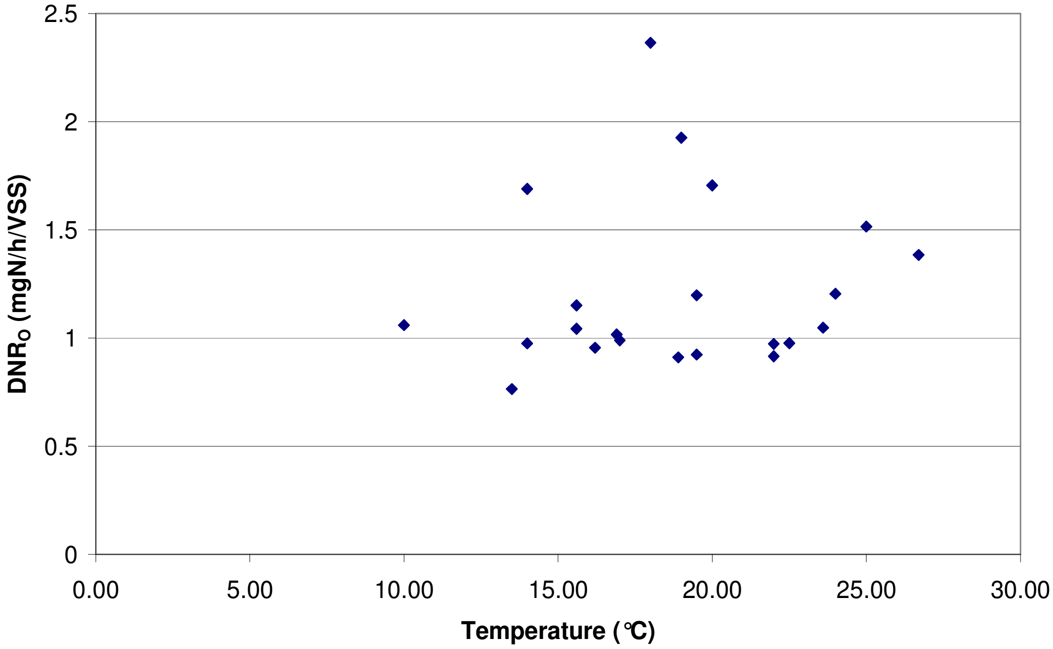


Figure 30 Temperature influence on the DNR_O

Phosphorus Release Rate

The PRR was influenced by the nitrate recirculation from AX2 to AN (see V.2.4). In Figure 31 it is shown that this also influences the DNR_O. If the PRR drops below a certain value the effect of enhanced post-denitrification gets lost and only endogenous DNRs were measured. The border values are located between 1.5 and 2 mgP/gVSS/h. Above that value the DNR is not influenced anymore by the PRR but by other parameters like the sludge load or oxygen carry over. In Figure 31 only DNR_O values with corresponding sludge loads below 0.3 kg COD/kgTS/d and no oxygen carry over are shown to reduce this influence.

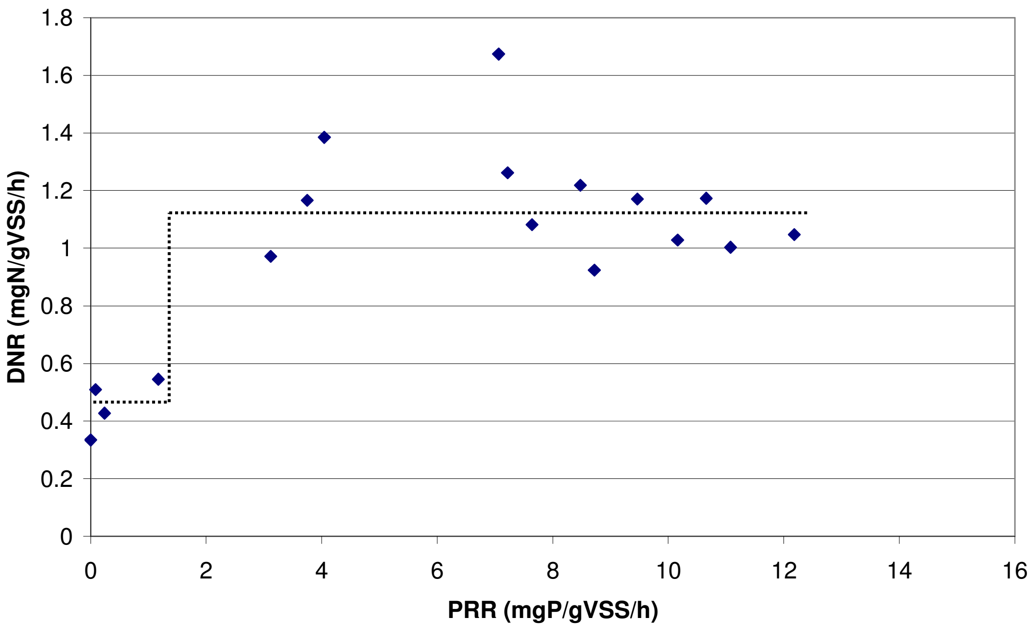


Figure 31 Influence of the PRR on the DNR_O

VI.3. INVESTIGATIONS CONCERNING THE CARBON SOURCE FOR ENHANCED POST-DENITRIFICATION

IMF outcomes concerning the post-denitrification

In the IMF project, where the enhanced post-denitrification was observed for the first time, it was found out that the anaerobic zone plays an important role for this special metabolism. Furthermore it was revealed that lysis and hydrolysis are unlikely to be the carbon source for post-denitrification [Vocks et al., 2005b].

Special DNR investigations in batch experiments

Closer investigations to reveal the mechanism of the process of enhanced post-denitrification were conducted with laboratory batch tests.

The organic loading by dosing acetate to the anaerobic phase was varied in numerous batch tests. The higher the organic loading of the anaerobic phase was, the higher was the denitrification rate in the anoxic phase (Figure 32). Observed DNRs were between 1 mgN/h/gVSS and 4 mgN/h/gVSS. An extrapolation of the found correlation to a F/M ratio of 0 shows a DNR of 0.4 mgN/h/gVSS, which is in the range of endogenous rates. Therefore, the build up of a storage compound under anaerobic conditions which is finally used in the anoxic phase is postulated.

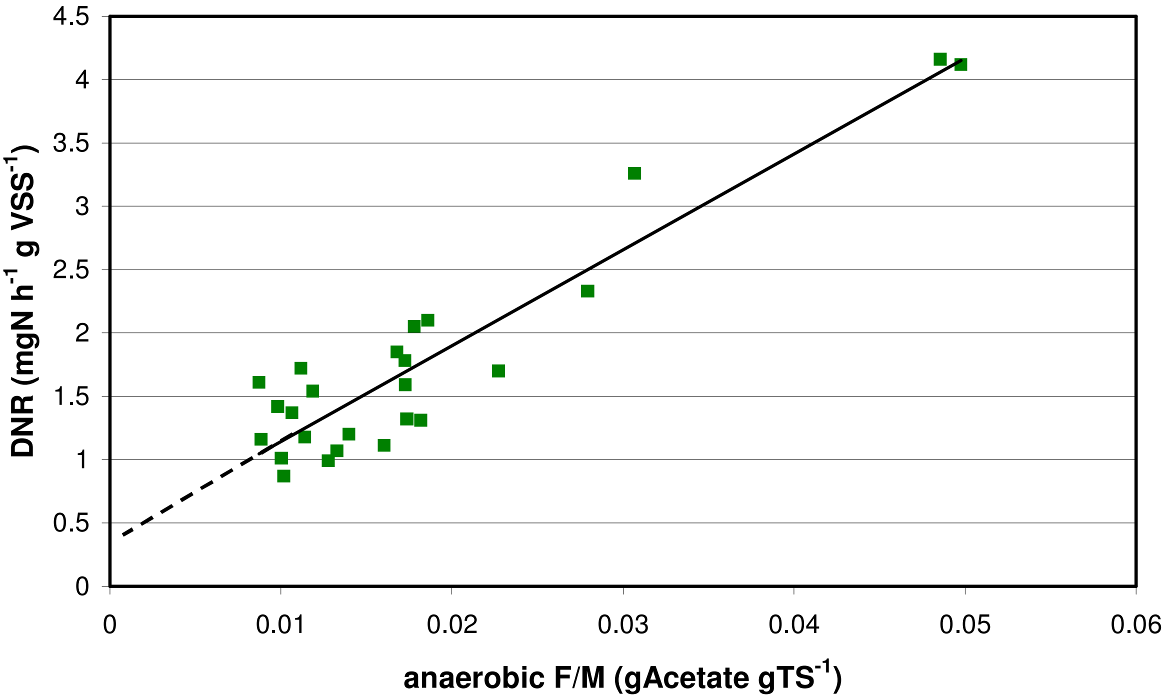


Figure 32 Influence of the *anaerobic* acetate loading on the DNR

Investigations with known carbon sources

Since the anaerobic zone is originally installed for the EBPR process but also plays an important role in the enhanced post-denitrification, investigations were made about the two major storage compounds build up during the EBPR process. In Figure 33 the result of a batch test in which PHB and glycogen were measured are displayed. In the anaerobic and aerobic phase the typical EBPR metabolism was observed. Under anaerobic conditions PHB is build up while glycogen is degraded and phosphate is released. Under aerobic conditions the phosphate is taken up accompanied with glycogen build up and PHB consumption. Finally in the anoxic phase PHB is on a low level and shows only very little dynamic and, hence it can not be the carbon source for the post-denitrification. For glycogen the situation is different. Although there is a lot of movement, there is no clear trend and the used amount of glycogen-C can not explain the higher post-denitrification. Furthermore, it is apparent that the higher post-DNR lasts only for the first 5h of denitrification. Afterwards the DNR declines to smaller rates in the range of ordinary endogenous rates. Hence, there is a shift of C-source resulting in different rates. This strengthens the assumption that a C-source different to typical endogenous C-sources, and different of the carbon sources considered in the EBPR theory, is responsible for the enhanced post DNR.

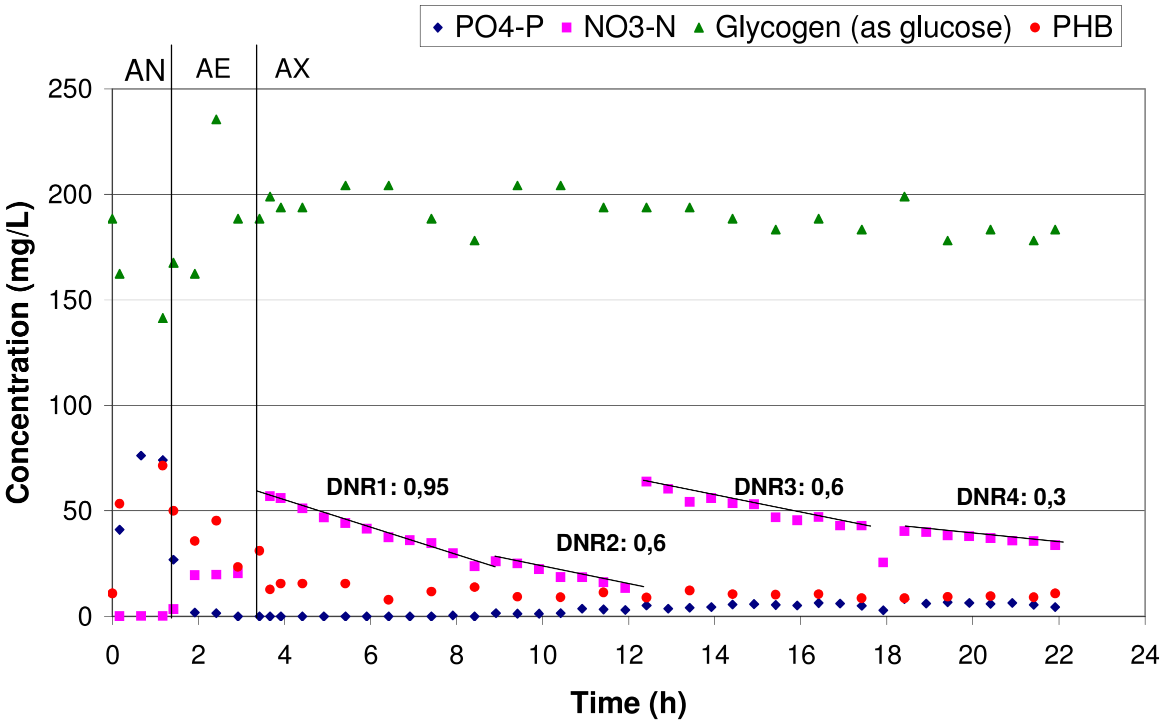


Figure 33 24h batch test with monitoring of glycogen and PHB storage.

Carbon mass balance in anaerobic zone

Because it is assumed, that the storage compound is build up under anaerobic conditions C-mass balances were performed for the anaerobic phase. All known C compounds such as dissolved COD, dosed acetate, PHB and PHV, glycogen and CO_2 production were taken into account. The result is given in Figure 34. It is visible that the carbon mass balance was not closed. 70 mg/L of carbon which should be detectable vanished and are not among the known compounds. This corresponds to almost 100% of the acetate mass injected in the system. Hence, the formation of a different, so far unknown storage compound is assumed.

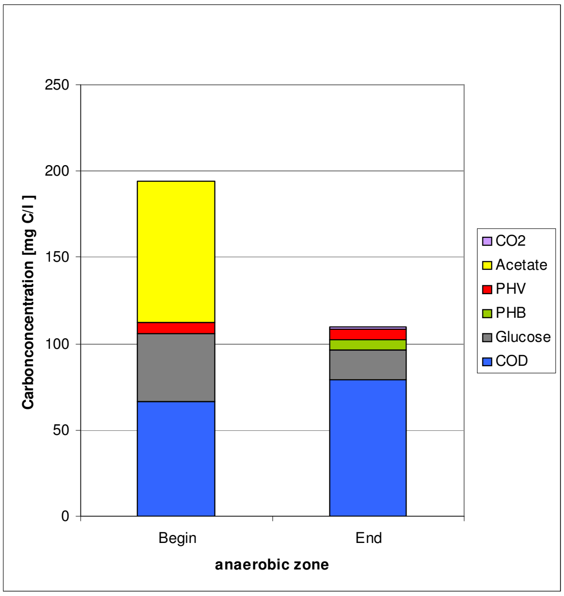


Figure 34 Carbon mass balance for the anaerobic phase

Investigations with Nuclear Magnetic Resonance (NMR)
In order to evaluate the used storage compound a lab scale membrane sequencing batch reactor was constructed and operated with the ENREM process scheme (AN→AE→AX→Filtration). The reactor was adapted to, and operated with a synthetic mono-carbon-source substrate. This enabled special *in vivo* nuclear magnetic resonance (NMR) measurements. This study was done in cooperation with the department of chemical engineering at the Universidade Nova de Lisboa, which is specialized for these unusual NMR measurements. These investigations are still in process and results can not be resumed here. No results are so far available since major trouble with the reactor operation and the measurement techniques occurred.

VII. FILTRATION PERFORMANCES

VII.1. FILTRATION OPERATION PARAMETER

Table 14 summarises the main operation parameters for specific periods of the trials.

Table 14 Filtration operation parameter

Parameter **Period**		**1**	**2**	**3**	**4**
Time		**1.3.06-30.4.06**	**1.5.06-31.08.06**	**1.9.06-31.3.07**	**1.4.07-30.6.07**
Number of Filter in operation	-	1	2	2	2 / 1**
Net flux	l/m²/h	6 (2 – 13)	6 (4 – 10)	7 (3 – 10)	12** (10 – 17**)
TMP	mbar	6 - 50	40 - 180	80 - 240	50 - 170
Permeability	l/m²/h/bar	200 - 600	50 - 350	50 – 130	70 - 170
Specific air demand	Nm³/h/m²	0.3 – 1.0	0.7	0.5 – 0.8	0.5 – 0.6

** values from the new module (A3 Water solutions)

VII.2. CHEMICAL CLEANING

The intention was to identify an appropriate cleaning protocol coping with the following constraints: no chlorine, no heating and a maximum cleaning time of 5 hours. The cleaning conditions attempted during the trials are listed in Table 15.

Cleaning 1 (March to December 2006)
It was first attempted to stick to the usual cleaning strategies of flat sheet membranes, performing a chemical soaking on a 3-month basis. The H202 cleaning showed a mediocre permeability recovery of 10 to 30%, at the end well below 10%. Both the quick permeability drop (probably due to great extent to module clogging) and the low permeability recovery, leading TMP values approaching the upper limit, were not satisfying.

Cleaning 2 (August to December 2006)
In the second half of 2006, another cleaning strategy of the membrane filters was therefore attempted, consisting of regular maintenance cleaning. A chemical solution (citric acid and hydrogen peroxide in a row) was being backwashed in sludge, mostly after mechanical cleaning. This mode of cleaning showed only short-term results and was stopped in Jan 2007.

Cleaning 3 (October 2006 to January 2007)
Heavy clogging required a disassembling of the modules and a manual cleaning of the interspaces of the flat sheet membranes with a water jet.

Cleaning 4 (January to April 2007)
A last attempt was to resort to chlorine soaking. The cleanings performed better but were still mediocre, showing a 10 to 15% permeability recovery.

Table 15 Cleaning conditions

Cleaning 1 (chemical soaking)	Cleaning 2 (chemical backwash in sludge)	Cleaning 3 (mechanical cleaning)	Cleaning 4 (chemical soaking)
2006/06 – 2006/12	2006/09 – 2007/01	2006/10 – 2007/01	2007/01 – 2007/04
Citric Acid 2000 ppm / 1h pH 3.4	Citric Acid 2000ppm/0.5h pH 3.3	Module disassembling	Citric Acid 2000 ppm / 1h pH 3.4
H2O2 1000 ppm / 3h pH 8.5	H2O2 2500 ppm /3h pH 8.7	Manuel plate interspace cleaning with water jet	Active Chlorine 1000 ppm /4h pH 9.5

VII.3. EVOLUTION OF PERMEABILITY

The filtration performance is analysed on the basis of the measured permeability recalculated at 20°C to take into account the impact of permeate viscosity (see Figure 35). The membrane modules started with a permeability in sludge of around 700 L/m²/h/bar and decreased below 200 L/m²/h/bar after 2 – 3 month of operation (net flux of 4-8 L/m²/h). The first cleaning of two filters took place in June 2006. The permeability increased up to only 350 and 250 L/m²/h/bar respectively but dropped down below 100 L/m²/h/bar in August 2006. During this time, module clogging was observed the first time (see III.6.4) but it is supposed that clogging occurred before. Because of this problem an extra cleaning step was necessary, the so-called *mechanical cleaning*: The filters had to be disassembled and each 6 modules were then cleaned manually with a water jet to spray the solid sludge parts out of the channels between the membrane plates. This step took more than 4 hours for a single filter. After the reconstruction works in December 2006, filter clogging was not observed any more, however the permeability remained very low for the 3 filters (in the range of 50-150 L/m²/h/bar for a flux of 6-11 L/m².h), with a mean daily fouling rate of about 3mbar/d. The TMP rose frequently to the upper limit of 250 mbar, which was a cause of stress to the operators. It was therefore decided to replace the filtration system with another technology.

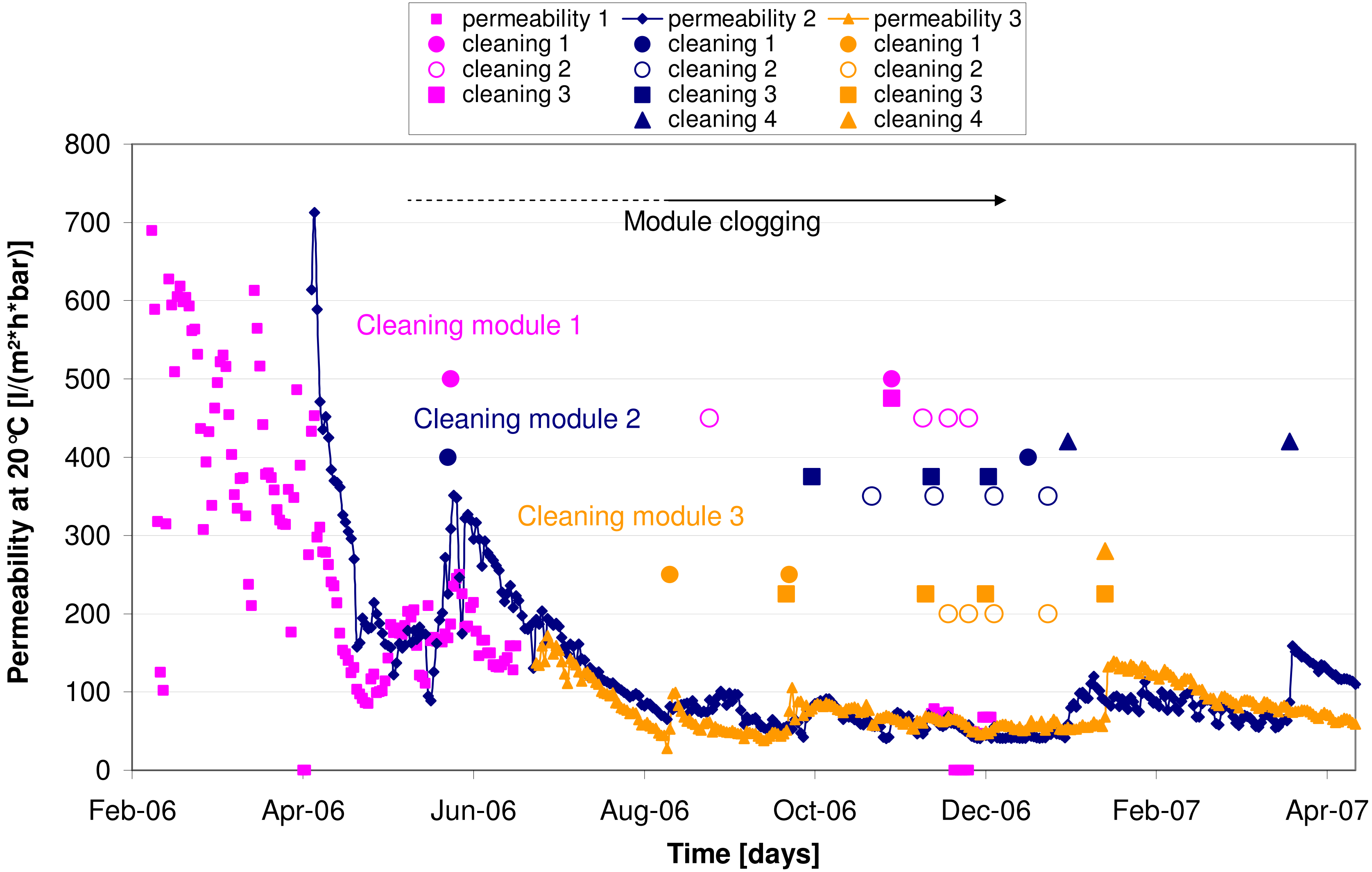


Figure 35 Filtration performance and module cleaning

VII.4. CHANGE OF MEMBRANE MODULES

Due to the unsatisfying filtration performance the primary modules were changed end of April 2007. From May 2007 forth two new modules of A3 are in operation alternately. Because of the high initial flux and permeability only one filter is running that causes air and energy reduction compared to the months before. Additionally a new operation strategy is implemented with a one month run followed by a chemical cleaning and a one month stand-by of each filter. The details of membrane and filtration parameter are given in Table 16. The initial clear water permeability of the two new installed modules was about 1500 L/h.m^2.bar.

The filtration performance of the first two months is shown in Figure 36. To be noted that the modules are still under investigation and a final evaluation cannot be provided yet.

Table 16 Details of membrane and operation parameter

Type	**-**	**Microfiltration / Flatsheet**
Material	**-**	**Polyvinylidenfluorid (PVDF)**
Pore diameter	**nm**	**200 (MF)**
Membrane area	**m^2**	**31.8 (per line / double deck)**
Specific air demand	**Nm^3/m^2/h**	**0.4 – 0.9**
TMP max	**mbar**	**300**
Operating instant flux	**L/m^2/h**	**9 – 20**
Filtration time	**sec**	**999**
Relaxation time	**sec**	**143**
Productivity rate	**%**	**~ 85**
Operating net flux	**L/m^2/h**	**8 – 17**

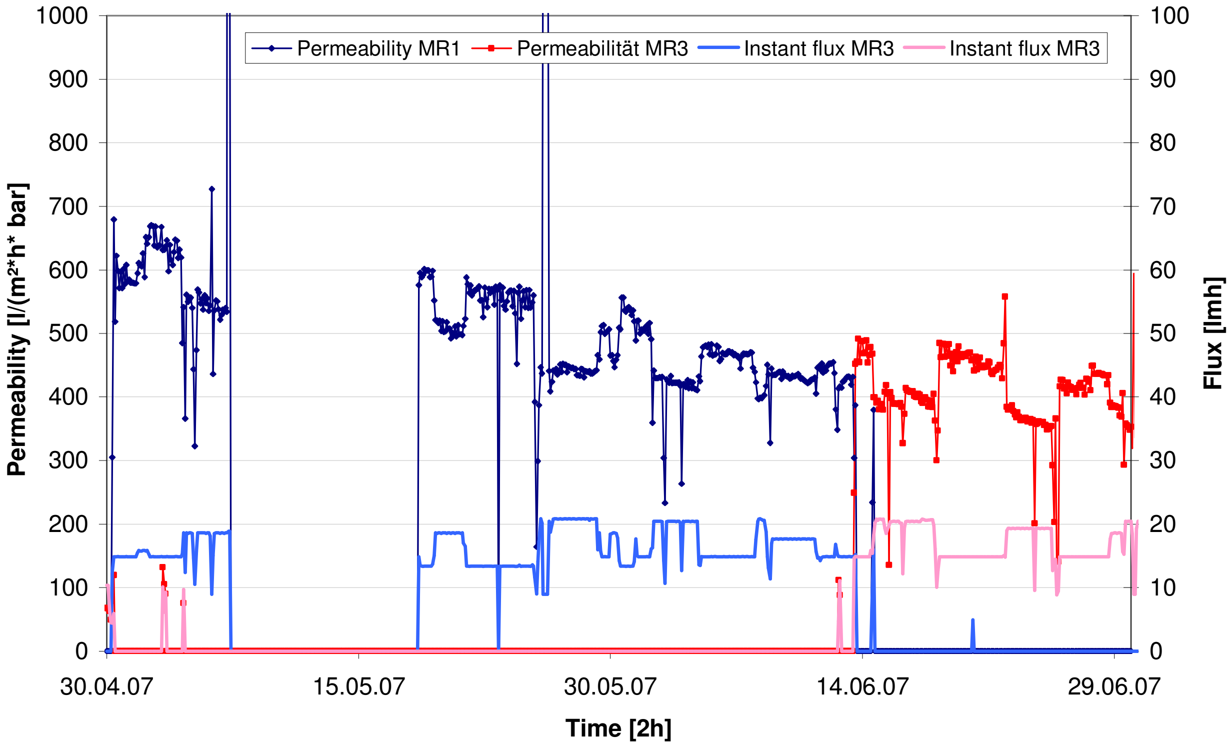


Figure 36 Filtration performance of new modules

VII.5. Fouling investigations

To get a better understanding of the fouling of the membranes several investigations were conducted. Since exocellular polymeric substances (EPS), composed of polysaccharides (PS) and proteins (PR), are considered to be a group of fouling substances, they were measured in the feed water, mixed liquor and effluent of the demonstration plant twice a week over the duration of the trials. Furthermore special investigations on EPS formation and degradation and on the fouling potential of EPS on flat sheet membranes were conducted.

EPS Concentration in the plants

Out of a large set of data the polysaccharides (PS) concentration in the demonstration plant from June 2006 to March 2007 is shown in Figure 37, as well as the proteins concentration (PR) in Figure 38. In the period from June to November the biggest influence on the PS concentration within the plant was the PS influent concentration. It comes also apparent, that the concentration in the plant is always clearly below the influent concentration and it can be concluded, that most PS are not build up in the plant but degraded. However, it has to be considered, that the measuring method is determining a sum parameter. A conclusion about the different fractions of PS can not be made. In November a sudden increase of the PS concentration was observed in the plant. At the same time the dosage of anti- foaming chemicals started. Afterwards it stays on a high level although the dosage of chemicals was stopped. This can be due to several reasons: colder temperatures, bad nitrification and higher biomass concentration.
The same sudden increase in November is also found for proteins in the plant and might be due to the same reasons. The protein influent concentration was high and changeful during the whole monitored period and most of the proteins were degraded in the plant. The effluent concentration was completely independent from the concentration in the

influent and plant. Most of the time the membrane retained all proteins and the effluent concentration was below the detection limit.

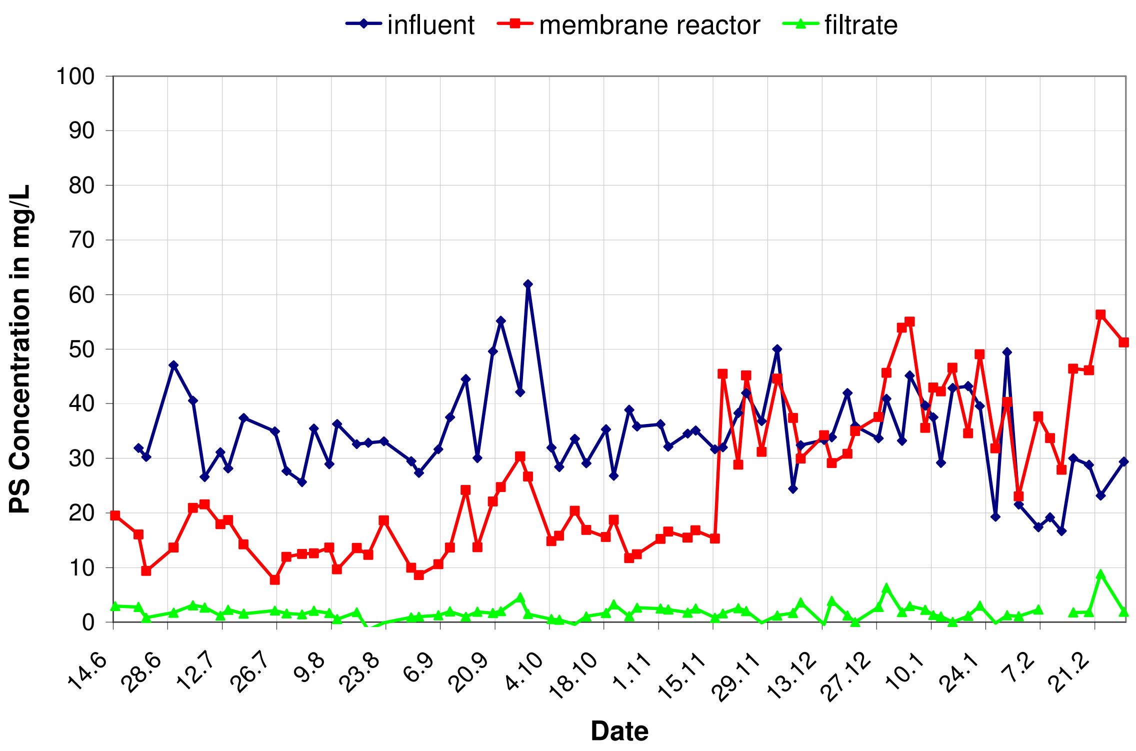


Figure 37 Polysaccharides concentration in the demonstration plant in 2006 and 2007

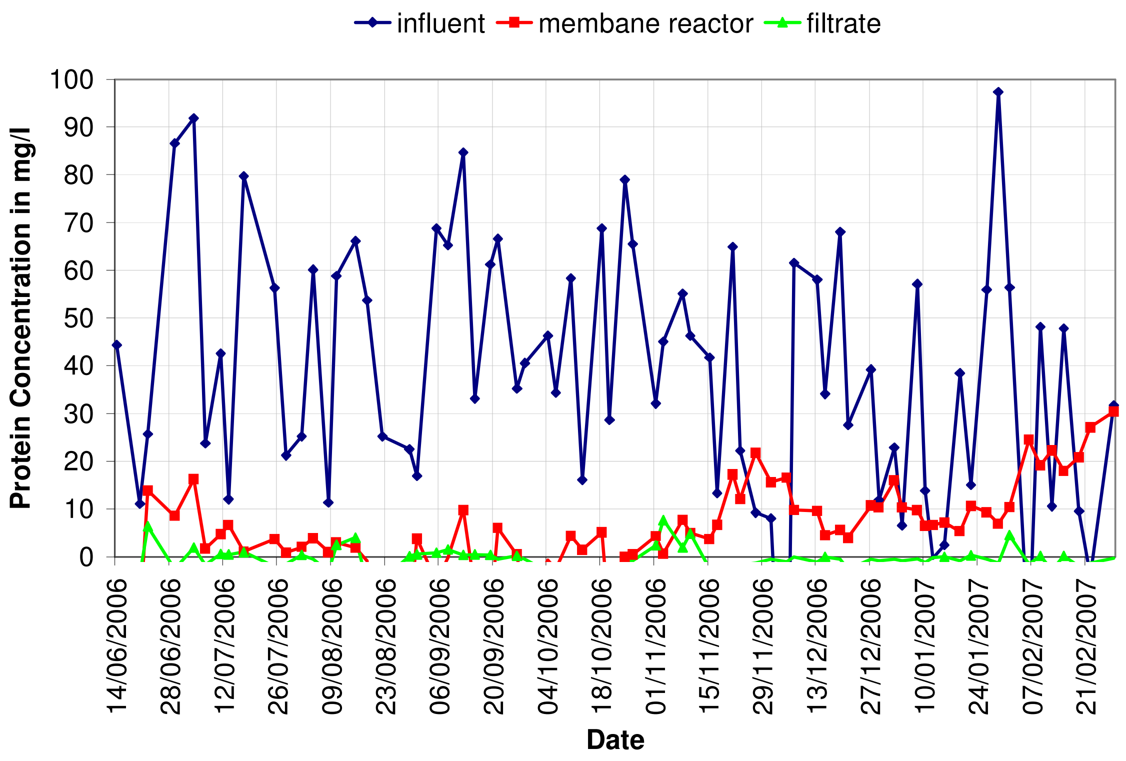


Figure 38 Proteins concentration in the demonstration plant in 2006 and 2007

Special EPS investigations
To examine closer different conditions on EPS formation in MBR plant a lab scale MBR was constructed and operated continuously with real wastewater. It was tested on low oxygen concentration, nitrate concentration, temperature and nitrification performance. It was found that low oxygen concentrations combined with low nitrate concentrations can lead to EPS formation and that sudden shifts in temperature will result in temporary higher EPS concentrations. The results for bad nitrification are presented in Figure 39. Due to uncompleted nitrification and the build up of nitrite and hence rising nitrous acid concentrations clearly increasing PS concentrations were observed. This could be a protection mechanism of the bacteria.

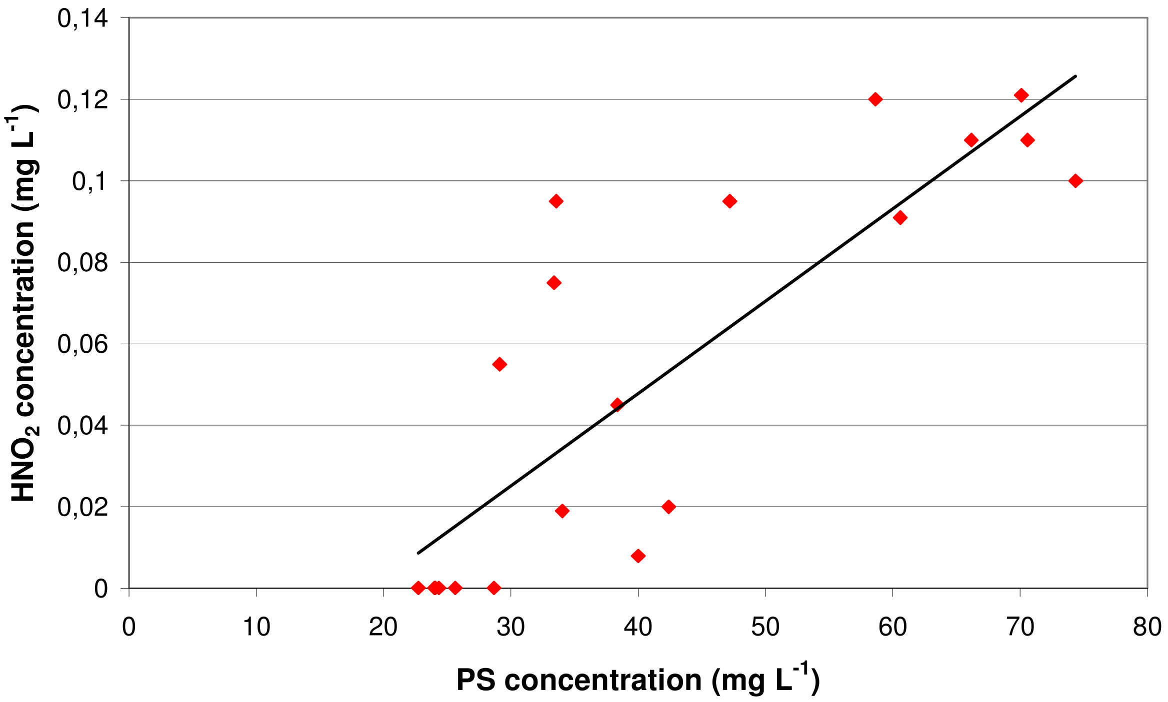


Figure 39 PS formation due to build up of nitrous acid

Relation to fouling
However a major outcome of the EPS studies is related to the fouling potential of EPS. It was demonstrated in the previous IMF project that the membrane fouling rate is proportional to the PS concentration. This could not be reproduced in this study. The data gathered in the pilot study (Figure 40) exemplary shows that neither the PS nor the PR concentrations had an influence on the fouling rate. This was also found in the demonstration plant and in the lab scale reactor. The main differences to the IMF project were the use of ultrafiltration flat sheet membranes operated below the critical flux without backwash instead of mircofiltration hollow fiber modules operated close the critical flux with backwash. A small filtration device was constructed and operated above the critical flux. Again no correlation of EPS and fouling rate was observed, hence the difference must be related to dissimilar pore size or operation of hollow fibers (backwash, moving membranes) and flat sheets (no backwash, static membranes), to the biological conditions (8-15d in IMF, 25-30d in present study), or to the membrane type (PVDF in IMF vs PES in present study). Furthermore, fouling might be related to just special fractions of EPS which was not determined with use measurement methods.

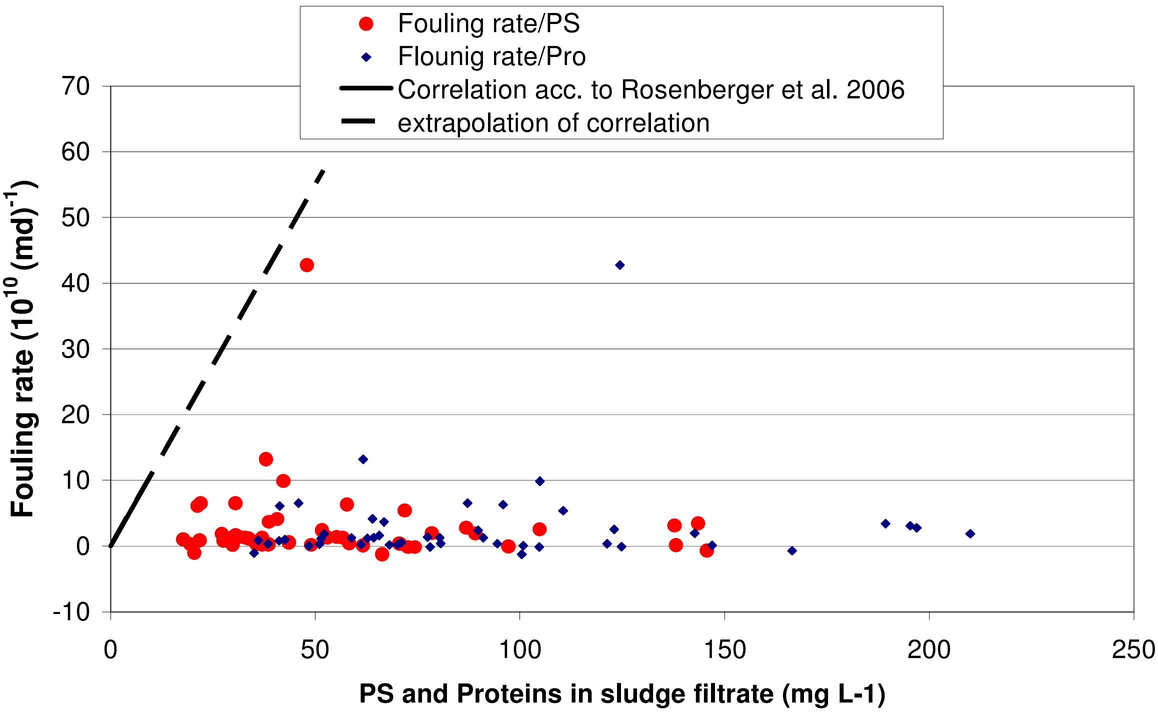


Figure 40 Fouling potential of polysaccharides (PS) and proteins (PR) in the pilot plant

VII.6. MEMBRANE ANALYSES AND FOULING DIAGNOSIS

Sampling protocol

As each module is composed of 6 independent filters of 6.25 m² each mounted in triple-deck, it was possible to extract and replace one or two of these filters in selected occasions to conduct an autopsy of these filters. The filters were always selected after mechanical / chemical cleaning and as showed in Figure 41, and few membranes were sampled and sent to Anjou Recherche for full analysis. In September 2006, the top left module of filter 3 was replaced and two membranes from the mid-module were sent to Anjou Recherche: one presenting strong “sludging” (accumulation of thicken dark sludge in the channel), and the other one with moderate sludging. In May 2007, the right top middle and bottom modules of filter 3 were replaced and 2 membranes from each module were sent (one from the middle and one from the side of the module). In June 2007 the left middle module of filter 2 was extracted and 3 membranes were sampled and sent to Anjou Recherche. To be noted that all extracted modules had been in operation since March 2006 and that the membranes were simply rinsed with tap water to remove excess sludge before being freighted to Anjou Recherche. Water sample from the plant (filtered raw water, sludge supernatant and permeate) have been also analysed to characterize the organic matter. The full report of these analyses can be found in Annex V.

Autopsy protocol

Membrane autopsy starts with a visual inspection and deposit description. After deposit extraction, several analyses were carried out:

- Measurement of mineral elements by Inducted Coupled plasma (ICP) for a semi-quantitative screening
- Measurement of TOC to evaluate the organic part of the deposit
- Organic matter characterization: analysis on LC-OCD system (Liquid Chromatography-Organic Carbon Detection)

- Scanning Electronic Microscopy (SEM) and EDAX

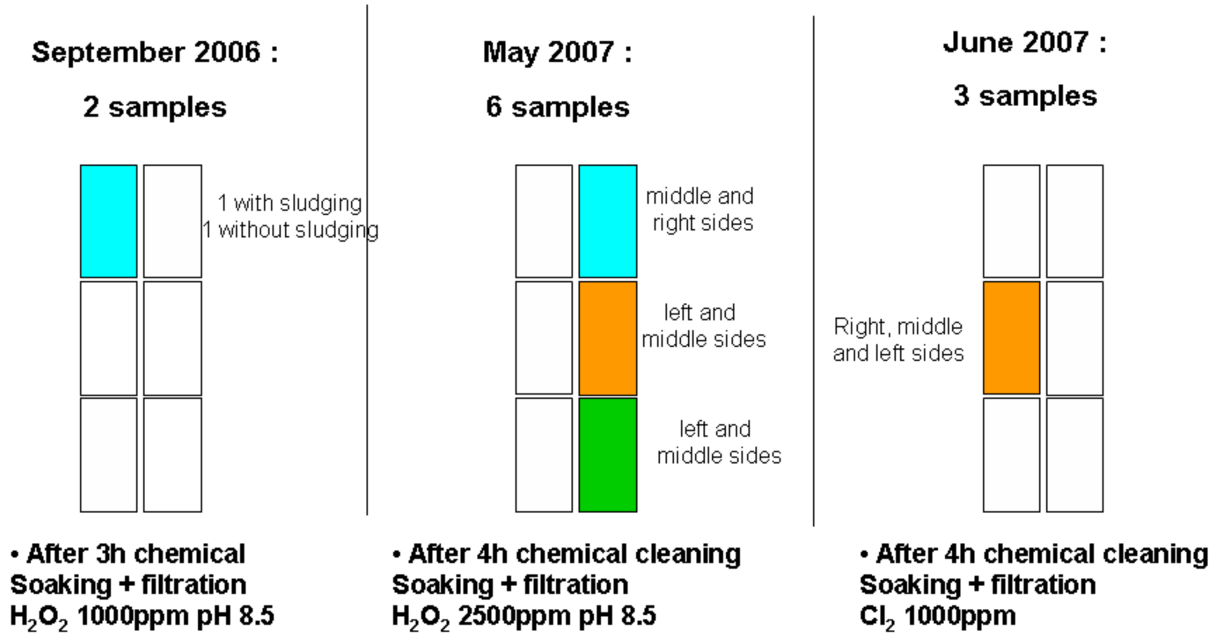


Figure 41 Extraction of filters for autopsy in module 2

Deposit composition

Deposit was very slight on all membranes sampled after cleaning with peroxide or chlorine and is composed by organic and inorganic matter. The organic part is greater than inorganic, and bacteria observed inside the membrane structure (despite complete retention of faecal bacteria, see IV.4), perhaps due to biofilm growth on substances released during phases anaerobic clogging.

After cleaning, residual organic deposit is 2µg/cm² minimum, and the main observations could be done:

- Organic deposit is higher in middle position whatever the side location
- In June 2007, organic accumulation observed by LC OCD is confirmed for the right side of the membrane after chlorine cleaning
- Humic substances represented 65-80% of DOC extracted from membrane surface with lower value monitored after NaOCl cleaning compared with H2O2 cleaning.

Main conclusions on mineral composition depending on samples are the following:

- September 2006: small amount of Iron
- Sulphur, calcium and sodium, not detected after 2 months of membrane operation, become major elements on following sampling membranes.
- Mineral elements concentrations are quite steady whatever the location or the module side.

Water analysis

The organic fractionation in the different water samples showed that humic substances represented about 50% of DOC in sludge supernatant, with a significant membrane retention rate. As humic substances were also showed to be the main constituent of the membrane deposit layer, they can be identified as main foulant of the UF membranes, but causing chemically irreversible fouling (permeability not recovered). This irreversible fouling is better recovered with NaOCl cleaning than with H2O2 cleaning.

VIII. COSTS EVALUATION

VIII.1. INVESTMENT AND OPERATIONAL COSTS FOR THE LOW-PRESSURE SEWER

Capital costs are evaluated on basis of 50 year period with straight-line depreciation and 6% interest rate.

Investment costs for the network are mainly caused by the following positions:

1. Households tanks with a pump and electricity displays
2. Pressure pipe on real estate
3. Pressure pipe on public ground and power supply
4. Street construction (done by the State)
5. Air flush system (not required in Margaretenhöhe)

In Berlin there is a fixed price for the connection to the sewer system (1.) but a variable price for pressure pipe (2). Each customer was able to choose the site for the installation on his parcel. Therefore costs per household depend on the pipe length on parcel and lie between 2,500 and 7,000€. In total the costs for the BWB are 390,000 € for all households (approx. 4,150€/house) and 484,000 € for 2,000m network (250 p.e.). The total investment costs in Margaretenhöhe sums up to **874,000€** (costs for street work estimated!). The **capital costs** up to this state can be given with

55,412 €/a (**222€/p.e./a**).

In Table 17 the operational costs for the network are given in detail. Maintenance of pumps is estimated with two replacements of the pumps per 50 years. Pumping energy is calculated with the real data. The transport of the wastewater to the MBR-plant is between 20m and 500m and in average the pumps need 27 sec/d/p.e. (=2.74 h/y/p.e.) to evacuate the wastewater. The calculation for the energy costs are very low with 0.91 €/y/p.e. and 0.04€/m³. The total operational costs for the network are estimated with

5,243 €/a (**21€/p.e./a**).

Total capital costs (investment + operational) are: **60,655 €/a (243€/p.e./a)**.

Table 17 Operational costs – network

Maintanance, Pumps			**Transport costs**		
	unit	**average**		**unit**	**average**
Replacement of the pumps	€/50 y	**50000**	**House Pump**	kW	**1.9**
Work force	€/50 y	**7000**	**Electricity price**	€/kWh	**0.18**
Maintenance	€/50 y	**22000**	**Pumps runtime**	h/(y*p.e.)	**2.74**
Total	€/50 y	**79000**	**Pumps energy**	kWh/(y*p.e.)	**5.13**
Total for one year	€/ y	**5008**	**Total for one year**	€/ y	**235**
Maintanance, Pumps	€/ (y* p.e.)	**20**	**Transport costs**	€ /(y*p.e.)	**0.94**
Maintanance per wastewater	€/m³	**0.91**	**Transport cost per wastewater**	€/m³	**0.04**

VIII.2. INVESTMENT AND OPERATION COSTS OF THE CONTAINER PLANT

Capital costs are evaluated on basis of 15 year period with straight-line depreciation and 6% interest rate. The tender process for the MBR-plant led to four valid offers. The corresponding investment costs are presented in Figure 42. A wide range for the specific membrane costs with 50 – 395 €/m² and for the specific net costs between 760 – 1,500 €/p.e. were offered. The company A, Martin Systems, proposed the most economic offer with investment costs of 190,000 € (net). The contract was signed with Martin Systems for the MBR-plant including some additional MSE-technique with 226,000 € (brutto). Infrastructure, fundament, fence, gardening, water supply, power, telephone, discharge pipe and air conditioning system added in total up to **381,263 €** (brutto), or **1,525€/p.e.** Not taken into account is an increase of the biological reactor which would be required due to the higher load. Because Margaretenhöhe is a remote suburb of Berlin, on one hand real estate was very cheap with only 6000 €/216 m², and the other hand energy and telecommunication was quiet expensive.
The total **capital costs** of the MBR-Plant can be given with

39,270 €/a (157€/p.e./a).

Evaluation concerning the scale up of a MBR plant with the same treatment requirements for 1000 p.e. on the same site it is expected that about 40% are fixed costs (construction and EMSR technique), and 60% is only affected by linear increase. A rough estimation with the same standard leads to 1,059,263 € or about 1,000 €/p.e.

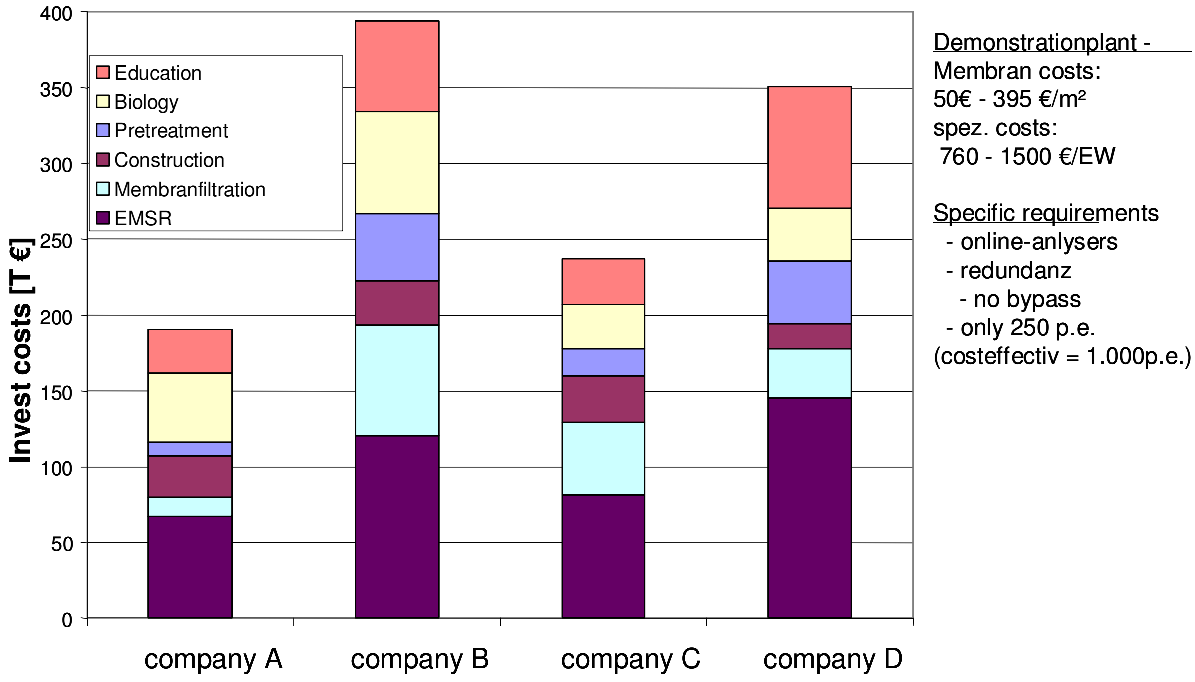


Figure 42 Cost comparison tender process (net)

The tender process required detailed information on operational costs such as membrane replacement, energy and maintenance. Every company had to estimate these costs for a low and high wastewater flow. The result showed that the operational costs are mainly fix costs. The summary of all costs for the company Martin Systems is given in Table 15 (for 12 m³/day). The specific costs for membrane replacement, energy and maintenance are 531 €, 2,264 € and 2,746 (3,277-531) €, respectively. Energy demand is strongly impacted by low wastewater capacity (mixers and pumps are not optimised in the used range) but very high effluent requirements. Pumps, Mixers and blowers have to be operated all day long without any difference in the wastewater flow. The estimation leads to a specific value of 77.5- 114 kWh/d or ~ 6 kWh/m³. Comparisons of other systems lie in the range of 4-7 kW/m³ for small WWTP (see Chapter I). The total energy consumption of the MBR-plant was measured in the first year of operation by a meter and the consumption for every aggregate was calculated (Figure 43). An optimization of mixers and change of filtration technology (less crossflow aeration) could lower the very high consumption from 128 to 100 kWh/d (w/o Lab container). The average energy demand is 6.6 kWh/m³ or 0.4 kWh/d/p.e. It is obvious that the electrical aggregates of small plants are far from energy efficient. Therefore the evaluation of operation costs was performed considering that a plant treating up to 18 m³ /d would have a similar energy requirement. Air conditioning was installed in October 2006 and therefore no energy requirement can be given yet.

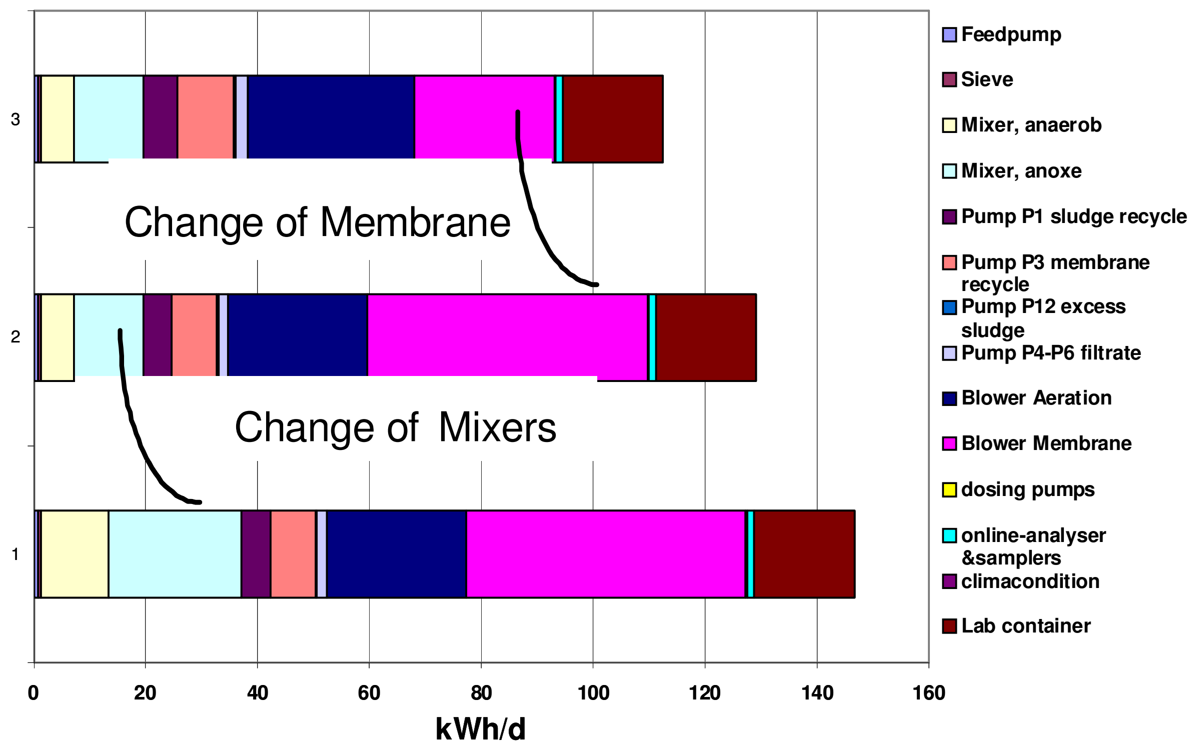


Figure 43 Energy consumption of the MBR plant

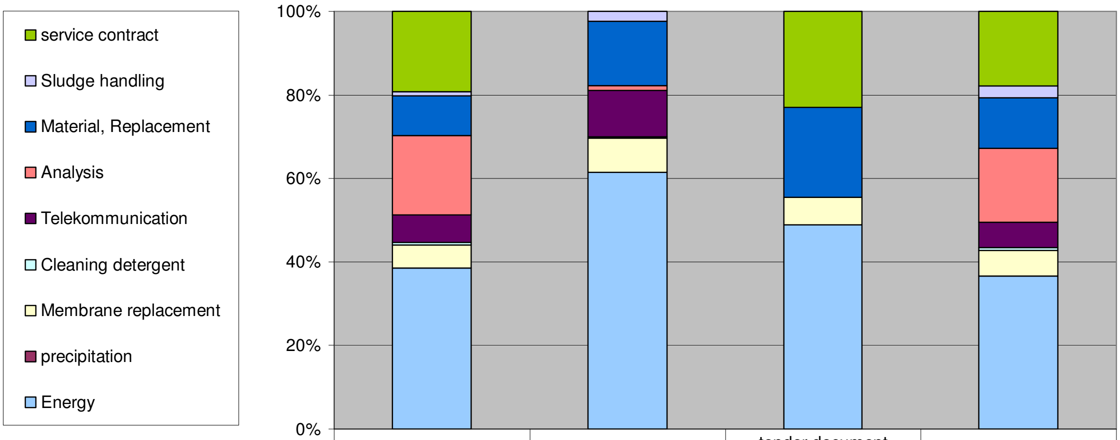
Table 18 Cost estimation for the Martin Systems MBR-Plant as given in the Tender Documents*

Flow= 12 m³/d	unit	Construction	Engineering	Membrane	Electro	instrumentation	PCL	Total
1.1 Total invest costs (w/o maintenance contract)	€	79.869,80	21.116,16	3.540,48	9.735,53	31.966,55	12.628,00	158.856,52
1.2 year	a	20,00	10,00	5,00	10,00	5,00	5,00	
1.3 Annuity		0,0872	0,1359	0,2374	0,1359	0,2374	0,2374	
2. Amortization	€/a	6.965	2.870	841	1.323	7.589	2.998	22.585
3.Repair/maintenance								
3.1. as % of Invest.	%	0,01	0,04	0,15	0,01	0,04	0,01	0,26
3.2. Repair/ Mainten-ance (1.1x 3.1)	€/a	399,35	844,65	531,07	97,36	1.278,66	126,28	3.277,37
4 Energy costs								
4.1. Price for Energy	€/kWh	0,08	0,08	0,08	0,08	0,08	0,08	0,48
4.2. Power consumption	kW/a	200,00	27.375,00	0,00	365,00	180,00	180,00	28.300,00
4.3. Energy costs	€/a	16,00	2.190,00	0,00	29,20	14,40	14,40	2.264,00
5 Operational costs (3.2+ 4.3)	€/a	415,35	3.034,65	531,07	531,07	1.293,06	140,68	5.945,88
6 Total costs (2+ 5)	€/a	7.380,35	5.904,65	1.371,58	1.371,58	8.881,92	3.138,57	28.048,65

* price for energy is too low for Berlin: 0.22 €/kWh

The operational costs for the MBR plant Margaretenhöhe are the real costs from the first 1.5 years of operation with a daily flow of 15 m³/d. It has to be emphasised that some costs are related to very intensive measurement requirements given by the Senate of Berlin (Annex II) and the demonstration status of the project. Many investigations are done on site and some typical start up problems due to the unique process and new team cannot be clearly estimated. The real and the expected optimised costs are given in Table 19. As a comparison the estimated costs from the Tender documents are shown for a flow of 12 m³/d. The interpolation for the 1000 p.e. MBR-Plant is a rough estimation but indicates the above mentioned contradiction of flow and a quality requirements to be still economic. The operational costs would be four times lower.

Table 19 Operational costs for the MBR-plant



	250 p.e.	optimised	tender document (table 15)	1000 p.e.
service contract	2922		2922	2922
Sludge handling	150	150		450
Material, Replacement	1446	1000	2746	2000
Analysis	2900	80	0	2900
Telekommunication	1000	720	0	1000
Cleaning detergent	100	25	0	120
Membrane replacement	840	530	841	1000
precipitation				
Energy	5861	4000	6226	6000

Margaretenhöhe [2006/2007] **∑15219** **∑6505** ∑ 16392

The operational costs of the MBR plant without optimisation are **15219 €/a or (61 €/p.e./a.)**

That means that the operational costs with 2.80 €/m³ - even without labour –, which exceeds the price of the wastewater tariff in Berlin 2.25 €/m³ but still is lower than the costs borne by each residents to truck the wastewater away (7€/m³).

The total costs (investment + operational) of the MBR plant are: **54489 €/a (217€/p.e./a)**

However, it is expected that in future the operation costs will be reduced at least by 50% due to optimization and saving in the field of energy, service contract and analysis as shown in Table 19.

VIII.3. INVESTMENT AND CAPITAL COSTS OF THE ENTIRE SCHEME

Total life costs (Invest + Operational costs):

- Network: (investment + operational): **60,655 €/a (243 €/p.e./a)**.
- MBR-plant (investment + operational): **54,489 €/a (217 €/p.e./a)**

115,144 €/a

The amortization of the MBR-plant with all peripheries is around 10 €/m³.

The process and cost evaluation will continue in 2008. A detailed cost evaluation will be done within the financial department of Berliner Wasserbetriebe when the project is completed.

IX. CONCLUSION, TECHNICAL RECOMMENDATIONS AND OUTLOOKS

ENREM process for enhanced biological nutrients removal in MBR

Following the identification and pilot assessment of a promising MBR process configuration for advanced biological nutrients removal (> 99% P-elimination and > 90% N-elimination), the ENREM demonstration project was proposed to perform a full-scale technical and evaluation of this process. A new sewer scheme featuring households storage tanks with grinding pumps and a low-pressure sewer was built in a peri-urban area of Berlin with 250 inhabitants (Margaretenhöhe) to serve one MBR unit built in one freight container and designed with the novel process. The novel process includes a buffer tank (required to flatten out hydraulic and pollution loads), one anaerobic zone (to foster enhanced biological phosphorus removal), two aerobic zones (for the nitrification), one short "deox zone" (to protect the downstream denitrification), two anoxic zones (for the denitrification) and 1 up to 3 membrane filtration reactors equipped with aerated submerged modules.

During the project preparation phase, the site was selected, the legal authorisations were collected, the plant specifications were finalised and the design and validation criteria were validated with a pilot study which was performed in a representative area of Berlin. The pilot investigation demonstrated that regular excess sludge extraction in storage in a sludge tank was the preferred sludge management strategy. The restricted public tender awarded the construction of the containerised plant to the German company Martin Systems.

Biological performances

With regards to the biological process, the salient outcomes of the 16 months of commissioning and operation from March 2006 up to June 2007 with the real domestic wastewater are:

- The selected design and operation criteria were proven to be adequate for a container installation (up to 2,000 p.e.)
- The buffer tank of up to 10h contact time was shown to be very efficient to flatten out over the day the highly profiled hydraulic and pollutant loadings, as well as the presence of the valve to disconnect the low-pressure network when the buffer tank is full (additional buffer capacity in the network). The buffer tank was however of no help to cope with the weekly variations (up to + 50% more throughflow in weekends or public holidays)
- Under the design range (nitrogen load 0.05-0.14 kgN/m^3/d, and TS up to 14g/L in biological reactor), 85%-tile phosphate and nitrate values as low as 0.05 mgP-PO_4/L and 10 mgN-NO_3/L can be achieved without using any chemical (carbon source or metal salt)
- Good treatment performances could be achieved with nitrogen loads up to 0.2 kgN/m^3/d, but this required dosing of supplementary carbon source in the anaerobic zone (acetate for example) or dimensioning of larger anoxic volumes
- As for conventional activated sludge systems, the enhanced biological phosphorus removal (EBPR) is a sensitive biological mechanism and may show some irregularity of performance in time: it is advised to back up the process with metal salt precipitation or perhaps to sustain the EBPR mechanism while dosing propionate (on-going tests, also useful for the denitrification)
- With the domestic wastewater of Berlin (high background of humic substances), about 2% of the incoming total nitrogen and 0.5-1% of the incoming total phosphorus relate to the soluble and refractory fraction: they will therefore be found in the MBR filtrate as organic-nitrogen or –phosphorus fraction. This was in Margeretenhöhe about 3 mgN/L and 0.1 mgP/L, in relation to the high influent concentration of 124 mgN/L and 22 mgP/L, and represent the ultimate value which can be achieved with an MBR process when all nitrate and phosphate is eliminated.

- As already seen during the pilot trials, denitrification rates of 0.9-1.5 gN/h/gVSS in the final anoxic zones were monitored. This is higher than endogenous denitrification (typically 0.2-0.6 gN/h/gVSS). This is accounted for by a mechanism of carbon storage in the anaerobic zone (but not glycogene or PHBs, the EBPR storage compounds). The anaerobic zone is therefore necessary for the establishment of good denitrification rates and the usage of relatively small anoxic volumes.
- Some preliminary tests on full-scale conventional WWTPs in Berlin indicate that a similar mechanism can be expected with conventional activated sludge process, however further investigations are required to validate a process combining both pre-denitrification and post-denitrification with an anaerobic zone.

Operational experience with container MBR plant

The following conclusions can be drawn with regards to the operational experience with the container plant constructed by Martin Systems:

- The design advantages identified during the tender process were confirmed (compactness and discretion, buried buffer and sludge tanks, separation wet/dry areas, access to biological reactors from the top of the container with side platforms, screening step included in container with gritting “washed on-line” and discharged in sludge tank, adequate level of redundancy etc).
- The operation of the drum-screen manufactured by Martin Systems was a good surprise as it operated well and did not require much maintenance.
- However some design features were not optimal and required few adaptations in the first year, such as the flush pipe of the gritting tank, the overall hydraulic head though the unit (at least 30 cm is advised), the sludge distribution channel. The 3 mixers and motors were replaced as they were too energy consuming, 2 diffuser plates were added per aerator system to improve the oxygenation capacity, and feet were set up on the membrane modules to enable better sludge hydraulic in the reactor.
- The control and data acquisition system is a crucial aspect of membrane processes and was not at the expected level of implementation: some control loops were not programmed as desired and many debugging, setting or optimisation were required in the first year which cost much care and time.
- The industrial PC installed with Microsoft appeared to be instable and sensitive to instabilities of the local power supply (regular computer interruptions). It was decided to program an automatic restart of PLC and PC and to install a power stabiliser.
- The industrial PC installed with Microsoft appeared to be instable and sensitive to instabilities of the local power supply (regular computer shut-down). It was decided to program an automatic shut-down and restart of PLC and PC in case of power failure in combination with installing a power stabiliser unit (about 15 min of autonomy).

Instrumentation and on-line analysers

It was decided to equip the demonstration plant with much more instrumentation and on-line analysers than what would be required for a commercial unit. The intention was to facilitate the evaluation but also to identify which devices would be helpful for routine operation. Most of the equipment was provided by the German company Endress + Hauser. The implementation and maintenance of these equipments were very time consuming and costly. At the time of the redaction, the following evaluation can be done on the different equipments:

- Oxygen sensors (1 per aerobic zone, about € 2,000 each): Quite unstable in the first months, they finally enabled to control the aeration level through a PID and are recommended for future installations. For good results, the probes have to hang free in the middle of the reactor and 50 cm below water level.
- Nitrate analyser (about € 5,000): Reliable, easy and low-cost maintenance and would enable on-line monitoring and control of a crucial parameter for the biology. Recommended even for container installations.

- Phosphate analyser (about € 15,000): threshold value of 0.01 mgP-PO_4/L and precision value of 0.05 mgP-PO_4/L, but require regular maintenance (change of piping + chemicals, about € 1,000 per year). Recommended only for plants above 5,000 p.e. or for control of metal salt or carbon addition when strict values are required at grab-sample level.
- Sludge concentration probe (about € 5,000, low maintenance): was intended to help remote plant monitoring and excess sludge control. However the signal appeared not being reliable even with weekly calibration. Probes from other suppliers may be appropriate.
- Turbidity probe (about € 5,000, low maintenance): was planned in permeate for monitoring of membrane integrity. It was however poorly mounted by Martin Systems (not enough water depth in front of the sensor) and the calibration of real absolute value was not possible. It was however monitored that the relative value reacted quickly when the water was slightly turbid. It is not recommended for commercial units, unless strict requirements of disinfection are specified (water reuse, bathing water guidelines). Alternatively, microbiological measurements at start-up and at regular interval may also provide evidence of the system integrity. A cartridge filter with pressure sensor (for hollow fiber systems, can be installed on backwash circuit as supplementary protection) may be also a good indicator of system integrity.
- Redox probe measured in anoxic zones (about € 2,000, low maintenance): Not recommended at this stage as the signal drifts much, rendering the interpretation or utilisation difficult.
- pH probe (about € 2,000, low maintenance): Not recommended for hard water, as the pH appeared to be stable without requirement of pH control. Weekly manual measurement may be sufficient.
- Electromagnetic air flow meters (about € 6,000 each, no maintenance): were built on the biology and membrane aeration lines. They were reliable and useful for the evaluation but may not be required for commercial applications, although the information is advantageous for diagnosis and trouble-shooting.
- Electromagnetic sludge flow meters (about € 6,000 each, no maintenance): were built on each sludge recirculation loop. Would be always recommended for setting and/or control of the sludge recirculation rates (crucial parameters for the biological performances)

Filtration performances

The following conclusions can be drawn with regards to the operation of the Martin Systems MBR filtration system:

- In a first stage, very strong clogging of the module channels were observed, which required time-consuming manual cleaning with a water jet. This was a consequence of the bad sludge distribution between the filtration reactors and a bad hydraulic in each reactor. After these problems were cured (from January 2007 onwards) no more sludge clogging was observed, therefore the triple-deck design of Martin Systems can be implemented in the applied conditions (flux of 6-11 L/h.m^2 and Specific Aeration Demand of 0.6 $Nm^3/h.m^2_{membrane}$) while keeping clear of sludge accumulation.
- However it was not possible to find a filtration and cleaning regime that could ensure sustainable filtration performances with the PES ultrafiltration modules. Many cleaning strategies were attempted with hydrogen peroxide and chlorine in weekly maintenance cleaning or curative cleanings when required. However only up to 20% of the initial permeability could be recovered, and the modules were often operated with a transmembrane pressure close to the maximum threshold (300 mbar). It was therefore decided to replace the modules with another technology.
- The analysis performed by Anjou Recherche indicate that the main fouling substances of the ultrafiltration membrane was the humic substance fraction: 65 to 80% of the organic deposit extracted from 11 sampled membranes after chemical cleaning, i.e. of the chemically irreversible cleaning, consisted of humic substances (lower value recorded after chlorine cleaning rather than hydrogen peroxide), and this fraction represented about 50% of the DOC in the supernatant. To the authors' knowledge, this is the first time

that humic substances were reported to be major fouling species in microfiltration / ultrafiltration applications.

- Since June 2007, two filtration modules supplied by the German company A3 Water Solutions have been operated with a flux range of 15–20 L/h.m^2 and Specific Aeration Demand of 0.6 Nm^3/h.m$^2_{membrane}$). The following operation and cleaning strategy is implemented: only one module is in operation, therefore halving the aeration needs compared with the previous technology, while the other one soaks in a chemical solution, with a switch each month. So far, the technology and filtration / cleaning mode has proven to provide sustainable operation: stable transmembrane pressure of about 100 mbar was monitored with high permeability value.

Cost evaluation

A first evaluation of the capital and operation cost was performed for the 250 p.e. scheme, based on the performance of the system with the A3 Water Solutions filtration technology. The total investment costs for the low-pressure sewer in Margaretenhöhe sums up to 874,000€, with annual operation costs of 5,243 €/a (21€/p.e./a). The total construction costs of the plant was 381,263 € (brutto), or 1,525 €/p.e. An extrapolation for a plant of 1,000 p.e. leads to capital costs of about 1 million €, therefore about 1,000 €/p.e. This is in the top range of conventional systems or usual MBR plants (see Figure 1) and can be explained by the high treatment quality of the process and the construction standard of Berliner Wasserbetriebe.

The main cost limitation relates to the energy demand, as the average energy demand was 6.6 kWh/m^3 or 0.4 kWh/d/p.e. (to be compared with 0.8-1 kWh/m^3, or about 0.1 kWh/d/p.e. for current municipal MBR above 10,000 p.e.). This high energy demand is not related to the process scheme, but rather to the scale: it is obvious that the electrical aggregates of small plants are far from energy efficient. It is expected that the energy demand would drop already down to 3 kWh/m^3 for a 1,000 p.e. installation. After the energy, other main operation costs relate to analyses (due to stringent discharge permit, to be renegotiated with the Water Authority) and service contracts (due to numerous electromechanical adaptations in the first months of operation) followed by material replacement and telecommunication. Membrane replacement and chemicals play only a minor role in the overall operation costs. Realistic operation costs, assuming a reduction of analyses costs and service contracts, are 6505 €/a or 26 €/p.e./a (and less for larger systems).

To summarize, the total life cost (Invest + Operational costs) of the system was in the first year:

▪ Network: (investment + operational):	**60,655 €/a (243 €/p.e./a)**
▪ MBR-plant (investment + operational):	**54,489 €/a (217 €/p.e./a)**
	115,144 €/a

Outlook and perspectives

Berliner Wasserbetriebe and the Berlin Centre of Competence for Water have decided to extend the investigations up to the end of 2008, with the following objectives:

- Assess on long terms the filtration performances of the A3 Water Solutions technology, and of the novel cleaning strategy, optimising when possible the energy costs
- Compare performance, capital and operation costs with a commercial MBR system designed for nitrification only (a unit treated 50% of the water flow in the demonstration plant will be operated over 12 months)
- Identify technological solutions and costs for long term operation, including plant upgrade to treat the 30% of wastewater currently trucked away and future plant increase
- Prepare transfer to operation team of Berliner Wasserbetriebe (prepare operation guideline for safe operation at lower labour)
- Further investigate the carbon storage compound(s) responsible for the post-denitrification in the process

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Self-organised dissemination events

11 january 2005 **Local information meeting** with inhabitants of Margaretenhöhe

2 June 2005 **5th KWB Berlin Water Workshop** "Membrane technologies for decentral and semi-central wastewater treatment" (about 60 local and national water business professionals present)

19 June 2006 “**Day of opening doors**” (for local residents) + **official inauguration** of the plant in presence of representatives of partners, local authorities, local scientific community and journalists.

6 June 2007 **Final Project Workshop & Technical Tour**s “Membrane-based concepts for decentralised municipal wastewater treatment“ (about 100 national and international attendees and 40 site visitors). Organised in parallel to the 2nd IWA National Young Water Professionals Conference, Germany (see www.iwa.kompetenz-wasser.de)

XII. LIST OF ANNEXES

Annex I Extract of report on site selection (German)
Annex II Extract of discharge permit from Water Authority (German)
Annex III ENREM process flow scheme
Annex IV Evaluation of impact on local environment (German)
Annex V Report on membrane analysis and fouling diagnosis (Anjou Recherche)

Annex I Extract of report on site selection (German)

Among the areas of Berlin that are to date not connected yet to the central sewer system, or not in planning to be connected in the next years, the data of 19 of them were carefully gathered and checked in order to pre-select those that could be relevant as demonstration site for the ENREM project. The following criteria were used for the pre-selection:

- Inhabitants: > 200 pe, < 1,000 pe (representative and practical size for demonstration)
- Distance to central sewer: > 400 m (below would not be economical)
- Distance to discharge water bodies (as soil infiltration was not considered): < 1,000 m
- Population density: > 10 pe/ha (below would not be economical)

Area name	**Council**	**Inhabitants** pe	**Area size** ha	**Population density** pe/ha	**Distance to central sewer in Berlin** m	**Distance to discharge waterbody** m
Sites coping with pre-selection criteria						
Margaretenhöhe	Hohenschönhausen	250	14.3	17.5	1.000	200
Stadtrandsiedlung Blankenfelde	Pankow	670	52.9	12.6	1.000	700
Gatow-Siedlung Habichtswald	Spandau	260	13.0	20.0	1560	800
Steinstücken	Zehlendorf	319	12.6	25.3	930	800
Sites coping with pre-selection criteria except 'inhabitants < 1,000 pe'						
Blankenburg Altsiedlung	Weissensee	3,500	173.0	20.2	400 (river to cross)	On site
Sites too small (< 200 pe)						
Am Stener Berg	Pankow	60	6.1	9.8	530	2,300
Kladow - Gutstrasse	Spandau	100	1.7	58.7	0	On site
Schmöckwitz Werder	Köpenick	90	20.2	4.5	3,000	On site
Schmöckwitz Schwarzer Weg	Köpenick	12	5.3	2.3	515	On site
Rahnsdorf-Süd	Köpenick	70	23.5	3.0	430	On site
Sites too close to central sewer system (< 400 m)						
Buchholz-West II	Pankow	900	37.9	23.7	0[3]	500
Schönholz	Pankow	360	8.2	19.3	0[1]	1,000
Mahlsdorf-Nord IV	Marzahn - Hellendorf	3,500	217.2	16.1	0[1]	1,500
Heinersdorf Altsiedlung	Pankow	737	38.2	19.3	30[1]	1,400
Karow Süd	Pankow	1,130	53.8	21.0	110	800
Neu Venedig	Köpenick	214	35.3	6.0	130	214
Buchholz-Nord	Pankow	550	41.6	13.2	270 (Berlin) 70 (Brandbrg)	200
Sites too far away from discharge water body (> 1,000m)						
Wartenberg	Lichtenberg	950	49.4	19.2	820 (Berlin) 430 (Brandbrg)	No possibility
Karow Ost	Pankow	400	18,3	21,8	1,400	1,800

[3] Connection technically difficult

This qualitative analysis showed that only the four areas Margaretenhöhe, Stadtrandsiedlung Blankenfelde, Gatow-Siedlung Habichtswald and Steinstücken were the most relevant as demonstration site. A finer quantative analysis was then undertaken to pick up the best site to host the ENREM demonstration project.

A quantitative cost analysis was undertaken with the four pre-selected sites identified. A full-cost model developed by the Berliner Wasserbetriebe to compare different alternatives for sanitation of unsewered areas was used. This model enables to calculate the Net Present Value (NPV) of various technical scenarios (+/- 20%), taking into account the investition costs and the yearly operation costs over a pay-back duration of 50 years with a interest rate of 3%. For each of the four sites, nine sanitation scenarios, resulting from cross-combination of these alternatives for the sewer or the treatment plant, were analysed:

- Gravity sewer with pumping station / low-pressure sewer without pumping station / low-pressure sewer with pumping station (required when sewer length superior than 2,000m)
- Semi-central MBR plant / existing central WWTP with fix costs (the capital costs that would theoretically be required to treat the additional flow amount) / existing central WWTP without fix costs (as we can consider that no further construction or modification would be required to treat the additional flow amount)

Vacuum sewer was not considered, as previous analyses showed that it would not be competitive. The alternative of decentralised treatment with households treatment units (for example MBR or reed beds) was also not explored, as this concept is not supported by the Senate of Berlin as an option to upgrade the remaining unsewered areas.

The following table shows for each site the most economical options with the MBR technology or with connection to the central WWTP (with / without fix costs), and according to the corresponding analysis criteria:

Sanitation scheme	Capital costs (k€)	50y NPV (k€)	Yearly cost (k€)	Spec. ann. cost (€/pe)
Margaretenhöhe (250 pe)				
Pressure sewer + WWTP without fix costs	2,014	3,597	139.8	699
Pressure sewer + MBR	2,100	3,655	142.1	710 (+ 1.5%)
Pressure sewer + WWTP with fix costs	2,014	4,464	173.5	867 (+ 24%)
Stadtrandsiedlung Blankenfelde (670 pe)				
Gravity sewer with pumping station + WWTP without fix costs	6,417	8,289	322.2	481
Gravity sewer with pumping station + MBR	6,974	9,020	350.6	523 (+9%)
Gravity sewer with pumping station + WWTP with fix costs	6,417	11,194	435.1	649 (+35%)
Gatow-Siedlung Habichtswald (260 pe)				
Pressure sewer + WWTP without fix costs	2,550	4,595	178.6	687
Pressure sewer + MBR	2,699	4,714	183.2	705 (+2.6%)
Pressure sewer + WWTP with fix costs	2,550	5,722	222.4	855 (+24%)
Steinstücken (319 pe)				
Gravity sewer with pumping station + WWTP without fix costs	1,984	2,887	112.5	353
Gravity sewer with pumping station + MBR	2,311	3,338	129.7	407 (+15%)
Gravity sewer with pumping station + WWTP with fix costs	1,984	4,270	166.3	521 (+48%)

The following observations can be drawn from this analysis

- The decentral MBR solution is slightly more expensive than the central solution *without fix costs*, but it remains within the precision of the evaluation (+/- 20%) plus it is always more economical than the central solution *with fix costs*.
- The superior quality of MBR treatment is not taken into consideration in this economical analysis: for an equal net present value, the environmental performances of the MBR solution will be greater, with also superior potential of local water reuse.

Following this economical analysis, Margaretenhöhe was selected as demonstration site for the ENREM project. Habichtswald was also attractive given similar economical results with a slightly bigger site; however the long distance to the receiving water body (800m into an intermittent trench) oriented the choice towards the site of Margaretenhöhe. The ENREM project will enable to refine the estimations of capital and operation costs of the MBR technology, and therefore precise the economical interest of the solution for these sites and others.

Annex II Extract of discharge permit from Water Authority (German)

1

Senatsverwaltung für Stadtentwicklung
Planen Bauen Wohnen UmweltVerkehr

Senatsverwaltung für Stadtentwicklung
D - 10702 Berlin VIII D 312

Berliner Wasserbetriebe
z.Hd. Fr. Gnirrs

10864 Berlin

Bearbeiter Herr Schmidt
Zeichen VIII D 312
6793/04-Margaretengr.-K-1

Dienstgebäude: Ÿ
Brückenstraße 6
10179 Berlin-Mitte
Zimmer 3.023

Telefon (030) 9025 – 2080
Fax (030) 9025 – 2983
intern (925)

Datum 16.06.2005

Wasserbehördliche Erlaubnis zur Einleitung des gereinigten häuslichen Abwassers aus der Siedlung Margaretenhöhe in Berlin-Hohenschönhausen über eine semizentrale Abwasserbehandlungsanlage in den Margaretengraben bzw. in das vorgelagerte Luch einschließlich Genehmigung zum Bau und Betrieb der Kläranlage gemäß § 38 Abs. 1 BWG* sowie zur Errichtung eines Einleitungsbauwerks und einer Sohlschwelle im Margaretengraben

Anlagen: Fundstellenverzeichnis
1 Satz Fachstellungnahmen
1 Gebührenbescheid

Sehr geehrte Damen und Herren,

unter Bezugnahme auf Ihren Antrag vom 03.12.2004 erteile ich Ihnen unter Zugrundelegung der eingereichten Unterlagen gemäß §§ 2, 3, 5 und 7 WHG* in Verbindung mit §§ 14, 16 und 38 Abs. 1 Nr. 2 BWG* sowie § 3 AbwAGBln* unter dem Vorbehalt des jederzeitigen Widerrufs die Erlaubnis, biologisch gereinigtes und entkeimtes häusliches Abwasser aus der o.g. Abwasserbehandlungsanlage in den Margaretengraben bzw. in das vorgelagerte Luch einzuleiten. Gleichzeitig wird die Genehmigung zum Bau und Betrieb der Kläranlage gemäß den eingereichten Antragsunterlagen sowie zur Errichtung eines Einleitungsbauwerks und einer Sohlschwelle im Margaretengraben unter Beachtung der korrigierten Planunterlagen erteilt.

Sprechzeiten
nach telefonischer Vereinbarung

E-Mail
hans-juergen@senstadt.verwalt-berlin.de

Internet
www.stadtentwicklung.berlin.de

Fahrverbindungen:
Ÿ 2 Märkisches Museum
Ÿ 8 Jannowitzbrücke, Heinrich-Heine-Str.
ÿ 3, 5, 6, 7, 75, 9 Jannowitzbrücke
‡ 147, 265 Märkisches Museum

Zahlungen bitte bargeldlos an die Landeshauptkasse Berlin:

Postbank Berlin	Kto.Nr. 58-100	BLZ 100 100 10
Berliner Sparkasse	Kto.Nr. 0 990 007 600	BLZ 100 500 00
Berliner Bank	Kto.Nr. 9-919 260 800	BLZ 100 200 00
Landeszentralbank Berlin	Kto.Nr. 10 001 520	BLZ 100 000 00

Nach erneuter Diskussion der Erlaubnisvorgaben in Auswertung der Besprechung vom 11.04.2005 bzw. der Absprachen anlässlich des Ortstermins vom 18.04.2005 setze ich folgende Ableitungsmengen, Grenz- und Überwachungswerte fest:

1. Abwassermenge

1.1	max. Zufluss Q_{max}	2,4	m^3/h
1.2	Tageszufluss Q_d	12 - 24	m^3/d
1.3	Jahresmenge	8.760	m^3/a

2. In dem einzuleitenden Abwasser dürfen die folgenden Konzentrationshöchstwerte gemäß WHG nicht überschritten werden:

2.1	abfiltrierbare Stoffe	5,0 mg/l	qualifiz. Stichprobe
2.2	Chemischer Sauerstoffbedarf (CSB)	100,0 mg/l	„
2.3	Biochemischer Sauerstoffbedarf (BSB_5) in fünf Tagen	10,0 mg/l	„
2.4	pH-Wert	6,5-8,0	„
2.5	AOX	120,0 µg/l	„
2.6	Phosphor, gesamt (P_T)	0,5 mg/l	„
2.7	Stickstoff, anorgan.	25,0 mg/l	„
2.8	Ammonium-Stickstoff	5,0 mg/	„

3. Die Überwachungswerte gemäß AbwAG werden wie folgt festgelegt:

3.1	abfiltrierbare Stoffe	1,0 mg/l	qualifiz. Stichprobe
3.2	Chemischer Sauerstoffbedarf (CSB)	50,0 mg/l	„

3.3	Biochemischer Sauerstoffbedarf (BSB_5) in fünf Tagen	< 5,0 mg/l	qualifiz. Stichprobe
3.4	Phosphor, gesamt (P_T)	0,1 mg/l	„
3.5	Stickstoff, anorganisch	10,0 mg/l	„
3.6	Ammonium-Stickstoff	1,0 mg/l	„
3.7	AOX	80,0 µg/l	„
3.8	Quecksilber	0,8 µg/l	„
3.9	Cadmium	1,0 µg/l	„
3.10	Blei	30,0 µg/l	„
3.11	Chrom	30,0 µg/l	„
3.12	Nickel	30,0 µg/l	„
3.13	Kupfer	50,0 µg/l	„

Ist ein Überwachungswert nach dem Ergebnis einer Überprüfung im Rahmen der behördlichen Überwachung nicht eingehalten, so gilt er dennoch als eingehalten, wenn die Ergebnisse dieser und der vier vorausgegangenen behördlichen Überprüfungen in vier Fällen den jeweils maßgebenden Wert nicht überschreiten und kein Ergebnis den Wert um mehr als 100 % übersteigt. Überprüfungen, die länger als drei Jahre zurückliegen, bleiben unberücksichtigt.

4. Zusatzregelung zur Einhaltung der bakteriologischen Anforderungen

Escherichia coli	250 /100 ml	Stichprobe
Enterokokken:	100 /100 ml	"

5. Probenahmeort

Die behördliche Probenahme erfolgt am Ablauf des Anlagencontainers.

6. Nebenbestimmungen:

6.1 Allgemeine Auflagen

1. Diese wasserbehördliche Genehmigung gilt nur für denjenigen, für den sie ausgestellt ist. Jeder Eigentums- und Besitzwechsel des Grundstücks, auf dem die Benutzung erfolgt, ist der Senatsverwaltung für Stadtentwicklung - Wasserbehörde - mitzuteilen.
2. Die wasserbehördliche Genehmigung gilt nur für Anlagen, die in den geprüften Unterlagen dargestellt sind. Änderungen der Anlagen sind der Wasserbehörde anzuzeigen. Bei wesentlichen Änderungen ist eine neue Genehmigung zu beantragen.
3. Für die Standfestigkeit und Betriebssicherheit der Anlagen sowie für die Verkehrssicherung ist der Genehmigungsinhaber verantwortlich.
4. Die Anlagen bedürfen nach § 70 Abs. 1 BWG* der Bauabnahme. Die Abnahme ist schriftlich zu beantragen. Vor der Abnahme dürfen die Anlagen nicht in Benutzung genommen werden.
5. Die Anlagen sind in einem guten baulichen Zustand zu erhalten.
6. Die wasserbehördliche Genehmigung erlischt, wenn mit der Herstellung der Anlagen nicht innerhalb eines Jahres nach der Erteilung der wasserbehördlichen Genehmigung begonnen wird. Diese Frist kann auf Antrag verlängert werden.

6.2 Besondere Auflagen

1. Das Wasser soll durch den Einbau einer Sohlschwelle unmittelbar unterhalb des Einleitungsbauwerks im Luch zurückgehalten werden. Die Überlaufhöhe ist im Auftrag des Bezirksamts Lichtenberg durch ein hydrologisches Gutachten vorgegeben worden. Die Bauausführung erfolgt durch die Gewässerunterhaltung SenStadt XOW; die anfallenden Kosten müssen durch die Berliner Wasserbetriebe übernommen werden.

2. Die Gewässerunterhaltung XOW übernimmt die Beräumung der Gewässersohle sowie die Spülung des Durchlasses.

3. Die Berliner Wasserbetriebe errichten das Auslaufbauwerk und die Ablaufleitung DN 150 gemäß der korrigierten Planvorlage.

6.3 Analysen- und Messumfang der qualifizierten Eigenkontrolle

Der Erlaubnisinhaber hat als Mindestumfang im Rahmen der qualifizierten Eigenkontrolle **während der zweijährigen Einfahrphase** nachfolgend aufgelistete Abwasseruntersuchungen vorzunehmen und deren Ergebnisse der Wasserbehörde mitzuteilen; nach deren Ablauf werden die Beprobungsintervalle erneut festgelegt. Dabei kann die Analytik im Labor der Berliner Wasserbetriebe durchgeführt werden; Voraussetzung für die qualifizierte Eigenkontrolle ist der Nachweis einer gültigen Akkreditierung.

6.4 Analysenumfang am Kläranlagenablauf bzw. Ablauf der Belebung

6.4.1	abfiltrierbare Stoffe	2 x monatlich	24 h-Mischprobe
6.4.2	Chemischer Sauerstoffbedarf (CSB)	„	„
6.4.3	Biochemischer Sauerstoffbedarf (BSB_5) in fünf Tagen	„	„
6.4.4	Phosphor, gesamt (P_T)	„	„
6.4.5	Ammonium-Stickstoff (NH_4-N)	„	„
6.4.6	Nitrat	„	„
6.4.7	Nitrit	„	„
6.4.8	Organischer Stickstoff	„	„
6.4.9	Adsorbierbare organ. Halogene (AOX)	„	Stichprobe
6.4.10	Escherichia coli	„	“
6.4.11	Enterokokken	„	„
6.4.12	Quecksilber	6 x jährlich	24 h-Mischprobe
6.4.13	Cadmium	„	„
6.4.14	Chrom	„	„

6.4.15 Nickel	6 x jährlich	24 h-Mischprobe
6.4.16 Blei	„	„
6.4.17 Kupfer	„	„

6.5 Analyseverfahren

Im Rahmen der qualifizierten Eigenkontrolle sind die in der jeweils gültigen Fassung der AbwV* aufgelisteten Analyseverfahren anzuwenden. Besondere Auflagen im Hinblick auf die Analyse- und Messverfahren werden bei den kontinuierlichen (online) Messungen nicht vorgegeben.

6.6 Probenahmerhythmus

Der Beprobungswochentag für die Abwasseruntersuchung am Anlagenablauf soll nach jedem Probenahmetermin um jeweils einen Tag verschoben werden.

6.7 Berichtswesen

Während der Einfahrphase hat der Erlaubnisinhaber der Wasserbehörde halbjährlich die Ergebnisse aus der Eigenkontrolle vom Kläranlagenablauf sowie einen Jahresbericht für das zurückliegende Jahr einzureichen.

Der Jahresbericht muss mindestens beinhalten:

- Abwassermenge insgesamt
- Abwassermenge im Jahresmittel
- Jahresschmutzwassermenge Trockenwetter
- Ablaufkonzentrationen und -frachten im Jahresmittel als mg/l und kg/d
- Aufgetretene Betriebsstörungen und sonstige Vorkommnisse

Die vom Erlaubnisinhaber ermittelten Untersuchungsergebnisse sind mindestens 3 Jahre aufzubewahren.

6.8 Einfahrphase und Befristung

Dem Anlagenbetreiber wird nach Fertigstellung der biologischen Abwasserbehandlungsanlage eine zweijährige Erprobungszeit eingeräumt. Aus diesem Grund ist diese Erlaubnis bis zum 31.12.2007 befristet. Nach Ablauf dieser Frist und Auswertung der Betriebsergebnisse wird dieser Bescheid überarbeitet.

Sollte im Dauerbetrieb der Abwasserbehandlungsanlage - im Widerspruch zu den positiven Ergebnissen des Probelaufs im Klärwerk Ruhleben - die Reinigungsleistung des biologischen Reaktors bzw. des Membranfilters bei normalen Betriebsbedingungen nicht stabil gewährleistet werden können, sind in Abstimmung mit der Senatsverwaltung für Stadtentwicklung alternative Maßnahmen zur Einhaltung der beantragten Ableitungsmodalitäten einzuleiten.

6.9 Vorbehalt

Soweit sich die Anforderungen an die Klarwasserqualität verändern, behalten wir uns die Modifizierung der Erlaubnis bzw. die Änderung von wasserrechtlichen Begrenzungen, Auflagen und Nebenbestimmungen vor.

Begründung

Das Siedlungsgebiet Margaretenhöhe (ca. 250 Einwohner) wird über eine Druckentwässerung erschlossen (ein entsprechender Antrag vom 24.01.2005 zur Errichtung der o.g. Kanalisation wurde inzwischen genehmigt) und das dort anfallende Abwasser wird zu 100% durch eine Membranbelebungsanlage (MBR-Anlage) gereinigt. Das Ziel des ENREM Demonstrationsprojekts besteht in der Überführung einer bisher nur in kleintechnischem Maßstab betriebenen Versuchsanlage in eine im Dauerbetrieb stabil arbeitende Kläranlage im Betriebsmaßstab sowie in der Kostenermittlung für dieses innovative Verfahren. Das Abwasser ist für ein dezentrales Gebiet charakteristisch, d.h. es enthält weder industrielles Abwasser noch Regenwasser.

Dieses Demonstrationsprojekt schließt an ein erfolgreiches dreijähriges Forschungsprojekt der Berliner Wasserbetriebe im Klärwerk Ruhleben an, wo ein innovatives Membranverfahren zur weitergehenden Nährstoff- und Keimentfernung aus kommunalem Abwasser im Pilotmaßstab entwickelt wurde. Dieses Verfahren soll erstmals eine vermehrte biologische Phosphorentfernung und eine Post-Denitrifikation im Membranbelebungsverfahren (Abbildung 1) kombinieren. Zusätzlich zur vollständigen Desinfektion durch Mikrofiltrationsmembranen lässt sich durch die o.g. Technologie eine verbesserte Entfernung von Nähr- und Schadstoffen erzielen. Die Eliminationsraten betragen ca. 99 % für TP sowie ca. 95% für TN; die Ablaufwerte sollen somit bei <50µg P/l und <5 mg N/l. Die beschriebene Technik kann als Alternative für Gebiete angesehen werden, in denen die Anbindung an eine zentrale Abwasserreinigung nicht wirtschaftlich ist und sehr hohe Anforderungen an die Ablaufqualität gestellt werden (Badegewässerqualität bzw. strenge Gewässerschutzauflagen im Rahmen der Umsetzung der WRRL der EU).

Nachfolgend aufgelistete Messwerte bestätigen die sehr hohe Reinigungsleistung der Versuchsanlage im Klärwerk Ruhleben:

Tabelle 1: Ablaufergebnisse mit der MBR-Pilotanlage

		50%tile	90%tile	KW-Ruhleben Überwachungswerte
Probenart		24h Mischprobe	24h Mischprobe	qual. Stichprobe
Abfilt. St	mg/l	<1	<1	20
CSB	mg/l	< 40	< 60	60
BSB5	mg/l	< 2	< 5	10
NH4	mgN/l	< 0.5	< 2	5*
Nanorg	mgN/l	< 3	< 8	13*
TP	mgP/l	< 0.05	< 0.1	0.5
E. Coli	#/100ml	< 100	< 500	(100 – 2000**)
Trübung	NTU	0.5	1	-

* Bei Niederschlägen unterhalb 1 mm WS, vom 1.5. – 31.10.

** Leitwert und Grenzwert der EU-Badegewässerrichtlinie (nicht KW Ruhleben)

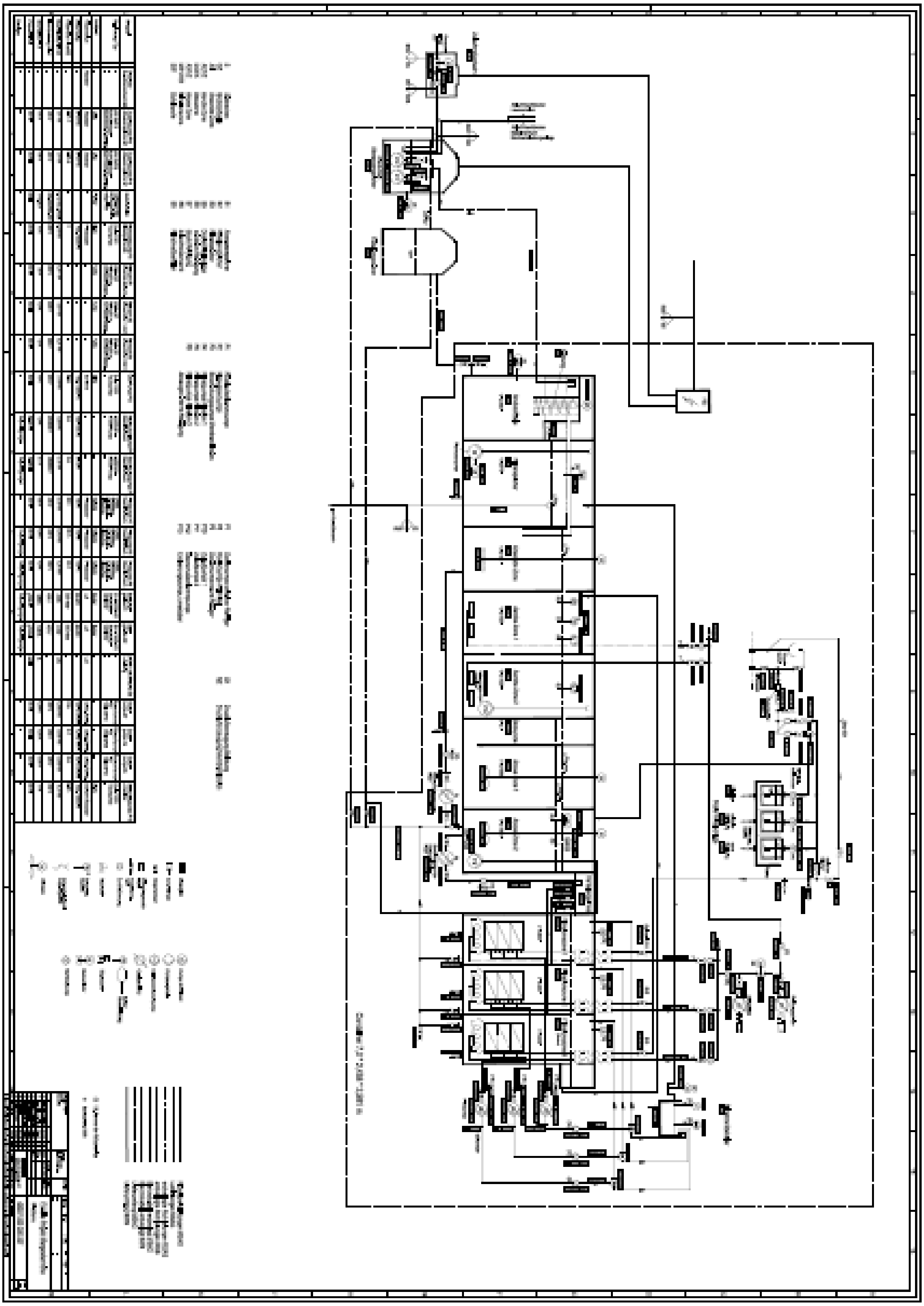
Die Anforderungen an ein Badegewässer werden im Ablauf der Kläranlage eingehalten. Bei der Eigenüberwachung der Membrananlage ist zu berücksichtigen, dass für kleine Kläranlagen eine geringere Probeanzahl ausreichend ist. Die beschriebene Technologie wird durch die EU gefördert und soll besonders im europäischen Raum eingesetzt werden, so dass eine Überwachung als 24-h-Beprobung günstig erscheint. Die behördliche Überwachung wird jedoch auf der Basis von 2-h-Mischproben durchgeführt.

Ein erfolgreicher Abschluss des Demonstrationsprojektes würde somit die Anwendung dieses Verfahrens zur dezentralen Erschließung von Siedlungsgebieten für kleine und mittlere Anlage bis 10.000 EW ermöglichen.

Beschreibung des Membranbelebungsverfahrens zur Reinigung von häuslichem Abwasser aus dem Trennsystem.

Der Abwasserzulauf erfolgt über ein Pumpwerk mit Vorlagetank. Die Membranbelebungsanlage enthält eine mechanische Vorreinigung sowie eine biologische Stufe, bestehend aus dem Belebungsbecken und einer 2-straßigen Filterkammern mit getauchten Membranfiltern. Weitere Anlagenbestandteile sind eine Überschussschlammspeicherung und eine Dosiervorrichtung für Reinigungschemikalien. Die biologische Stufe unterteilt sich in anaerobe, aerobe und anoxische Reaktoren.

Annex III ENREM process flow scheme



Annex IV Evaluation of impact on local environment (German)

Berlin

Bezirksamt Lichtenberg von Berlin
Abteilung Stadtentwicklung Bauen Umwelt und Verkehr
Amt für Umwelt und Natur

Bezirksamt Lichtenberg von Berlin, 10360 Berlin (Postanschrift)

Berliner Wasserbetriebe
12. Okt. 2007
V | F | P | T

Berliner Wasserbetriebe
OE Abwasserentsorgung
Frau Gnirß
Neue Jüdenstraße 1
10179 Berlin

Geschäftszeichen: UmNat NL 121
Bearbeiterin: Frau Köhler
Telefon: (030) 90296 4290
Telefax: (030) 90296 4289
Dienstgebäude: Altfriedrichsfelde 60, 10315 Berlin
Zimmer 2.304
E-Mail: Christina Köhler@libg.verwalt-berlin.de
E-Mail-Adresse gilt nicht für Dokumente mit elektronischer Signatur

Datum: 08.10.07

Semizentrale Abwasserreinigungsanlage (Membranbelebungsanlage) Margaretenhöhe
Ihr Zeichen: AE-T/V
Ihr Stellungnahmeersuchen vom 04.09.2007
Anlage: 2 Fotos

Die MBR-Anlage befindet sich in Nachbarschaft zum Geschützten Landschaftsbestandteil ‚Luch Margaretenhöhe'. Das Gebiet ist etwa 2,5 ha groß und wurde mit der GLB VO 1994 unter Schutz gestellt.[1]

Schutzzweck der VO ist es, „den Beitrag des Landschaftsbestandteils zur Leistungsfähigkeit des Naturhaushalts dauerhaft zu sichern und die von dem Landschaftsbestandteil ausgehende visuelle und ökologische Belebung des Orts- und Landschaftsbildes zu erhalten. Geschützt ist der Landschaftsbestandteil in seiner Gesamtheit sowie die für diesen Lebensraum typischen Tier- und Pflanzenarten und die Wasserfläche im Einzelnen".

Die verschiedenen Röhrichte, Strauchweidengebüsche, Kleingewässer und Verlandungsbereiche sind Lebensraum für besonders geschützte und streng geschützte Tierarten.

2004 hat die untere Naturschutzbehörde einen Pflege- und Entwicklungsplan in Auftrag gegeben, um Wiederherstellungs- und Pflegemaßnahmen festzulegen. Im Verlauf der Untersuchungen wurde festgestellt, dass sowohl verschiedene Biotope als auch nach Bundesartenschutzverordnung geschützte Tierarten durch Wassermangel gefährdet sind. Zur Pflege- und Entwicklung des Gebietes wurde empfohlen, das Wasserdargebot durch Rückstau des Margaretengrabens zu erhöhen. Begrenzende Faktoren hierfür sind allerdings die Sohllagen der Bausubstanz (Kellersohlen, Gründungstiefen) im Wohngebiet Margaretenhöhe.

---

[1] Verordnung zum Schutz des Landschaftsbestandteils Luch Margaretenhöhe im Bezirk Hohenschönhausen von Berlin, Ortsteil Malchow vom 5.9.1994 (GVBl.S.408)

Verkehrsverbindungen	Sprechzeiten	Zahlungen	Geldinstitut	Kontonummer	BLZ
S Friedrichsfelde Ost	Di/Fr 9.00.12.00 Uhr	bitte nur bargeldlos	Postbank Berlin	655 598 - 109	100 100 10
U Friedrichsfelde	Do 15.00-18.00 Uhr	an die Bezirkskasse	Berliner Bank AG	818 289 0000	100 200 00
Tram 17 27	und nach Vereinbarung	Lichtenberg	Berliner Sparkasse	178 392 2911	100 500 00

LICHTENBERG

Bitte benutzen Sie nach Möglichkeit die öffentlichen Verkehrsmittel

Im gleichen Jahr wurden Planungen der BWB zur MBR-Anlage mit der unteren Naturschutzbehörde abgestimmt. Die gereinigten Abwässer sollten dem Luchgebiet durch Einleitung in den Margaretengraben zugeführt werden, um – verbunden mit dem Bau einer Sohlschwelle - dessen Wasserverhältnisse zu verbessern. Für die Einleitung des gereinigten Abwassers war keine Befreiung nach der Schutzgebietsverordnung erforderlich.

Die MBR-Anlage wurde 2005 genehmigt mit den Auflagen, eine Gehölzpflanzung um den Anlagenstandort anzulegen und eine Sohlschwelle bzw. einen Sohlsprung im Margaretengraben herzustellen (bzw. die Kosten hierfür an die Wasserbehörde zu übertragen). Die Abnahme der Gehölzpflanzung erfolgte 2007. Die Fertigstellungs- und Entwicklungspflege endet 2010.

Nach den monatlichen Naturschutzwachtberichten hat sich 2007 der Wasserstand im Luchgebiet gegenüber 2006 wesentlich verbessert und stabilisiert. Der Margaretengraben wurde im März / April 2007 durch die Gewässerunterhaltung beräumt. Der Sohlsprung kurz unterhalb des Einlaufes der BWB bewirkt einen Rückstau in Richtung Luch Margaretenhöhe. Hiervon hat der Gewässeringenieur Herr Richter im September 2007 Fotos aufgenommen. Der Rückstau in Richtung Luch ist deutlich erkennbar.

Gleichwohl sind eine längere Beobachtungsdauer und ggf. auch neue faunistische Untersuchungen in den kommenden Jahren erforderlich, um den Erfolg der Maßnahme zu dokumentieren.

Mit freundlichen Grüßen
Im Auftrag

Köhler

Köhler


05.09.2007


05.09.2007

Annex V Report on membrane analysis and fouling diagnosis (Anjou Recherche)

Centre d'Analyses Environnementales

Chemin de la digue, BP 76
78603 Maisons Laffitte Cedex
Tél. : + 33 1 34 93 31 31

VEOLIA ENVIRONNEMENT
Recherche & Développement
Centre de Recherche sur l'Eau

CONFIDENTIAL

AUTOPSY REPORT

Report number: RE 06026 / ATA MB 07-015

To : Boris LESJEAN

ENREM Project

Samples:

Martin Systems / Microdyn Nadir membranes:

- 1st campaign: 2 samples (September 2006)
- 2nd campaign: 6 samples (May 2007)
- 3rd campaign: 3 samples (June 2007)

Water samples from bioreactor:

- 3 samples (July 2007)

September 2007

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ANALYSES OF SAMPLES FROM THE BERLIN MEMBRANE BIOREACTOR
FIRST CAMPAIGN ON SEPTEMBER 2006

CONTEXT

The ENREM project (Enhanced Nutrients REmoval in Membrane bioreactor) is a European project included in the frame of the 6th Framework Program. The main goal is the development of MBR filtration technologies for municipal wastewater treatment. In this context, the Martin System membrane (PES) was evaluated for several months though a full scale plant located on the unsewered area of Berlin. The membrane bioreactor is composed by six independent modules and one of them can be removed and replaced by another one to maintain the process hydraulic. Then, regular autopsies have been planed during the full period of the project. Each module sent for autopsy was in operation since March 2006.

For the first campaign, 2 membrane sheets have been sampled from the left side, top position module and sent for autopsy. Membranes have been sampled after 3h chemical soaking and filtration with H_2O_2 1000ppm pH 8.5 and were located at the middle of module. During the membrane sampling, a dark sludge deposit has been observed at the membrane surface. This sludge deposit was heavier on one of both membranes (sludge clogging). Both membranes have been rinsed with tap water to remove the excess of sludge before sending membranes for autopsy.

MEMBRANE ANALYSES

Visual inspection

To discriminate both membranes, membrane displaying the most important dark deposit has been called « fouled +++ » (figure 1) and the other one « fouled + » (figure 2).

Figure 1: external side of membrane « fouled +++ »

Figure 2: external side of membrane « fouled + »

The following points have been noted:

- Membrane “fouled +” is yellowish, this color is homogeneous on the entire membrane sheet. No significant deposit or specific odor has been observed.

- Membrane “fouled +++” is also yellowish but dark areas are heterogeneously observed where the sludge deposit was detected previously. As for membrane “fouled +”, no significant deposit and specific odor have been detected.

Membrane deposit analyses

Deposit extraction

The low deposit quantity and the dryness of membranes when we received them did not allow us to perform a deposit extraction by scrapping. This latter has been performed by desorption of the entire membrane surface in deionized water and sonication.

Chemical and biological deposit characterization

The following analyses have been carried out:

- Scanning Electronic Microscopy (SEM) to determine the deposit morphology and EDAX for elementary composition of specific particles on the membrane,
- Measurement of mineral elements by Inducted Coupled Plasma (ICP) for a semi quantitative screening,
- Measurement of TOC to evaluate the organic part of the deposit,
- Organic matter characterization: analysis on LC-OCD system (Liquid Chromatography-Organic Carbon Detection)
- Quantification of reviviscent bacteria with HPC (Heterotrophic Plate Count) analysis, active cells by CTC staining and total cells by DAPI staining to evaluate the microbiological part of the deposit.

Results

Chemical and biological analyses

Results obtained for both membranes are exposed in the table 1.

	Membrane "fouled+"	Membrane "fouled +++"
Chemical analyses (µg/cm²)		
TOC	1.4	2.0
DOC	1.0	1.4
Al	<0.02	<0.02
Ca	<5.5	<5.5
Fe	0.02	0.1
Mg	<1.1	<1.1
Mn	<0.01	<0.01
K	<1.1	<1.1
Na	<1.7	<1.7
Microbiological analyses		
HPC (UFC/cm²)	3.2×10^4	4.1×10^4
Total cells /cm²	3.6×10^6	4.1×10^6
Active cells/ cm²	1.8×10^5	1.2×10^6

Table 1: Chemical and biological results for membrane analyses

For both membranes, the deposit is mainly composed of biological matter. The part represented by organic and inorganic matter is quite low.

Most of mineral elements, except for iron are present in concentration lower than quantification limits.
Microbiological analyses show that total cells are present in similar concentration at the both membrane surfaces but the active cell fraction is higher for membrane "fouled +++".
The difference between the cell number obtained by HPC and CTC staining can be explained by the fact that HPC takes only into account the fraction of bacteria which is able to grow on culture media whereas CTC quantifies all active cells. It is difficult to say if these bacteria are the result of bacterial growth at the membrane surface or just bacteria coming from the sludge. As a matter of fact, sludge can contain up to 10^{12} cells/mL.

<u>Organic matter characterization by LC SEC OCD</u>

> *The LC-OCD system (Liquid Chromatography-Organic Carbon Detection) consists of a size exclusion chromatography column for separation of hydrophilic organic molecules according to their molecular size. The underlying principle is the diffusion of molecules into the resin pores. This means that larger molecules elute first as they can not penetrate the pores very deeply, while smaller molecules take more time to diffuse into the pores. The separated compounds are then detected by 2 different detectors: a UV detector (absorption at 254 nm) and a DOC detector. Depending on the size of the molecules, the response from both detectors, we can define the composition of the sample in term of organic fractions. Because, samples with large amounts of particles need to be filtered prior to injection on chromatography column, detectors only measure the dissolved organic fraction of the total organic carbon* ***i.e an average value of 70% for both membranes.***

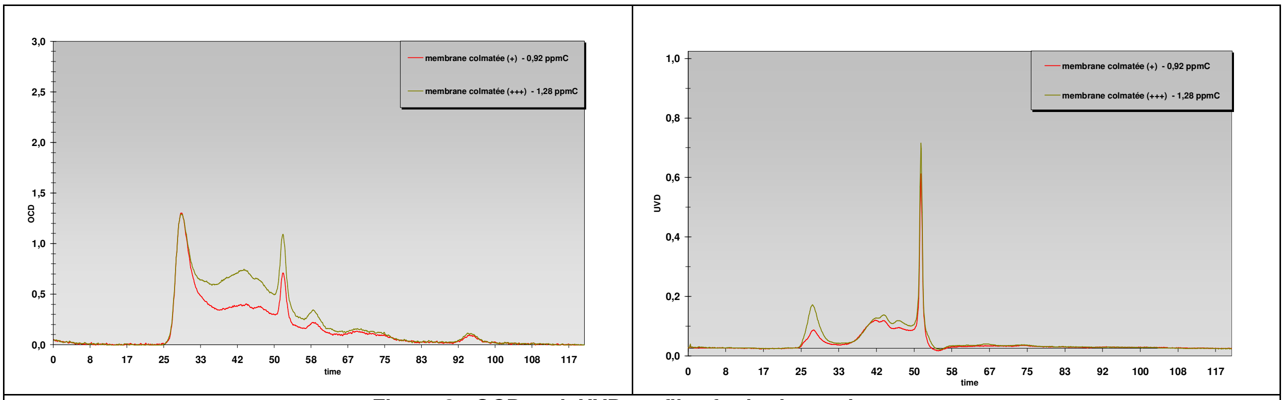


Figure 3: OCD and UVD profiles for both membranes

Similar profiles are obtained for both membranes in terms of dissolved organic matter nature, the only difference between these membranes consists of the fraction concentration which are higher for membrane "fouled +++".

The identified fractions are the following ones:

- peak at an elution time of 30mn: a mixture of polysaccharides and proteins with high molecular weight;
- the large peak between 35 and 50mn: humic substances and building blocks (by-products of the humic substance degradation);
- at 55min, this peak corresponds to organic acids;
- the latest peak observed indicates the presence of low molecular weight compounds aminoacids, alcohols).

<u>SEM</u>

Views obtained from both membranes after SEM analysis are exposed in figures 4 and 5.

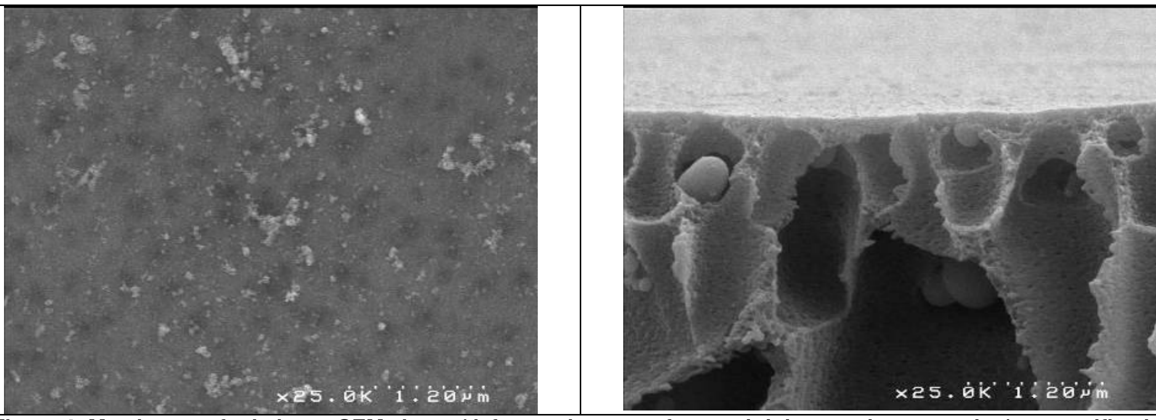


Figure 4: Membrane « fouled + » : SEM views (left :membrane surface and right: membrane section) – magnification X25000

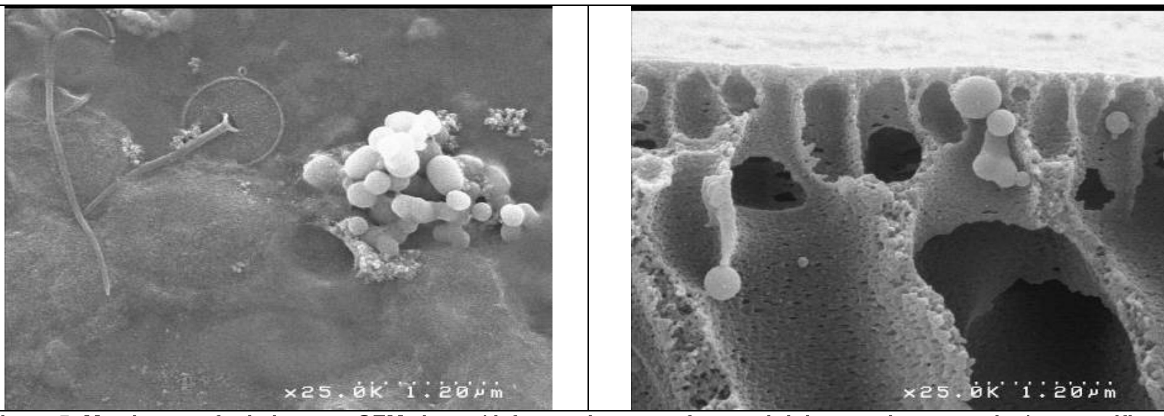


Figure 5: Membrane « fouled +++ » : SEM views (left :membrane surface and right: membrane section) – magnification X25000

The main elements observed on both membranes are bacteria clusters with a cocci shape. It is interesting to note that some bacterial cells are detected inside the membrane structure (see section views).

<u>EDAX</u>

EDAX profiles obtained for the main particles detected by SEM are displayed in figure 6 (« fouled +) and figure 7 (« fouled +++ »).

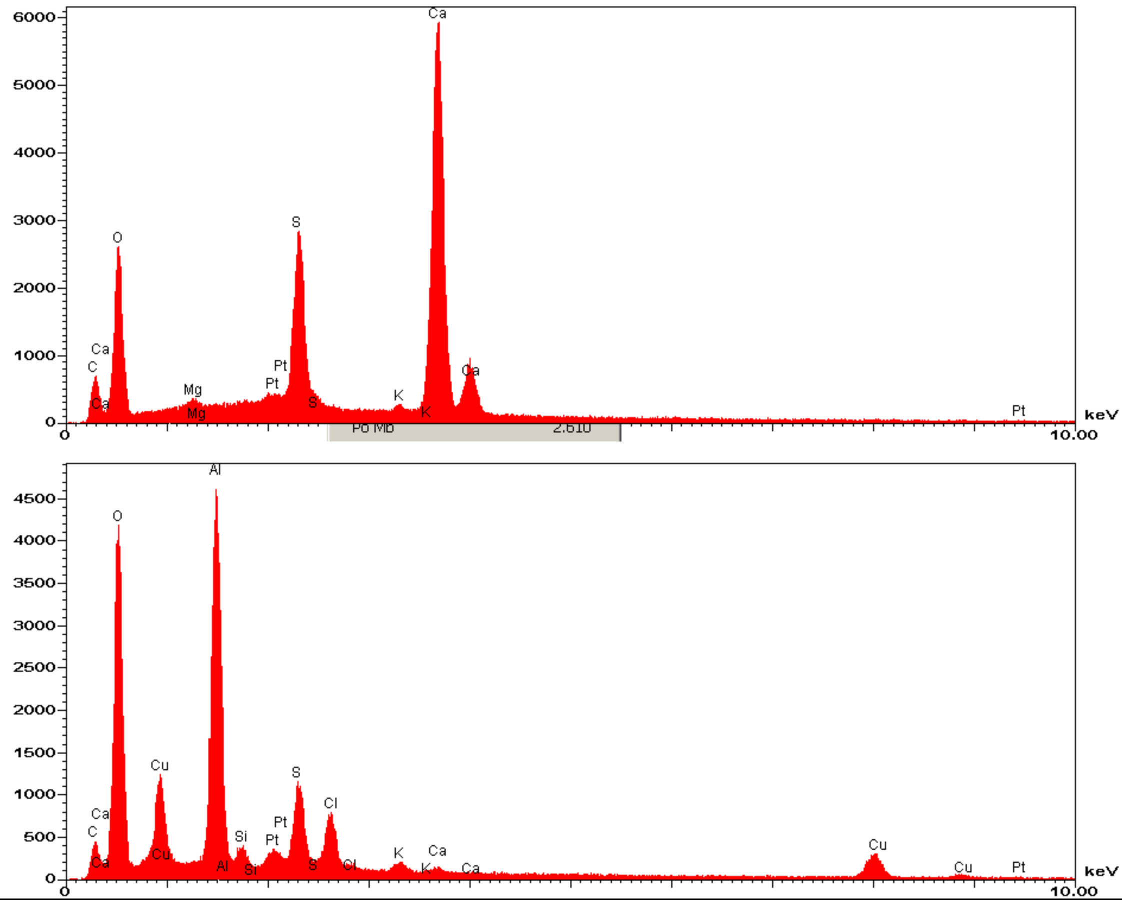


Figure 6: EDAX profiles for membrane "fouled +"

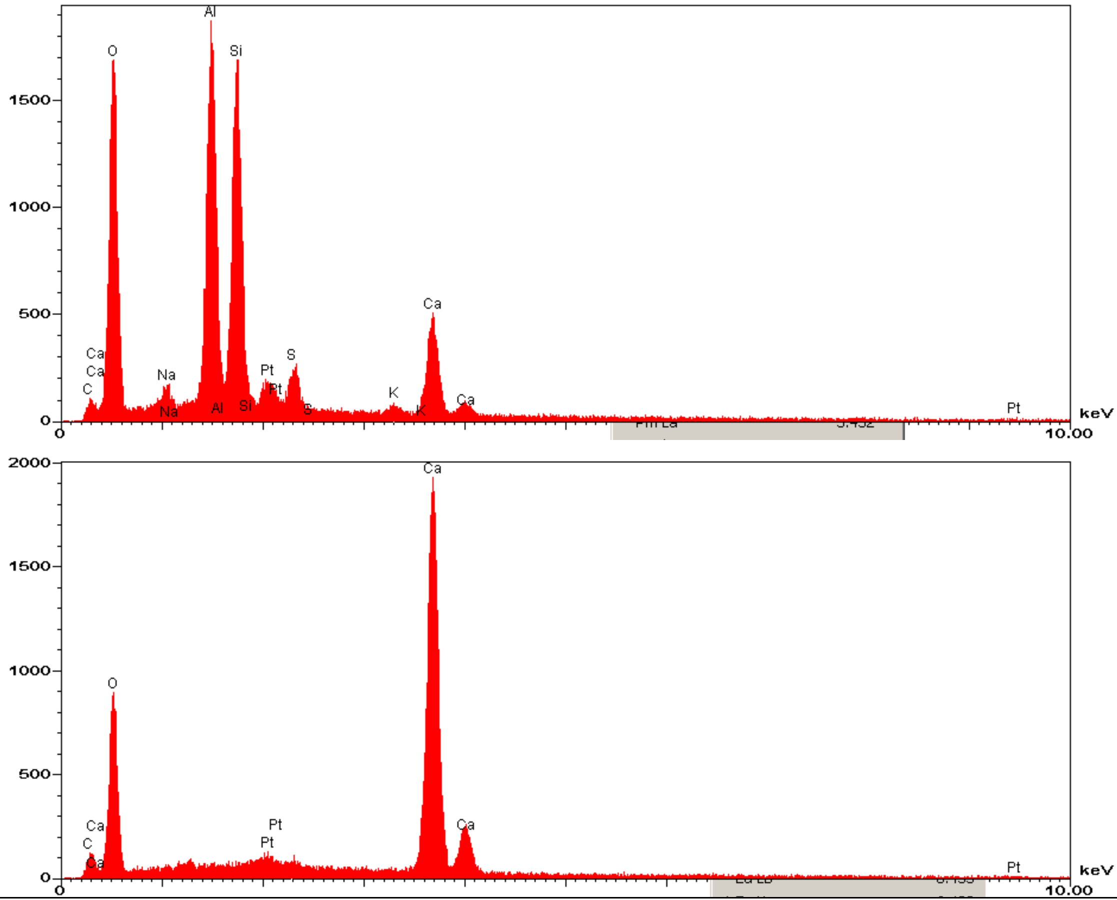


Figure 7: EDAX profiles for membrane "fouled +++"

The main inorganic elements detected at the membrane surface are oxygen, sulphur, aluminium, calcium and silica.

Conclusions

Membrane autopsies show several interesting points:

- The fouling deposit is quite light compared to those observed in other autopsy cases.
- The fouling deposit consists of a mixture of organic, inorganic and biological elements. However, concentrations of these different fractions are quite low (due to the H_2O_2 cleaning).
- Organic matter characterization shows the presence of proteins and polysaccharides and also humic substances.
- SEM analysis shows the presence of microorganisms not only at the membrane surface but also inside the membrane structure.

Analyses of samples from the Berlin Membrane BioReactor

Second campaign: sampled on 7th, May and arrived on 21st, May 2007

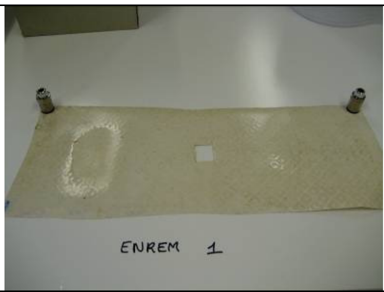
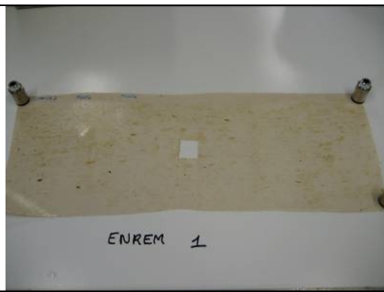
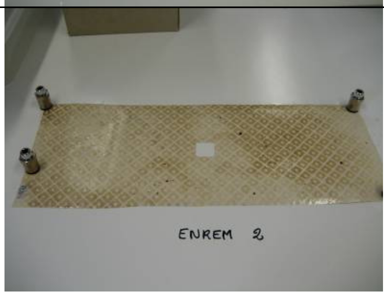
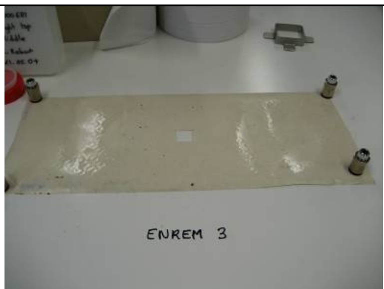
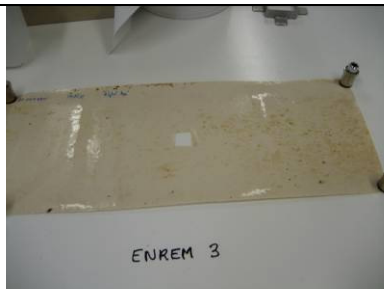
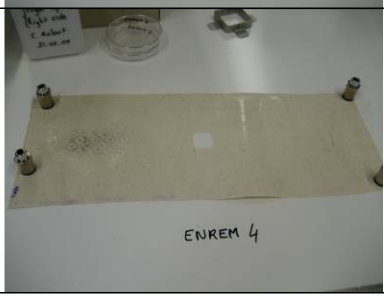
Context

For the second campaign, 6 membrane sheets have been sampled from the membrane bioreactor and sent for autopsy. Membranes have been sampled after about 14 months of operation and after 4h chemical soaking and filtration with H_2O_2 2500 ppm pH 8.5. Samples were located in 3 different modules on the right side: two membrane sheets from the middle position, two from the bottom position and two from the top. During the membrane sampling, only small sludge deposit has been observed at the membrane surface even on the bottom module. All membranes have been rinsed with tap water to remove the excess of sludge before sending membranes for autopsy.

Membrane analyses

Visual inspection

Deposits description and view of membrane are presented in table 2.

		Membrane inside	Membrane outside	Description
ENREM 1	06-000677 Right, middle module, Middle side			Yellowish Homogeneous deposit on both sides. No specific odour. Inside, clear spacer structure
ENREM 2	06-0000677 Right, middle module Left side			Yellowish Homogeneous deposit on both sides, more important inside No specific odour. Inside, more detectable spacer structure
ENREM 3	06-000681 Right top module, Middle side			Heterogeneous deposit only outside. No specific odour.
ENREM 4	06-000681 Right top module, Right side			Outside light heterogeneous deposit on membrane side but less in centre. Light dark spot

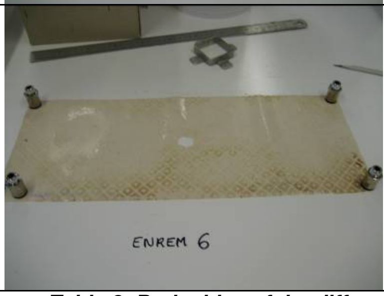
ENREM 5	06-000685 Right bottom module, Middle side			Light deposit and spacer structure not observed
ENREM 6	06-000685 Right bottom module, Left side			Outside, light deposit. Inside, spacer structure very strong

Table 2: Both sides of the different membranes and deposit description

Membrane deposit analyses

Deposit extraction

The low deposit quantity when we received them did not allow us to perform a deposit extraction by scrapping. This latter has been performed by desorption of the entire membrane surface (757cm²) in deionized water and sonication.

Chemical and biological deposit characterization

The following analyses have been carried out:

- Scanning Electronic Microscopy (SEM) to determine the deposit morphology and EDAX for elementary composition of specific particles on the membrane,
- Measurement of mineral elements by Inducted Coupled Plasma (ICP) for a semi quantitative screening,
- Measurement of TOC to evaluate the organic part of the deposit,
- Organic matter characterization: analysis on LC-OCD system (Liquid Chromatography-Organic Carbon Detection)

Results

Chemical analyses

Results obtained for both membranes are exposed in the table 3.

	ENREM 1	ENREM 2	ENREM 3	ENREM 4	ENREM 5	ENREM 6
Membrane reference and position in filter	**06-000677 Right middle Middle**	**06-000677 Right middle Left side**	**06-000681 Right top Middle**	**06-000681 Right top Right side**	**06-000685 Right bottom Middle**	**06-000685 Right bottom Left side**
Organic matter (µg/cm²)						
TOC	**5,5**	**8,8**	**4,4**	**2,3**	**2,0**	**3,3**
DOC	**1,0**	**1,1**	**0,6**	**0,7**	**0,6**	**0,7**
Mineral elements (µg/cm²)						
Ca	**2,9**	**4,1**	**2,7**	**2,8**	**2,3**	**2,5**
P	**0,5**	**0,9**	**-**	**-**	**-**	**-**
K	**0,7**	**0,7**	**-**	**-**	**-**	**0,6**
Na	**3,0**	**3,3**	**2,2**	**2,2**	**2,3**	**3,1**
S	**1,5**	**2,9**	**1,3**	**1,3**	**1,2**	**1,6**

Table 3: Chemical results for membrane analyses

Table 3 shows that all deposit membranes are composed by organic and inorganic matter; the organic part is greater than the inorganic one.
Whatever the module location, TOC values of the both membranes are different but DOC values are similar. This non soluble part is linked to the residual sludge deposit observed on the membrane.
For the inorganic matter, there are 3 main mineral elements: calcium, sodium, sulphur and concentrations for those one are greater on side than on middle.

If we compare both side for each module, the conclusion are the following:

- Right middle module:
  - For organic or inorganic elements, concentrations on left side are slightly higher than on middle side
  - For mineral elements, calcium is the main element detected and two other mineral elements are detected in lower concentration: potassium and phosphorus
- Right top module:
  - For organic matter, TOC concentration is greater on middle compared to the right side
  - Results of mineral elements are similar on both membranes: calcium is major element detected
- Right bottom module:
  - For organic matter, TOC concentration is higher on left side than on middle one
  - Results of mineral elements are equivalent on both membranes except for sodium which is higher on left side

Organic matter characterization by LC SEC OCD

The LC-OCD system (Liquid Chromatography-Organic Carbon Detection) consists of a size exclusion chromatography column for separation of hydrophilic organic molecules according to their molecular size. The underlying principle is the diffusion of molecules into the resin pores. This means that larger molecules elute first as they can not penetrate the pores very deeply, while smaller molecules take more time to diffuse into the pores. The separated compounds are then detected by 2 different detectors: a UV detector (absorption at 254 nm) and a DOC detector. Depending on the size of the molecules, the response from both detectors, we can define the composition of the sample in term of organic fractions. Because, samples with large amounts of particles need to be filtered prior to injection on chromatography column, detectors only measure the dissolved organic fraction of the total organic carbon ***i.e between 15 and 30% for both membranes.***

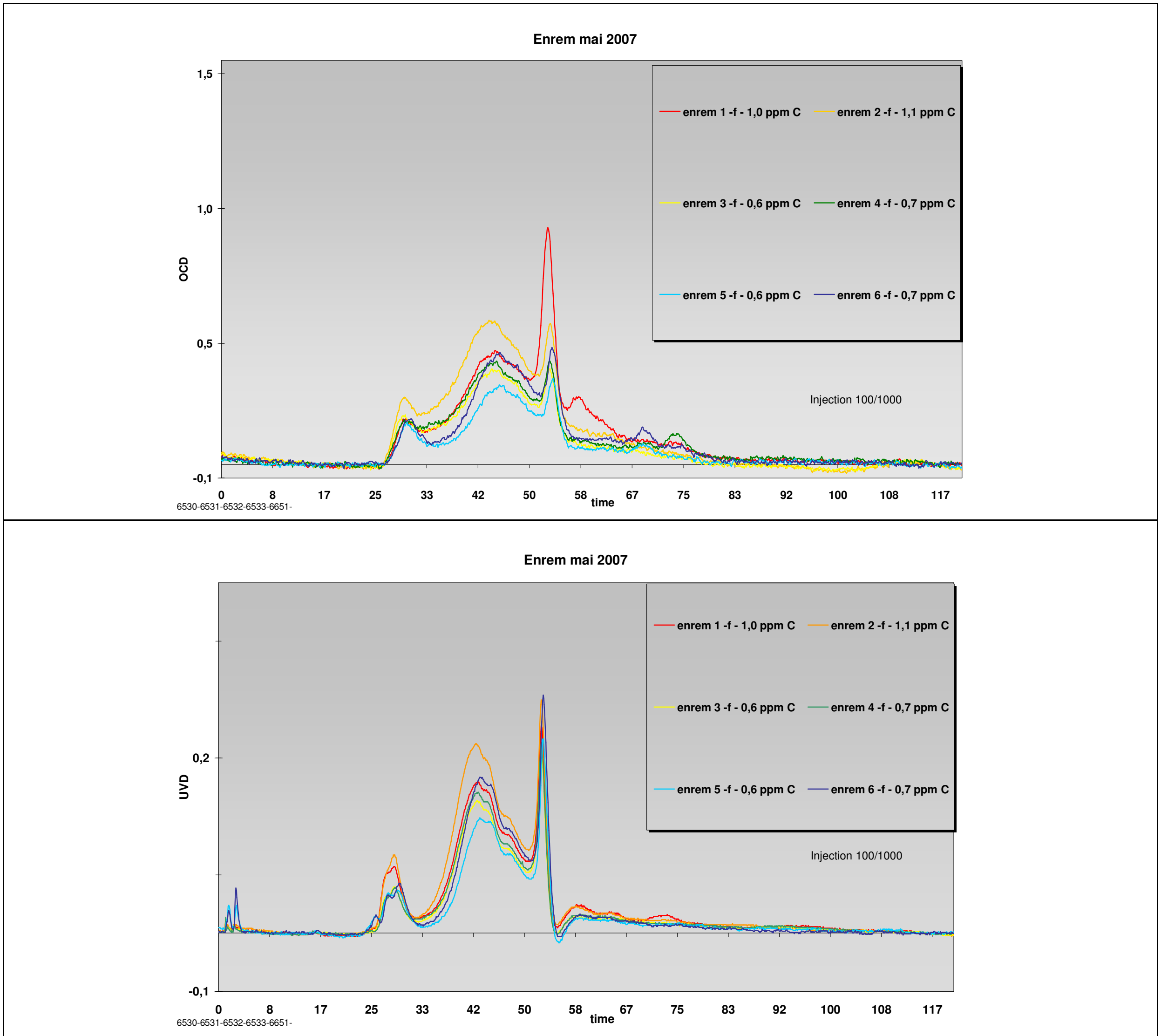


Figure 8: OCD and UVD profiles for deposits of membrane

Samples	TOC	= HOC + POC	CDOC	CDOC: P	CDOC: HS+BB	CDOC: A+N	HS: Aromaticity (SUVA)	HS: Mol-Weight (Mn)	UVD Colloid. Inorg.
	ppm-C	ppm-C	ppm-C	% TOC	% TOC	% TOC	L/(mg*m)	g/mol	SAC(m-1)
enrem 1 -f	1,0	0,0	1,1	6	64	33	2,64	993	0,22
enrem 2 -f	1,1	0,0	1,1	9	72	14	2,12	760	0,26
enrem 3 -f	0,6	-0,1	0,7	12	80	16	2,42	846	0,16
enrem 4 -f	0,7	-0,1	0,8	11	79	31	2,80	1143	0,17
enrem 5 -f	0,6	0,0	0,6	15	66	21	3,08	707	0,17
enrem 6 -f	0,7	-0,1	0,8	13	77	27	2,23	504	0,17

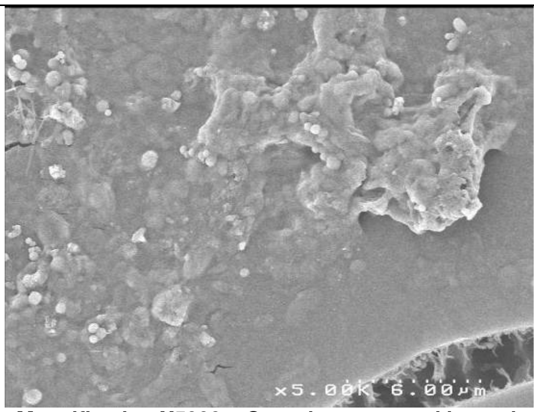
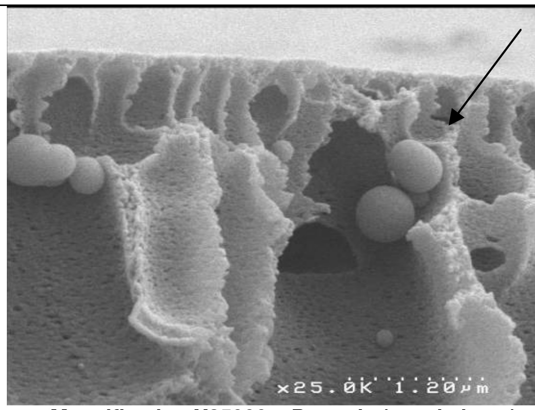
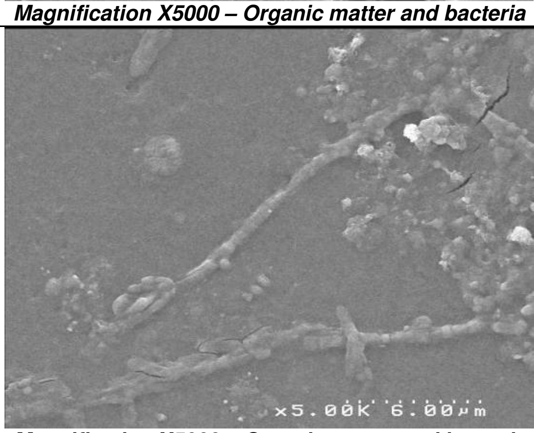
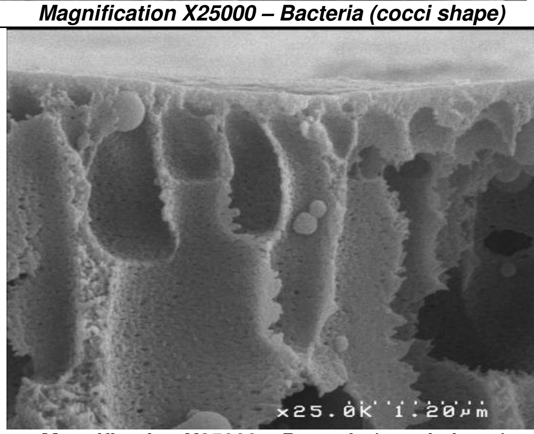
Table 4 : Distribution of organic matter for 6 samples:

TOC: Total Organic Carbon
HOC: "non-chromatograph able", hence hydrophobic part of organic carbon
POC: particulate organic carbon, thus TOC may be too low for some surface waters
DOC: dissolved organic carbon
CDOC: "chromatograph able", hence hydrophilic part of organic carbon
SAC: spectral absorption coefficient, l = 254 nm
"P" or "Biopolymers" = Polysaccharides, Proteins, Aminosugars, Colloids
"HS" = Humic Substance
"BB" = Buildings Blocks - mostly breakdown products of humics
"A" for acids = Summaric value for monoprotic organic acids < 350 Da; low molecular molecules of Acids and HS
"N" for neutrals = include mono-oligosaccharides, alcohols, aldehydes, ketones and amino sugars and low-molecular weight compounds

Figure 8 shows the overlay, for each detection, of profiles obtained for dissolved fractions of the 6 samples.

Table 4 presents the distribution of organic matter for the 6 samples. The major fraction is fraction SH + BB. This fraction contains the humic substances (HS) and "Buildings Blocks" (BB) corresponding to the major fraction present in natural water (usually ~60% of TOC). The *SH* group contains generally organic molecules with high molecular weight (~100-10.000 g/mol).This group is usually subdivided into humins (non-soluble), humic acids (insoluble in acids) and fulvic acids (soluble in acids). Building Blocks represent about 15-25% of TOC in natural waters. They probably are highly substituted aromatic or conjugated acids with molecular weights of 350-500 g/mol. These sub-units may reflect HS hydrolysis products by age or sunlight photolysis. Building Blocks are more acidic than fulvic acids and are intermediates in the degradation process: fulvic acids – building blocks – low-molecular weight organic acids.

<u>SEM</u>
Views obtained from all membranes after SEM analysis are exposed in table 5.

		Membrane surface	Membrane section
ENREM 1	06-000677 Right, middle module, Middle side	 ***Magnification X5000 – Organic matter and bacteria***	 ***Magnification X25000 – Bacteria (cocci shape)***
ENREM 2	06-0000677 Right, middle module Left side	 ***Magnification X5000 – Organic matter and bacteria***	 ***Magnification X25000 – Bacteria (cocci shape)***

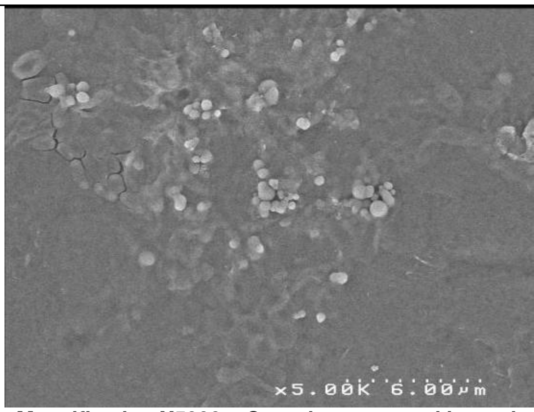
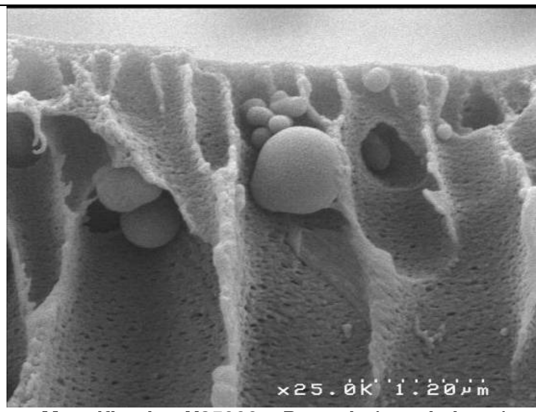
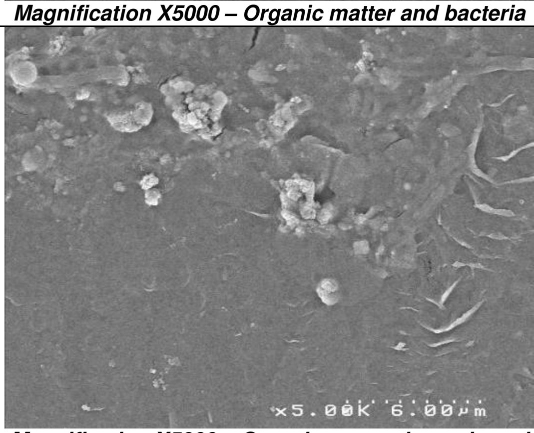
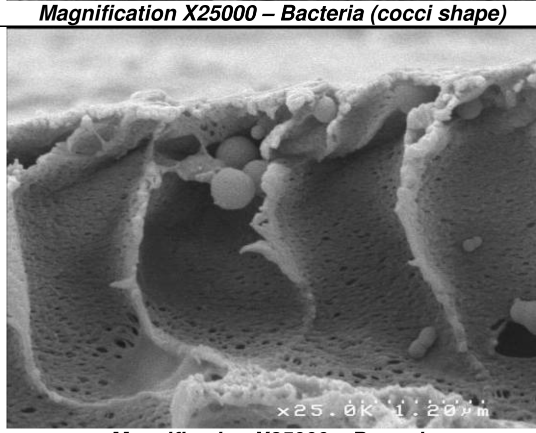
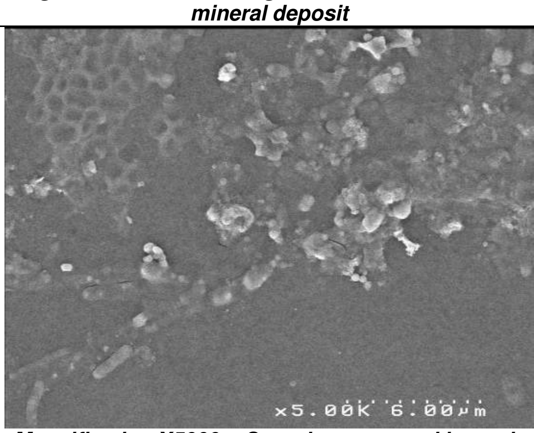
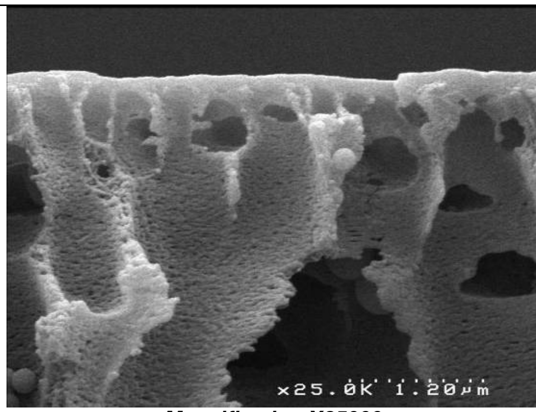
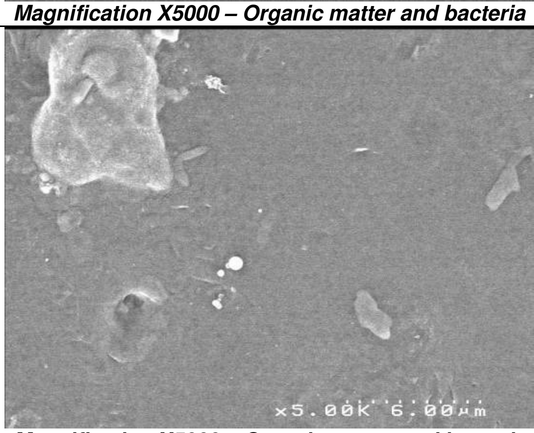
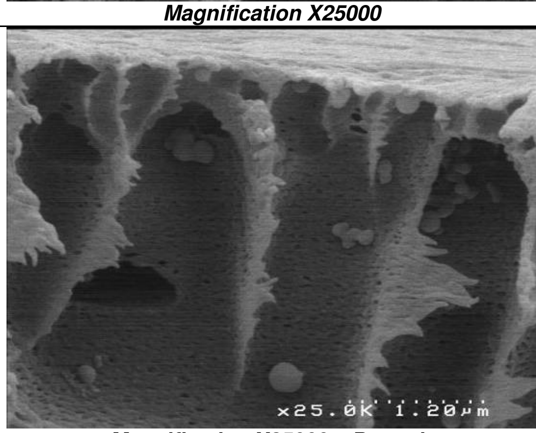
ENREM 3	06-000681 Right top module, Middle side	 ***Magnification X5000 – Organic matter and bacteria***	 ***Magnification X25000 – Bacteria (cocci shape)***
ENREM 4	06-000681 Right top module, Right side	 ***Magnification X5000 – Organic matter ,bacteria and mineral deposit***	 ***Magnification X25000 – Bacteria***
ENREM 5	06-000685 Right bottom module, Middle side	 ***Magnification X5000 – Organic matter and bacteria***	 ***Magnification X25000***
ENREM 6	06-000685 Right bottom module, Left side	 ***Magnification X5000 – Organic matter and bacteria***	 ***Magnification X25000 – Bacteria***

Table 5: SEM views from different membranes

On membrane surfaces, we could observe organic matter, bacteria and sometimes mineral deposit. It is interesting to note that some bacteria cells were inside the membrane structure.

EDAX:
EDAX profiles obtained for the main particles detected by SEM are displayed in table 6.

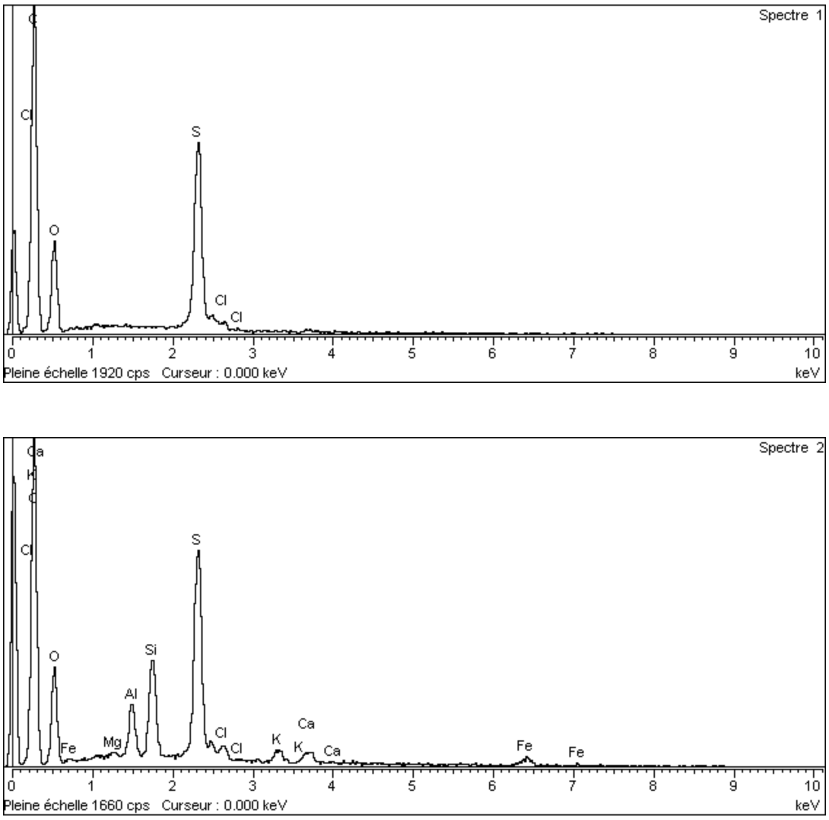


Table 6: EDAX profiles with main chemical elements

Only representative profiles with main chemical elements are presented in the table 6:

- On the first one, we observed:
    - C, O and S which are also the membrane constituents
    - Cl which probably come from membrane soaking
- On the second one:
    - Ca, K, S which are elements from sewage
    - C and Cl like in the first profile.

Conclusions

For all membranes received for this 2nd campaign, we observed that:

- deposit was very light and was composed by organic and inorganic matter
- organic part was greater than inorganic

Mineral composition was globally the same for six membranes. The three main mineral elements are calcium, sodium and sulphur.

The composition of organic part of the deposit is also quite similar for all membrane:

- A non soluble part probably linked to sludge deposit on the membrane
- Characterization of dissolved organic matter shows that humic substance fraction represented 60-80% of DOC

On SEM pictures, we could observe bacteria on membrane surface but also inside the membrane structure.

Analyses of samples from the Berlin Membrane BioReactor

Organic matter characterization of Water samples

Context

Three water samples have been sent from the membrane bioreactor (received the July 26th):
- raw water (waste water filtered on paper filter)
- sludge supernatant (sludge from the BRM filtered on paper filter)
-permeate (effluent)

Principle of LC/SEC/OCD

The LCSEC-OCD system (*Liquid Size Exclusion Chromatography-Organic Carbon Detection*) consists of a size exclusion chromatography column in order to separate hydrophilic organic molecules according to their molecular size.
The underlying principle is the diffusion of molecules into the resin pores. This means that larger molecules elute first as they can not penetrate the pores very deeply, while smaller molecules take more time to diffuse into the pores and out again. The separated compounds are then detected by two different detectors: a UV detector (absorption at 254 nm) and a DOC detector (after inorganic carbon purging). Depending on the size of the molecules, the composition of the organic matter can be obtained. With a bespoke algorithm program, the different peaks can be integrated to evaluate the proportion of each organic fraction. Figure 9 shows an example of waste water treatment plant water chromatogram.

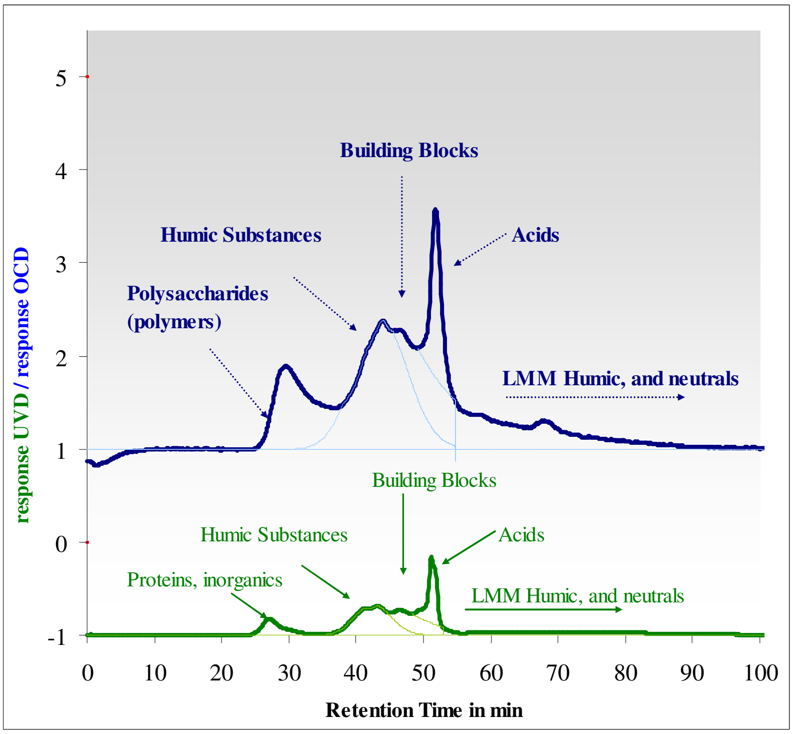


Figure 9: Profiles obtained for a sample of waste water treatment plant

The detection limit of the LC-OCD is 0.1 mg C/L (by compound). Each sample are analysed with a SEC HW-50S column during 130 minutes.

Analyses were performed by LC-OCD (manufacturer DOC-Labor Dr. Huber (D-76229, Karlsruhe, Germany).

The main fractions of organic matter are:

- **Tr = 25 à 35 min** : ***Fraction P***

This fraction is composed by polysaccharides (including amino sugars, polypeptides) bio polymer, colloids and proteins (molecular weight >50.000 - 2 Mio. g/mol). The polysaccharides are hydrophilic and not UV-absorbing and may be associated with amino acids and proteins (amino sugars). Polysaccharides in surface waters originate from algal and bacterial cellular material or metabolic activity. Polysaccharides appear to be the most problematical class of compounds in water treatment. For information, fraction P represents 5-10% of COT for surface water.

<u>Inorganic Colloids (only detectable with UV, not with OCD)</u>

Negatively charged inorganic colloids < 1µm, neutral polyhydroxides and oxidhydrates of Fe, Al and Si appear in the chromatograms at the exclusion volume of the column. Also ferric salts used in flocculation processes will elute in this fraction and appear in UV detection.

- **Tr = 35-50 min : fraction SH+BB**

Humics are the most abundant organic substances on earth. They are usually subdivided into humins (non-soluble), humic acids (insoluble in acids) and fulvic acids (soluble in acids):

- ***Humins:*** They are present in soils, in waters only when washed out by high turbulence waters, i.e. rainfall. Humins are not dissolved and should be regarded as microparticles;
- ***Humic acids:*** Intermediates between humins and fulvic acids. They contain less aromatic rings and more carboxylic groups. Molecular weight ranges from 100 to about 10.000 g/mol;
- ***Fulvic Acids:*** These are usually dominating aquatic systems. Fulvics are either washed into the aquatic system by run off or percolating waters or formed in the water body itself (by degradation of algae and bacteria). Fulvics are much lower in aromatic rings and much higher in carboxylic groups. Molecular weights range from 600 to 1.000 g/mol.

<u>Building Blocks (HS-Hydrolysates)</u>

Building Blocks present about 15-25% of TOC in natural waters.

They probably are highly substituted aromatic or conjugated acids with molecular weights of 350-500 g/mol. These sub-units may reflect HS hydrolysis products by age or sunlight photolysis. Building Blocks are more acidic than fulvic acids and are intermediates in the degradation process: fulvic acids – building blocks – low-molecular weight organic acids.

- **Tr = 50-60 min Fraction Low Molar Mass Organic Acids, Neutrals and Amphiphilics**

Neutrals make up about 10-30% of TOC in surface water. <u>Low Molar Mass Organic Acids:</u>

LMMOA are the final degradation product of organics, but LMMOA are also released by algae and bacteria. In ground waters LMMOA are usually absent.

<u>Low-Molar Mass Neutrals and Amphiphilics</u>

They are molecules such as alcohols, aldehydes, ketones and amino acids. Some have amphiphilic character (between hydrophobic AND hydrophilic).

The ***Hydrophobic Organic Carbon*** (HOC) is present in the composition of sample. It is the difference between COT and the sum of all fractions in the chromatogram by OCD detection (CDOC : Carbon Organic Dissolved hydrophilic Chromatographiable). HOC fraction is also hydrophobic organic compounds and *non-chromatographiables*, retained in the chromatographic column (natural lipids, lipoides and hopanoides).

In this report, COT is the total quantity of the dissolved organic carbon, obtained with oxidation at UV 180 nm in the reactor. COD is the quantity of dissolved organic carbon obtained after separation of sample on the SEC column and oxididation at UV 180 nm.

Results and discussion

All samples were diluted and filtered with 0.45 µm filter. Results of dissolved organic carbon in mg/L of carbon represent obtained values during analysis by OCD detection. Profiles obtained for the three samples are shown in figure 10 (OCD detection) and 11 (UV detection). Figure 12 shows the distribution of organic matter.

Samples	TOC =	HOC + POC	CDOC	CDOC: P	CDOC: HS+BB	CDOC: A+N	HS: Aromaticity (SUVA)	HS: Mol-Weight (Mn)	UVD Colloid. Inorg.
	ppm-C	ppm-C	ppm-C	% TOC	% TOC	% TOC	L/(mg*m)	g/mol	SAC(m-1)
Raw water-f	142	13	129	4	19	68	1,64	699	10,43
sludge-f	26	-2,7	29	12	52	47	2,01	549	5,52
permeat-f	22	0,3	21	2	50	47	2,40	542	0,43

Table 7 : Composition of samples

TOC: Total Organic Carbon
HOC: "non-chromatographable", hence hydrophobic part of organic carbon
POC: particulate organic carbon, thus TOC may be too low for some surface waters
DOC: dissolved organic carbon
CDOC: "chromatographable", hence hydrophilic part of organic carbon
SAC: spectral absorption coefficient, l = 254 nm
"PS" or "Biopolymers" = Polysaccharides, Proteins, Aminosugars, Colloids
"HS" = Humic Substance
"BB" = Buildings Blocks - mostly breakdown products of humics
"A" for acids = Summaric value for monoprotic organic acids < 350 Da; low molecular molecules of Acids and HS
"N" for neutrals = include mono-oligosaccharides, alcohols, aldehydes, ketones and amino sugars and low molecular weigh compound.

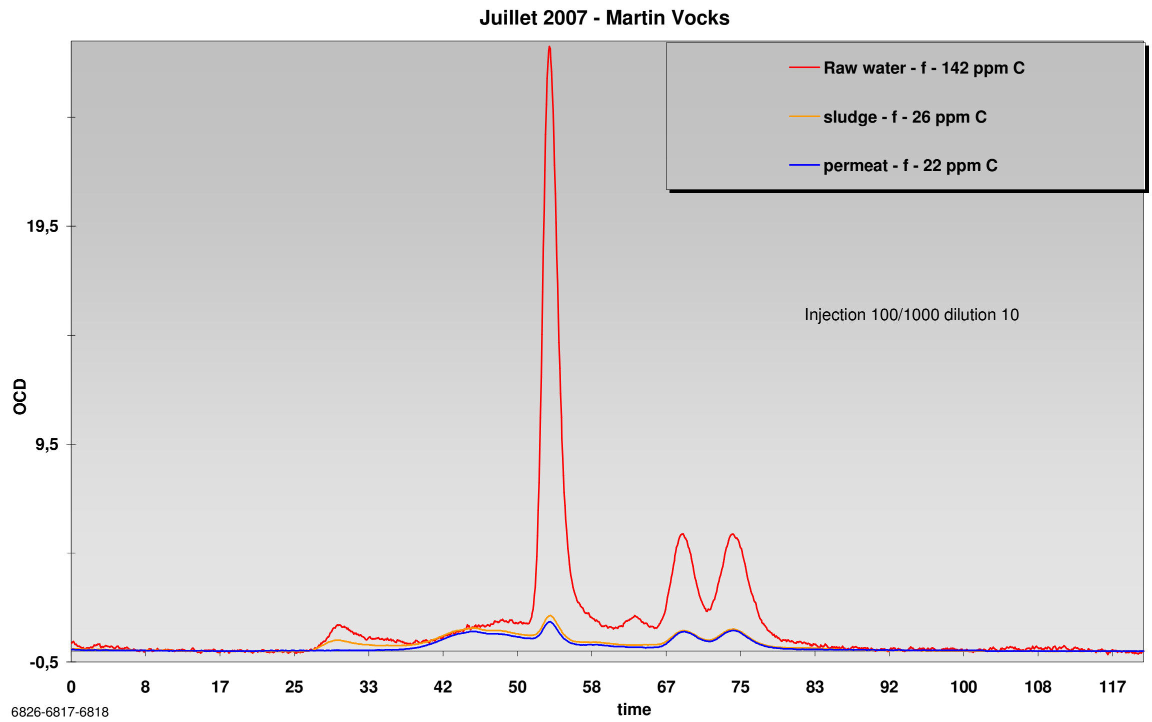


Figure 10: Profiles obtained in OC detection

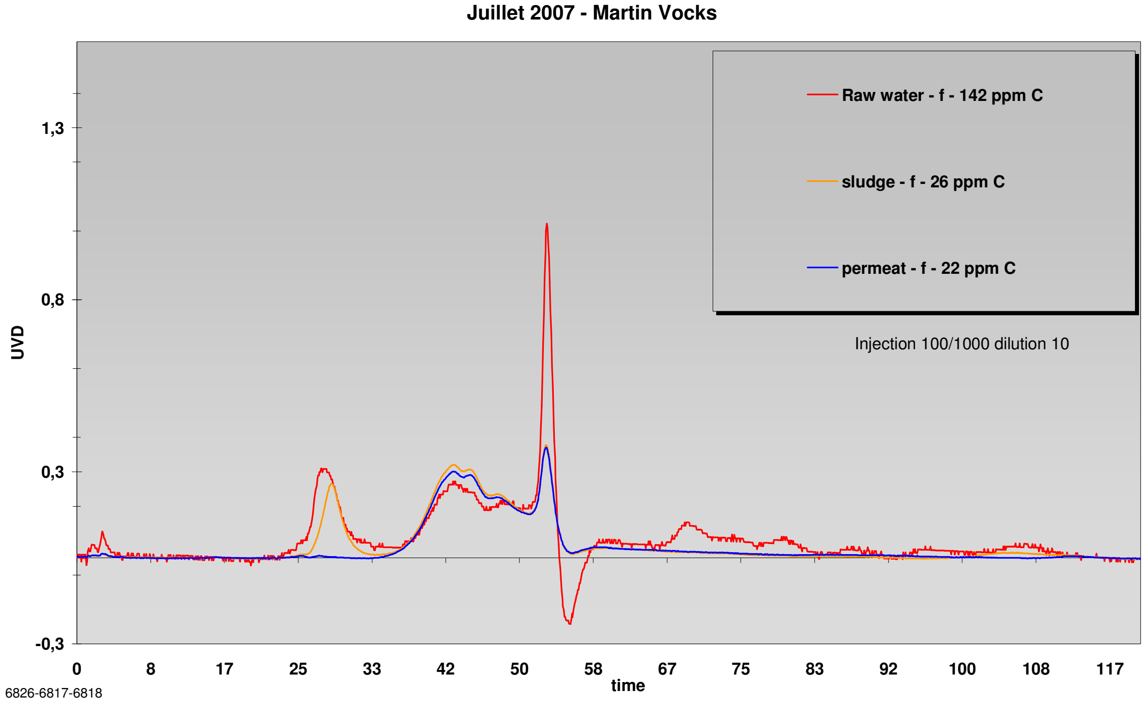


Figure 11: Profiles obtained in UV detection

Raw Water:

This sample presents a value of dissolved organic carbon of 142 mg C/L. The identified fractions are the following ones:

- Fraction A + N. Then, it is composed of small molecular compounds with a molecular weight < 350 g/mol. The peak at 52 minutes of low molar molar mass organic acid (non aromatic) is particularly high.
- Inorganic colloïds (table 7).

Sludge supernatant:

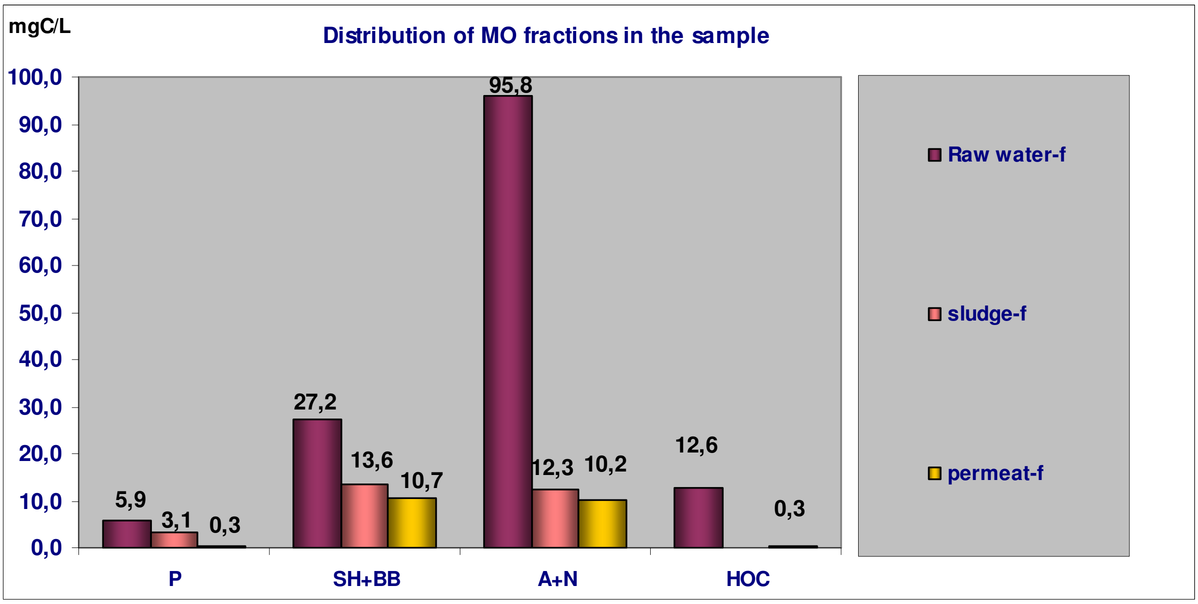
This sample presents a value of dissolved organic carbon of 26 mg C/L. The identified fractions are the following ones:

- the large peak between 35 and 50 min: humic substances and building blocks (by-products of the humic substance degradation);
- Fraction A + N. Then, it is composed of small molecular compounds with a molecular weight < 350 g/mol.

Permeate:

This sample presents a value of dissolved organic carbon of 22 mg C/L. The identified fractions are the following ones:

- the large peak between 35 and 50 min: humic substances and building blocks (by-products of the humic substance degradation);
- Fraction A + N. Then, it is composed of small molecular compounds with a molecular weight < 350 g/mol.



F

igure12: Diagram of organic matter distribution

Evolution of organic matter between influent and effluent:

The DOC removal rate is of 85% between raw water and permeate. Figure above shows the difference with both profiles. All fractions decrease: fraction P, SH+ BB, A+N and inorganic colloids. But the best removal concerns the A+N fraction : the acid peak at 52 min collapses and lead to a decrease from 96 mg C/L to 10 mg C/L of the A+N fraction.

The membrane filtration (difference between sludge supernatant and permeate) remove high molecular weight compounds: PS, proteins and colloids.

Conclusion

Organic matter characterization shows especially the presence in:

- Raw water: fraction A+N, organic acids and low molecular compounds, inorganic colloids;
- Sludge: fractions SH+BB, humic substances and A+N;
- Permeate: fractions SH+BB and A+N.

The treatment remove 85% of dissolved organic carbon and main part of the A+N fraction from the raw water is remove by treatment (divided by 8 in permeate).

ANALYSES OF SAMPLES FROM THE BERLIN MEMBRANE BIOREACTOR
THIRD CAMPAIGN SAMPLED ON 13TH, JUNE 2007

CONTEXT

For the third campaign, 3 membrane sheets have been sampled from the membrane bioreactor and sent for autopsy. Membranes have been then sampled after 4h chemical soaking and filtration with Cl_2 solution (1000ppm). Chlorine has been used to evaluate the efficiency compared to oxygen peroxide used for previous cleaning. Samples were located only in a module at different positions. During the membrane sampling, only small sludge deposit has been observed at the membrane surface. All membranes have been rinsed with tap water to remove the excess of sludge before sending membranes for autopsy.

MEMBRANE ANALYSES

Visual inspection

Deposits description and view of membrane are presented in table 8.

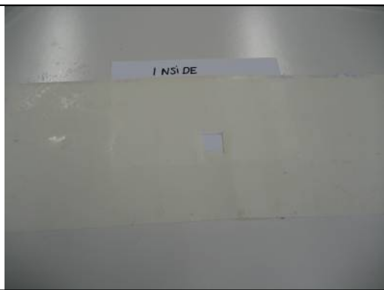
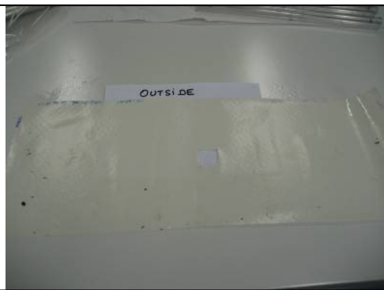
		Membrane inside	Membrane outside	Description
ENREM 1 LML	06-000441 Left middle module, Left side			On both side: - white - low deposit Strong chlorine odour
ENREM 2 LMM	06-000441 Left, middle module, Middle side			On both side: - white - low deposit Strong chlorine odour
ENREM 3 LMR	06-000441 Left, middle module, Right side			More deposit than others membranes White on both side Spacer structure is more visible in part of the membrane

Table 8: Both sides of the different membranes and deposit description

Membrane deposit analyses

Deposit extraction

The low deposit quantity when we received them did not allow us to perform a deposit extraction by scrapping. This latter has been performed by desorption of the entire membrane surface (863cm²) in deionized water and sonication.

Chemical and biological deposit characterization

The following analyses have been carried out:

- Scanning Electronic Microscopy (SEM) to determine the deposit morphology and EDAX for elementary composition of specific particles on the membrane,
- Measurement of mineral elements by Inducted Coupled Plasma (ICP) for a semi quantitative screening,
- Measurement of TOC to evaluate the organic part of the deposit,
- Organic matter characterization: analysis on LC-OCD system (Liquid Chromatography-Organic Carbon Detection)

Results

<u>Chemical analyses</u>

Results obtained for both membranes are exposed in the table 9

	LML	LMM	LMR
Membrane reference and position in filter	06-000441 Left, middle Left	06-000441 Left, middle Middle	06-000441 Left, middle Right
Organic matter (µg/cm²)			
TOC	3,6	3,3	11,6
DOC	2,3	2,2	2,7
Mineral elements (µg/cm²)			
Al	0,4	-	-
Ca	3,5	2,4	2,4
Fe	0,3	-	-
Mg	0,3	-	-
P	1,2	0,5	0,4
K	0,6	0,6	0,7
Na	3,3	3,7	3,6
S	1,2	1,2	1,0

Table 9: Chemical results for membrane analyses

Regarding the chemical results, all deposit membranes are composed by organic and inorganic matter.

For the organic matter, we observe that:
- TOC is equivalent on left and middle of the module, but on the right it is more important
- DOC is the same on all position of the module

The high level of Toc for the right side is linked to the presence of sludge deposit observed on the membrane surface.

For the mineral part, it appears that:
- Na and Ca are main mineral elements
- Small amount of Fe, Mn and Al are also detected
- Elements concentration are nearly the same on all position of the module

Organic matter characterization by LC SEC OCD

The LC-OCD system (Liquid Chromatography-Organic Carbon Detection) consists of a size exclusion chromatography column for separation of hydrophilic organic molecules according to their molecular size. The underlying principle is the diffusion of molecules into the resin pores. This means that larger molecules elute first as they can not penetrate the pores very deeply, while smaller molecules take more time to diffuse into the pores. The separated compounds are then detected by 2 different detectors: a UV detector (absorption at 254 nm) and a DOC detector. Depending on the size of the molecules, the response from both detectors, we can define the composition of the sample in term of organic fractions. Because, samples with large amounts of particles need to be filtered prior to injection on chromatography column, detectors only measure the dissolved organic fraction of the total organic carbon, i.e. ***65% of TOC for the left and for middle side, 25% for the right side****.*

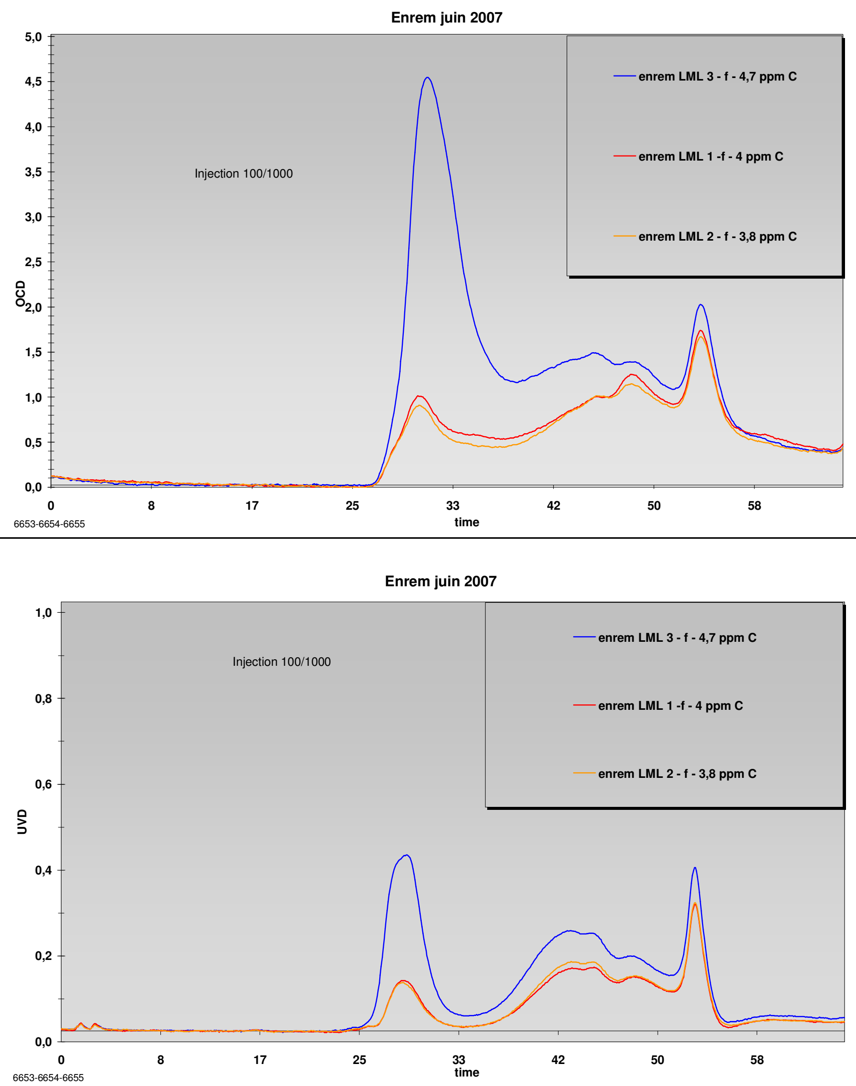


Figure 13: OCD and UVD profiles for deposits of membrane

Samples	TOC =	HOC + POC	CDOC	CDOC: P	CDOC: HS+BB	CDOC: A+N	HS: Aromaticity (SUVA)	HS: Mol-Weight (Mn)	UVD Colloid. Inorg.
	ppm-C	ppm-C	ppm-C	% TOC	% TOC	% TOC	L/(mg*m)	g/mol	SAC(m-1)
enrem LML 1 -f	4,0	2,1	1,8	11	32	3	1,47	727	0,34
enrem LML 2 - f	3,8	2,0	1,7	11	32	3	2,00	691	0,35
enrem LML 3 - f	4,7	0,6	4,2	44	41	3	1,70	784	1,32

Table 10 : Distribution of organic matter for 3 samples:

TOC: Total Organic Carbon
HOC: "non-chromatograph able", hence hydrophobic part of organic carbon
POC: particulate organic carbon, thus TOC may be too low for some surface waters
DOC: dissolved organic carbon

CDOC: "chromatograph able", hence hydrophilic part of organic carbon
SAC: spectral absorption coefficient, l = 254 nm
"P" or "Biopolymers" = Polysaccharides, Proteins, Aminosugars, Colloids
"HS" = Humic Substance
"BB" = Buildings Blocks - mostly breakdown products of humics
"A" for acids = Summaric value for monoprotic organic acids < 350 Da; low molecular molecules of Acids and HS
"N" for neutrals = include mono-oligosaccharides, alcohols, aldehydes, ketones and amino sugars and low-molecular weight compounds

Figure 13 shows for each detection, the overlay of obtained profiles for dissolved fractions of 3 samples.

Table 10 presents the distribution of organic matter for the 3 samples.

- The major fraction is fraction SH + BB. This fraction contains the humic substances (HS) and "Buildings Blocks" (BB) corresponding to the major fraction present in natural water (usually ~60% of TOC). The *SH* group contains generally organic molecules with high molecular weight (~100-10.000 g/mol).This group is usually subdivided into humins (non-soluble), humic acids (insoluble in acids) and fulvic acids (soluble in acids). Building Blocks represent about 15-25% of TOC in natural waters. They probably are highly substituted aromatic or conjugated acids with molecular weights of 350-500 g/mol. These sub-units may reflect HS hydrolysis products by age or sunlight photolysis. Building Blocks are more acidic than fulvic acids and are intermediates in the degradation process: fulvic acids – building blocks – low-molecular weight organic acids.
- Fraction P is more significant on the deposit from the right side than for the others. This fraction is composed of polysaccharides (including amino sugars, polypeptides) bio polymer, colloids and proteins (molecular weight >50.000 - 2 Mio. g/mol). Polysaccharides in surface waters originate from algal and bacterial cellular material or metabolic activity and they are hydrophilic and not UV-absorbing. Polysaccharides appear to be the most problematical class of compounds in water treatment in general. For information, fraction P presents 5-10% of COT for surface water.

<u>SEM and EDAX</u>
Views obtained from all membranes after SEM analysis and EDAX profiles obtained for the main particles detected by SEM are displayed in table 11.

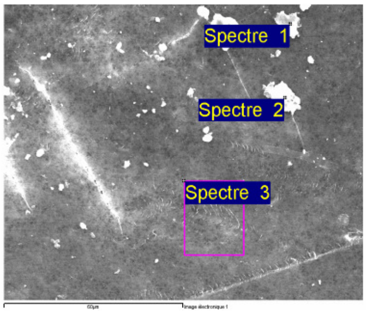
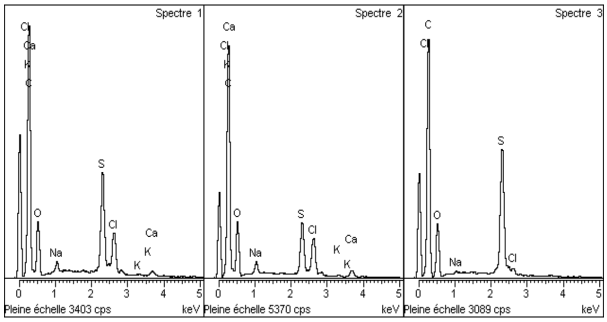
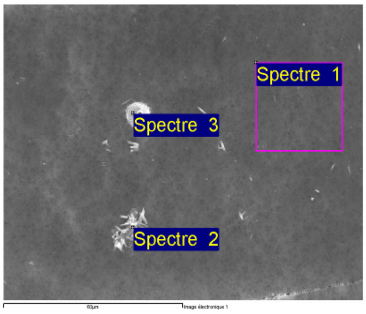
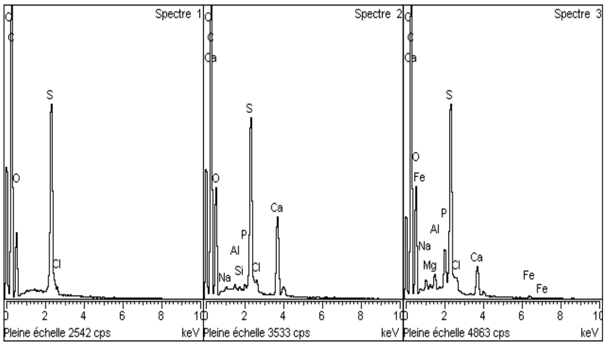
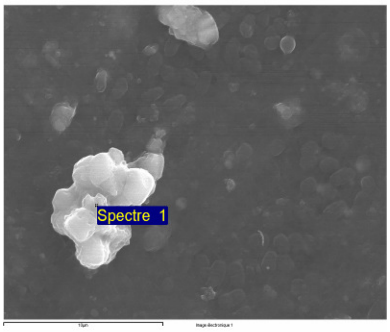
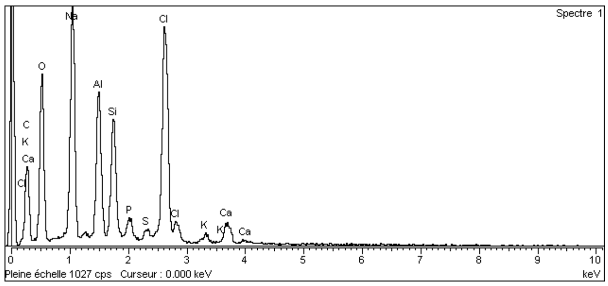
		SEM	EDAX
ENREM 1 LML	06-000441 Left middle module, Left side	 ***Magnification x1000***	
ENREM 2 LMM	06-000441 Left, middle module, Middle side	 ***Magnification x1000***	
ENREM 3 LMR	06-000441 Left, middle module, Right side	 ***Magnification x5000***	

Table 11: SEM views and EDAX profiles from different membranes

On SEM views, we observed, on membranes surface, organic matter, micro-organisms and mineral deposit.

On EDAX profiles, we can see main chemical elements:

- C, O and S which are also membrane components
- Cl and Na, probably comes from hypochloride soaking
- Ca, K, Al, Si from sewage

Conclusions

For all membranes received for this 3rd campaign, we observed that deposit was very slight and was composed by organic and inorganic matter.

Mineral composition was globally the same for three membranes. The two main mineral elements are calcium and sodium.

Characterization of organic matter showed that:

- humic substance fraction always detected like for the others campaigns, this fraction is also part of the sludge supernatant.
- polysaccharides and proteins fraction are very high for right side: 44% of DOC (11% for the other sides).

Moreover, the deposit from the right side shows also a higher concentration in non-soluble organic matter, probably linked to the “sludge clogging” observed on the membrane surface.

On SEM pictures, we could observe micro-organisms, organic matter and mineral deposit on membrane surface.

CONCLUSION OF AUTOPSY CAMPAIGNS

Membrane sampling for autopsy

The ENREM project (Enhanced Nutrients REmoval in Membrane bioreactor) is a European project included in the frame of the 6th Framework Program. The main goal is the development of MBR filtration technologies for municipal wastewater treatment. In this context, the Martin System membrane (PES) was evaluated for several months though a full scale plant located on the unsewered area of Berlin. The membrane bioreactor is composed by six independent modules and one of them can be removed and replaced by another one to maintain the process hydraulic. Then, regular autopsies have been planed during the full period of the project. Each module sent for autopsy was in operation since March 2006. Table 12 presents all samples received for autopsy: position in pilot and each test before extraction. After extraction, membrane was rinsed with tap water to remove excess sludge. Water samples from the plant have been also analyzed to characterize the organic matter.

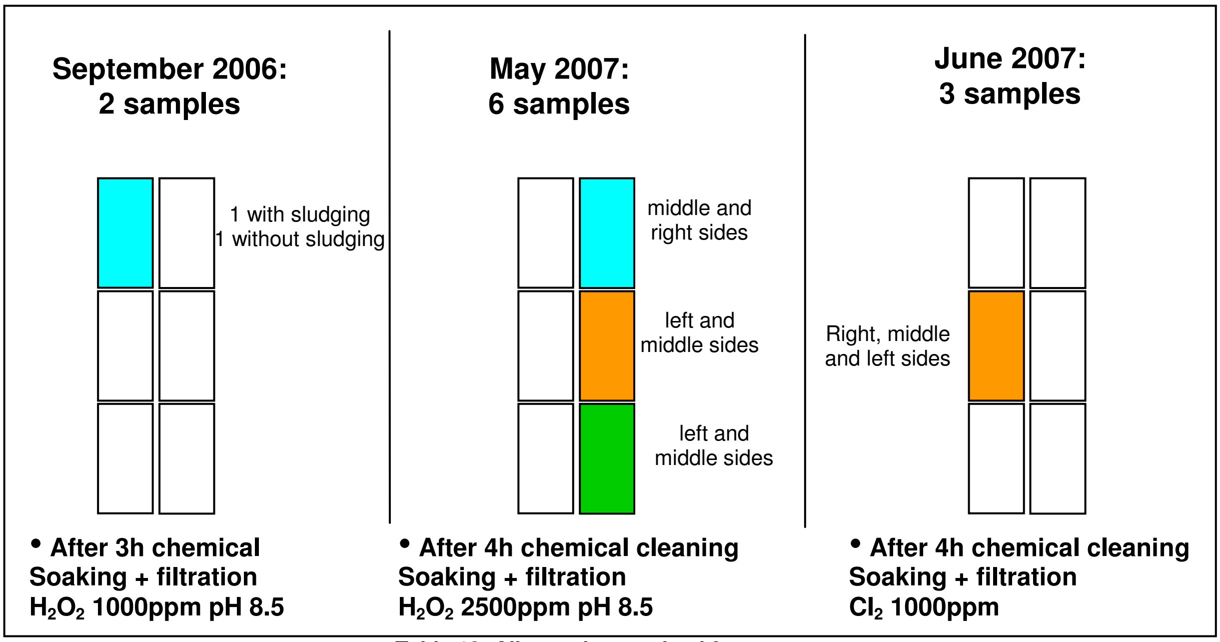


Table 12: All samples received for autopsy

Water characterization

Characterization of dissolved organic matter have been carried out by LC OCD technique for samples from the membrane bioreactor (waste water, sludge supernatant and permeate).

The main conclusions are the following 5 (Figure 14):

- The raw water (DOC 140 mg C/L) is mainly composed of small organic compounds with a molecular weight < 350 g/mol (fraction A + N) and colloids.
- The sludge supernatant is mainly composed of humic like substances (fraction HS+BB) and small organic compounds. Only a residual of the fraction A+N left after removal of the main part of this fraction from the raw water (divided by 8 in sludge supernatant)
- The permeate composition is similar from the one of the sludge supernatant. Membrane filtration removed high molecular weight compounds: PS, proteins and colloids. Total DOC removal from raw water is 85%.

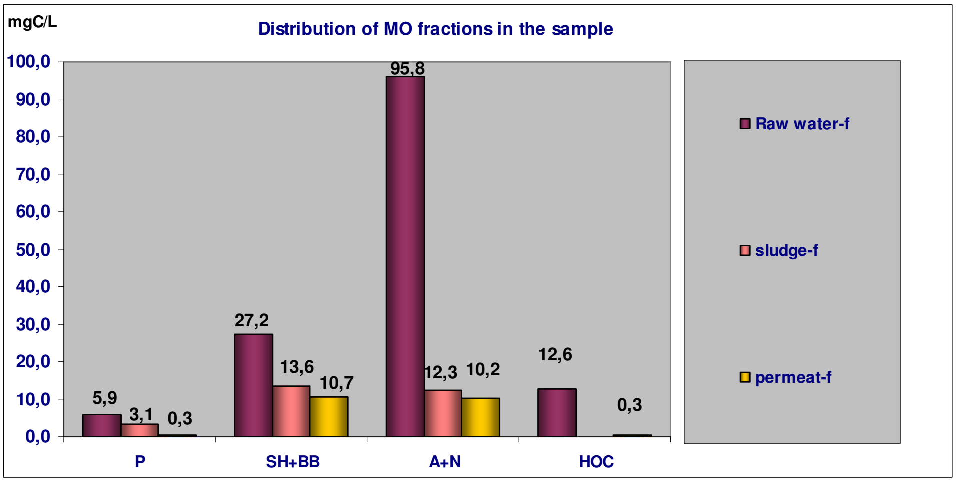


Figure 14: Organic matter composition evolution on water samples

Membrane autopsy protocol

Membrane autopsy starts with a visual inspection and deposit description. After deposit extraction, several analyses were carried out:

- Measurement of mineral elements by Inducted Coupled plasma (ICP)
- Measurement of TOC to evaluate the organic part of the deposit
- Organic matter characterization: analysis on LC-OCD (Liquid Chromatography Organic Carbon Detection) system
- Scanning Electronic Microscopy (SEM) and EDAX

Membrane deposit composition

For all samples, membrane deposit is very slight. The deposit is composed by organic and inorganic matter, but the organic part is greater than inorganic.

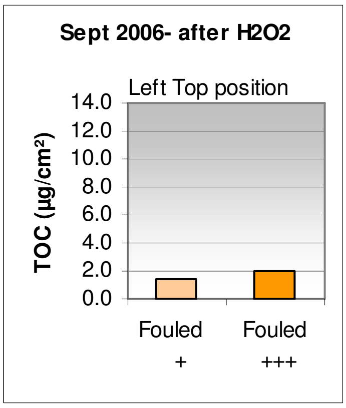
The dissolved part of the organic deposit is mainly composed of humic like substances (HS+BB fraction):

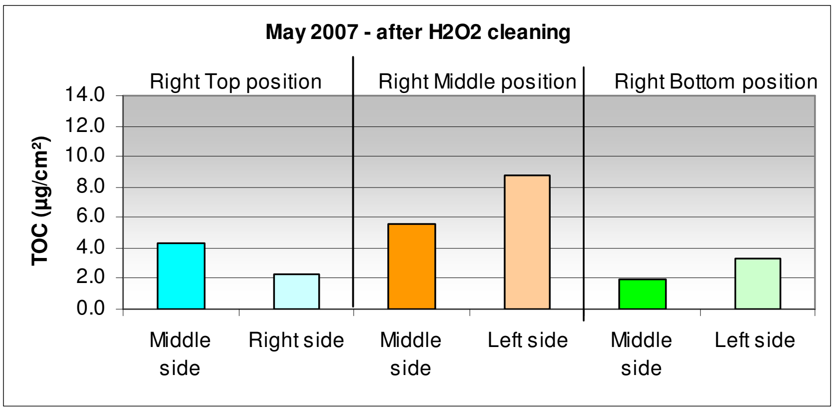
- September 2006: fraction HS+BB and PS are present in similar proportion
- May and June 2007: fraction HS+BB represents the main part of the DOC

Main conclusions on mineral composition depending on samples are the following:

- September 2006: small amount of Fe
- May 2007: three main mineral elements: Ca, Na and S
- June 2007: Ca, Na, S and small amount of Fe, Mn and Al

Organic matter evolution on membrane deposit





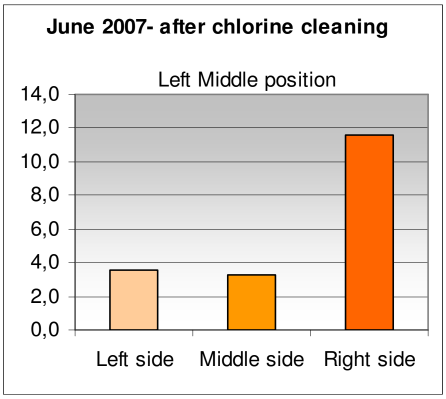


Table 13: Evolution of organic matter in deposit

Figures in table 13 shows:

- After cleaning, residual organic deposit is 2 µg/cm2 minimum for all campaigns
- Comparing the module position (may 2007), organic deposit is higher in middle position
- In June 2007, organic accumulation observed by LC OCD is confirmed for the right side of the membrane after chlorine cleaning

Mineral evolution on membrane deposit

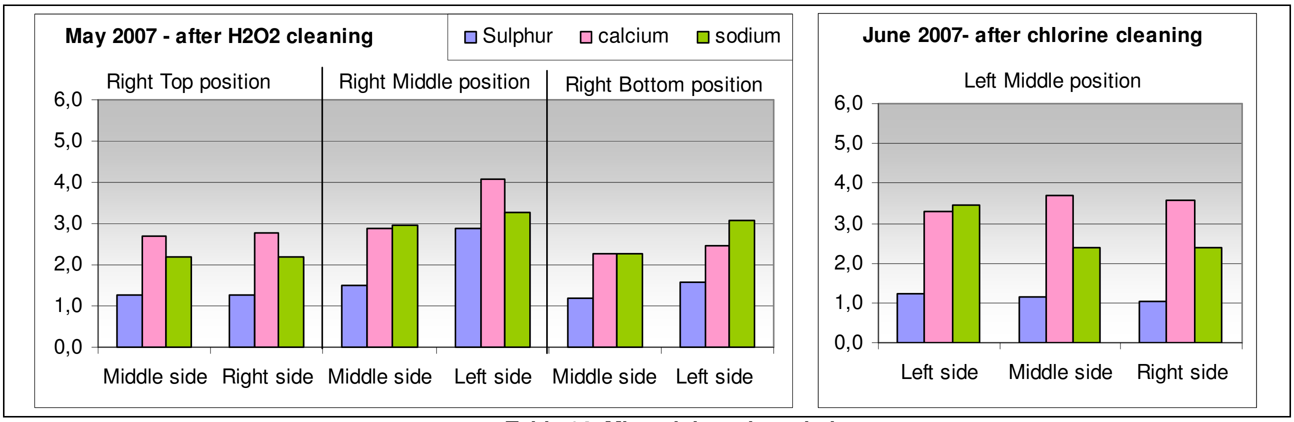


Table 14: Mineral deposit evolution

On table 14 representing mineral deposit evolution, we can conclude:

- Sulphur, calcium and sodium, not detected after 2 months of membrane operation, become major elements on following sampling membranes.
- Mineral elements concentrations are quite steady whatever the location or the module side.

Conclusions

With the different autopsy campaigns, the conclusions are the following:

- Deposit was very slight on all membranes sampled even after cleaning with peroxide or chlorine.
- Mainly organic deposit with slightly higher concentration is in the middle position of the module
- Bacteria observed inside the membrane structure perhaps because biofilm growth on substances released during phases anaerobic clogging.
- Humic substances identified are main foulant (UF membranes), better removed by NaOCl than by H_2O_2 but causing chemically irreversible fouling (permeability not recovered).

The following Annex gives a summary of the filtration performances which correlates the autopsy results (on figure 2 of the annex, the reference of the autopsied module is “cleaning module 2”).

ANNEX: FILTRATION PERFORMANCES OF TRIPPLE DECK MARTIN SYSTEMS MODULES IN ENREM PROJECT

FILTRATION SYSTEM AND MEMBRANE REACTORS

The membrane reactor had to be designed as small as possible (not more than 10% of biological reactor) but at least two parallel units. The third membrane zone is foreseen for the increase in flow capacity up to 24 m^3/d which means to increase the flux from usual 6 L/m^2h to 10 L/m^2h for all three membrane units. Another specification of the filtration system is that the filtration should not be completely off-line for longer than 5h (in case of cleaning etc). Martin Systems equipped each filtration vessel with two triple deck immersed flat sheet membrane modules as shown in Picture 1 (pore size app. 0.037 µm, and membrane area of 37.5m^2 for each module).

Picture 1 Martin Systems Membrane Module

The membrane reactors are fed by sludge originating from the last anoxic reactor AX2. The recycle rate of sludge concentrate from the membrane back to the first aerated reactor can be in the range of 400-700% related to inflow. This recycle rate results theoretically to a sludge thickening of 1.1-1.3 fold in the m

The strategies implemented to control fouling are adapted from the recommendations provided by Martin Systems and Anjou Recherche. The standard recommendations include the following:

4. *Membrane aeration:* Air scouring with ~0.6-1 $Nm^3/h/m^2$ through membrane aerators located at the bottom of the module. Ascending bi-phasic fluid sweeps up the membranes, and creates turbulent conditions that improves matter transfer and reduces solid or gel accumulation at the surface of the membrane.
5. *Relaxation cycle.* The membrane modules are operated with e.g. 10 filtration and 2 min relaxation time.
6. *Curative cleaning, or cleaning-in-place (CIP).* When the transmembrane pressure (TMP) reaches 30-40 mbar, extended curative cleanings are undertaken with hydrogen peroxide, acid or alkaline solutions.

ENREM aims to develop a process adapted to decentralised areas, therefore minimising the maintenance operation, and the use and handle of chemicals on site. It was therefore decided to operate the filtration system with very conservative filtration conditions below 10 L/m^2h. Also hydrogen peroxide (H_2O_2) was used for the CIPs. Chlorine was avoided as this chemical is not well accepted in the German water business due to the production of by-products such as AOX.
The data of the membrane and the filtration cycle are showed in Table 51. The productivity rate results from the situation that the operating flux is not given during the relaxation time and the starting period of the filtration pump.

Table 1: Details of membrane and filtration cycle parameter.

Type	**-**	**Ultrafiltration / Flatsheet**
Material	**-**	**Polyether sulfone (PES)**
Pore diameter	**nm**	**37 (UF)**
Membrane area	**m²**	**37.5 (per line / triple deck)**
Specific air demand	**Nm³/m²/h**	**0.6 – 1.0**
TMP max.	**mbar**	**300**
Operating instant flux	**L/m²/h**	**5 – 15**
Filtration time	**sec**	**700 – 999**
Relaxation time	**sec**	**100 – 143**
Productivity rate	**%**	**~ 85**
Operating net flux	**L/m²/h**	**4 – 13**

FILTRATION OPERATION PARAMETER

Table 2: Filtration operation parameter

Parameter **Period**		**1**	**2**	**3**	**4**
Time		**1.3.06-30.4.06**	**1.5.06-31.08.06**	**1.9.06-31.3.07**	**1.4.07-30.6.07**
Number of Filter in operation	-	1	2	2	2 / 1**
Net flux	l/m²/h	6 (2 – 13)	6 (4 – 10)	7 (3 – 10)	12** (10 – 17**)
TMP	mbar	6 - 50	40 - 180	80 - 240	50 - 170
Permeability	l/m²/h/bar	200 - 600	50 - 350	50 – 130	70 - 170
Specific air demand	Nm³/h/m²	0.3 – 1.0	0.7	0.5 – 0.8	0.5 – 0.6

** values from the new module

CHEMICAL CLEANING

The intention was to identify an appropriate cleaning protocol coping with the following constraints: no chlorine, no heating and a maximum cleaning time of 5 hours. The cleaning conditions attempted during the trials are listed in Table 153.

Cleaning 1 (March to December 2006)
It was first attempted to stick to the usual cleaning strategies of flat sheet membranes, performing a chemical soaking on a 3-month basis. The H202 cleaning showed a mediocre permeability recovery of 10 to 30%, at the end well below 10%. Both the quick permeability drop (probably due to great extent to module clogging) and the low permeability recovery, leading TMP values approaching the upper limit, were not satisfying.

Cleaning 2 (August to December 2006)
In the second half of 2006, another cleaning strategy of the membrane filters was therefore attempted, consisting of regular maintenance cleaning. A chemical solution (citric acid and hydrogen peroxide in a row) was being backwashed in sludge, mostly after mechanical cleaning. This mode of cleaning showed only short-term results and was stopped in Jan 2007.

Cleaning 3 (October 2006 to January 2007)
Heavy clogging required a disassembling of the modules and a manual cleaning of the interspaces of the flat sheet membranes with a water jet.

Cleaning 4 (January to April 2007)
A last attempt was to resort to chlorine soaking. The cleanings performed better but were still mediocre, showing a 10 to 15% permeability recovery.

Table 3: Cleaning conditions

Cleaning 1 (chemical soaking)	**Cleaning 2 (chemical backwash in sludge)**	**Cleaning 3 (mechanical cleaning)**	**Cleaning 4 (chemical soaking)**
2006/06 – 2006/12	2006/09 – 2007/01	2006/10 – 2007/01	2007/01 – 2007/04
Citric Acid 2000 ppm / 1h pH 3.4	Citric Acid 2000ppm/0.5h pH 3.3	Module disassembling	Citric Acid 2000 ppm / 1h pH 3.4
H2O2 1000 ppm / 3h pH 8.5	H2O2 2500 ppm /3h pH 8.7	Manuel plate interspace cleaning with water jet	Active Chlorine 1000 ppm /4h pH 9.5

EVOLUTION OF PERMEABILITY

The filtration performance is analysed on the basis of the measured permeability recalculated at 20°C to take into account the impact of permeate viscosity (see Figure 352). The membrane modules started with a permeability in sludge of around 700 L/m²/h/bar and decreased below 200 L/m²/h/bar after 2 – 3 month of operation (net flux of 4-8 L/m²/h). The first cleaning of two filters took place in June 2006. The permeability increased up to only 350 and 250 L/m²/h/bar respectively but dropped down below 100 L/m²/h/bar in August 2006. During this time, module clogging was observed the first time but it is supposed that clogging occurred before. Because of this problem an extra cleaning step was necessary, the so-called *mechanical cleaning*: The filters had to be disassembled and each 6 modules were then cleaned manually with a water jet to spray the solid sludge parts out of the channels between the membrane plates. This step took more than 4 hours for a single filter. After the reconstruction works in December 2006, filter clogging was not observed any more, however the permeability remained very low for the 3 filters (in the range of 50-150 L/m²/h/bar for a flux of 6-11 L/m².h), with a mean daily fouling rate of about 3mbar/d. The TMP rose frequently to the upper limit of

50 mbar, which was a cause of stress to the operators. It was therefore decided to replace the filtration system with another technology.

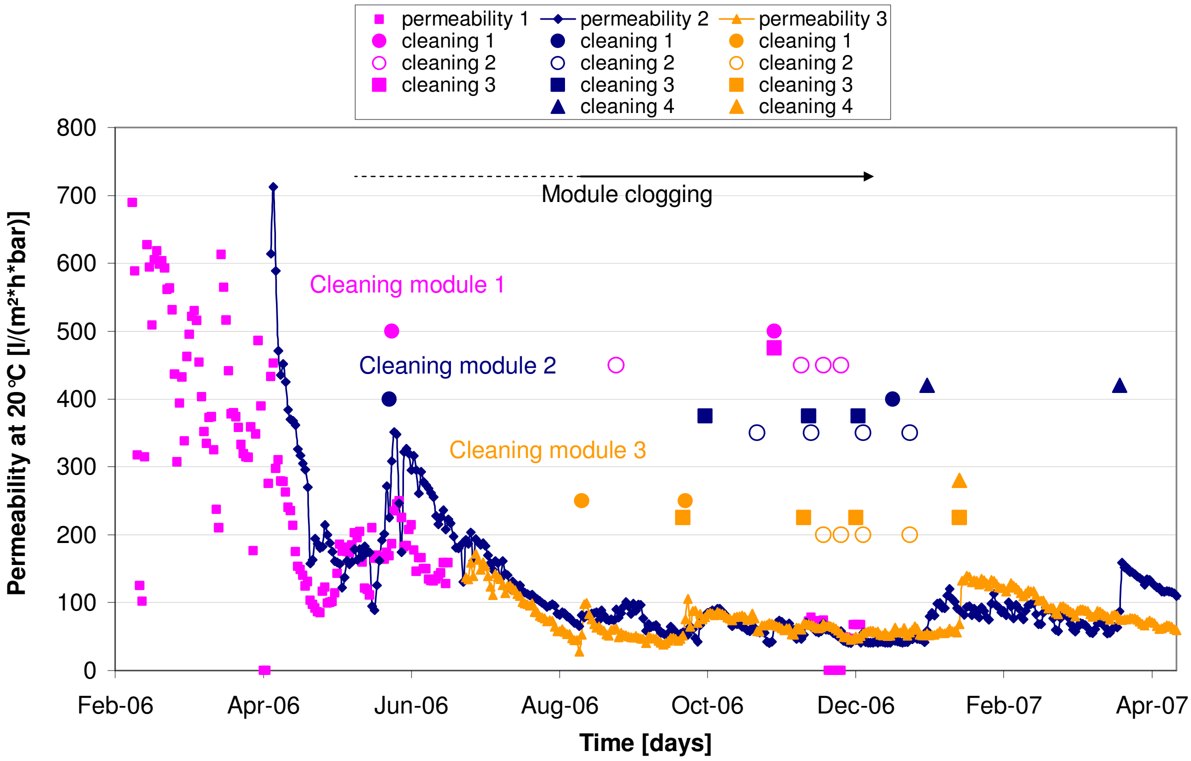


Figure 2: Filtration performance and module cleaning