

BMBF IWRM R&D Programme

Funding No.: FKZ 02WM1082

SMART – IWRM

Deliverable No. 316

**“Operation of a MBR pilot plant for
domestic waste water treatment and
influencing factors on the elimination
of micropollutants”**

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Date

08.03.2012

Funded by



**Federal Ministry
of Education
and Research**

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1 Objective

For the TZW one main objective of the SMART II project was the implementation of the MBR demonstration pilot plant for waste water treatment followed by further treatment to fulfill the water quality requirements with regard to artificial ground water recharge or irrigation. HUBER SE has planned and built a containerized MBR pilot plant and operated it for 10 months at a municipal waste water treatment plant (WWTP) in Berching. There the technical features were optimized and adjusted. In the second phase the MBR container was transferred to a TZW test site at a waste water treatment plant in Eggenstein-Leopoldshafen (WWTP EL). There start-up and operation were tested under remote control conditions for a time period of 6 months. The conditions of external operation were conducted in combination with simulated underground infiltration using soil columns. MBR effluent was infiltrated into two soil columns connected to the MBR treatment inside the container. The results of the operation of the soil columns are described in the deliverable 315.

Pollutant and pathogen elimination of the MBR are compared to conventional WWTP effluent. After the operation in Germany the container had to be transferred to the test site Fuheis in Jordan, where it will be operated for another 18 months.

In the present report the results of the MBR operation of the time period from April to September 2011 are described and discussed.

2 Operation of MBR container

2.1 Process description

A process scheme of the containerized MBR constructed by HUBER SE (Berching, Germany) is shown in Fig. 2.1. The treatment plant was operated from April to September 2011 at the conventional municipal WWTP in Eggenstein-Leopoldshafen (Germany). The daily throughput was adjusted between 5 to 6 m³ of waste water. Incoming waste water was first mechanically treated by a screening device (Rotamat Ro9-E®, HUBER SE) which removes particles with a diameter greater than 3 mm and then stored in the so called “Screening and buffer tank” (SBT). Preconditioned waste water from this intermediate tank is discontinuously (every 2-3 hours) pumped to the process tank, where the liquid level fluctuated.

The “Process chamber” (PC) ($V_{\text{Max}} \approx 6.1 \text{ m}^3$) included 2 stirrers for mixing, aeration devices for generating aerobic conditions, a pump for surplus sludge removal and online measuring devices for the determination of liquid level, the content of dissolved oxygen (DO) and total suspended solids (TSS).

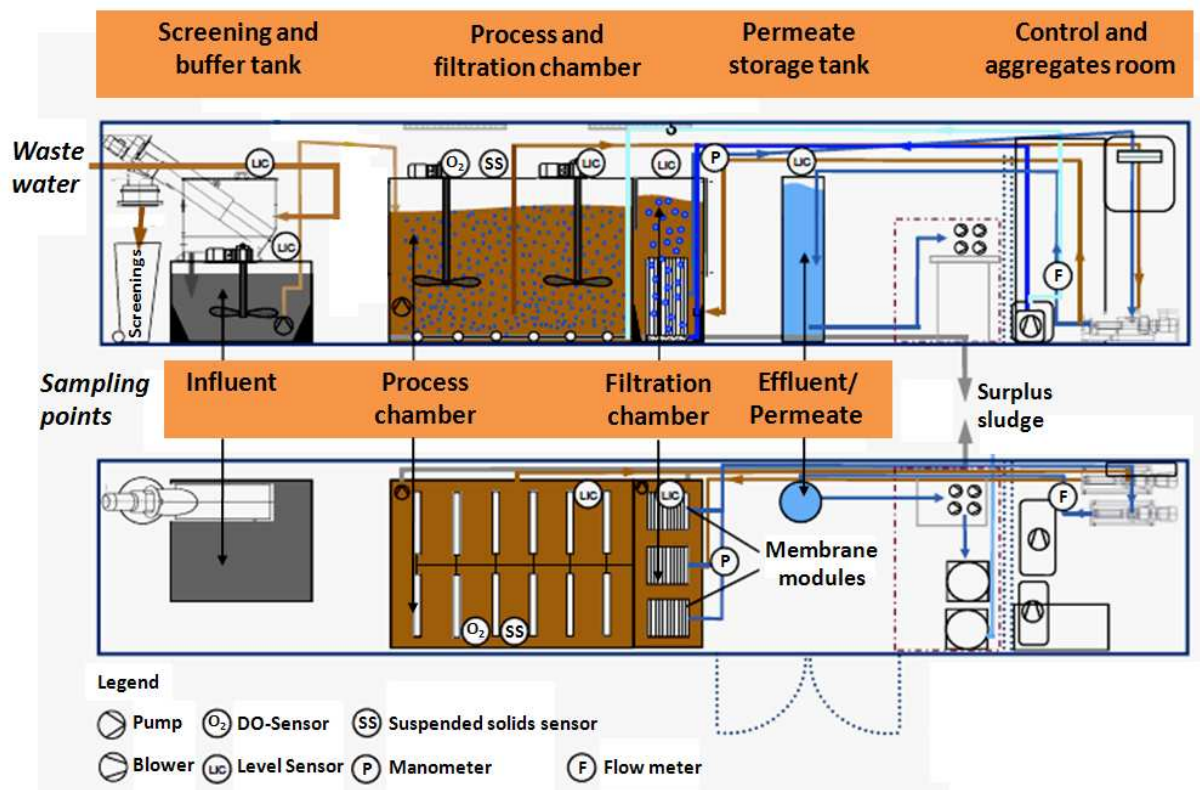


Fig. 2.1: Process scheme of the MBR.

The treatment in the MBR was started up with seeding sludge from WWTP EL. In the PC the activated sludge process with intermittent nitrifying and denitrifying conditions was realized. The sequence consisted of 4 phases as shown in Fig. 2.2.

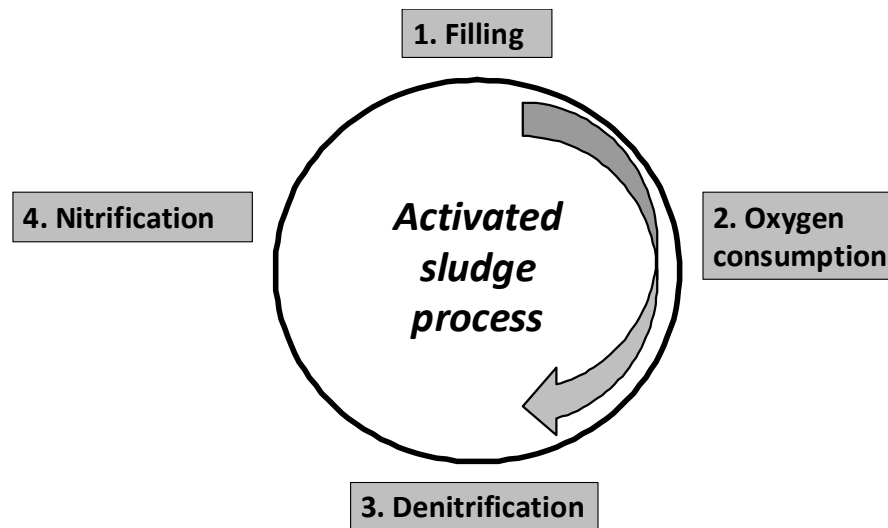


Fig. 2.2: Process cycle with 4 phases.

In the charging phase **(1.)** the PC was filled with the waste water from the SBT until the liquid level in the PC reached the maximum volume (6.1 m^3). In the second phase **(2.)** oxygen was consumed to a certain set point for DO ($\text{DO}_{\text{Set point}} = 0.5 \text{ mg/L}$). When this set point was reached denitrification **(3.)** started and was maintained over a preset time span. Only the stirrers were operated in the denitrification phase. Nitrification **(4.)** followed this third phase and continued over a given time. Both, aeration and stirrers were operated during nitrification. The DO concentration was controlled within this period.

Sludge was continuously removed from the PC by a (recirculation) pump and pumped into the so called "*Filtration chamber*" (FC) ($V \approx 2 \text{ m}^3$). There, excessive sludge dropped over a level drain back into the PC to regulate the biomass concentration in the FC.

In the FC a continuous membrane filtration with three module units (MembraneClearBox[®] MCB-4, HUBER SE) was operated. The modules were connected to a single suction pump and to a single pressure gauge. The flow rate was controlled by a flow meter. The membranes separated the biomass from the treated waste water called "*Permeate*" or "*Effluent*". The flat sheet Ultrafiltration membranes were made of Polyethersulfone, had a pore size of 38 nm and a membrane surface of 14 m^2 per module. The aeration of the membrane modules was applied as a cleaning measure necessary to prevent biofouling on the membrane surface. Aerobic conditions in the FC were maintained at all times.

Permeate from the membrane was pumped into the “*Permeate storage tank*” (PST) ($V \approx 0.1 \text{ m}^3$). From this tank permeate was used for infiltration of two soil columns and for further investigations like for example the operation of the filter column with activated carbon. Excess permeate was discharged into the sewer.

All processes within the MBR container were regulated manually or automatically by a programmable controller unit. The main settings during the long term experiment were documented in an operational diary.

After start-up of the pilot plant the biological processes of waste water treatment needed time for adaption. Because of an electrical defect of the dissolved oxygen sensor during the start-up phase the automatic control of the process was not possible until day 48. Aeration was timer controlled and the removal of surplus sludge was carried out manually. The adaption phase lasted until day 48 when surplus sludge removal and the regulation of the DO content were automatically controlled.

Thus, mean values and other derived values for the MBR and WWTP EL only include the period from day 49 to 149 covering 100 days of operation.

2.2 *Waste water characteristics*

The MBR was operated with mechanically treated waste water from the WWTP in Eggenstein-Leopoldshafen. The preconditioning included a bar screen (bar distance: 8 mm) and an aerated long grit chamber for sand and grease removal.

Further treatment in WWTP EL included the ASP with intermittent denitrification and phosphorus elimination by simultaneous precipitation.

The composition of the influent consisted mainly of domestic waste water with less than 12% extraneous water. WWTP EL was designed for 20.000 population equivalents (PE) and actually operated for 16.000 PE. Most of them were private households. A few farming businesses, a large bakery and a business working with metal were identified as greater polluters, but without significant influence on the treatment process. There were no hospitals or large medical practices connected to the drainage system. On the site of the WWTP EL an additional mobile unit for sludge dewatering and an overflow basin for rainwater were operated. Both units, during operation, introduced their process water to the influent.

As the biological activity of microorganisms and nutrient degradation is a function of **temperature** this parameter was measured on a weekly basis at all sampling points.

Measurements of **pH-value** were conducted on a weekly basis at all sampling points with a portable measuring instrument (pH 315i, Wissenschaftlich-Technische Werkstätten).

The concentration of **dissolved oxygen** (DO) was continuously measured with a process measuring sensor to be able to differentiate between the phases of nitrification and denitrification. The programmable controller unit regulated the DO concentration according to the set point values in Tab. 2.1.

Tab. 2.1: Regulation of DO.

DO-Regulation in the individual cycle phases						
	Charging	O ₂ consumption	Denitrification		Nitrification	
Time period	DO Set point	DO Set point	Duration	DO Set point	Duration	DO Set point
[d]	[mg/L]	[mg/L]	[Min.]	[mg/L]	[Min.]	[mg/L]
1-48	-	-	30	-	12	-
49-113	-	until 0.5	30	limit: 0.0	12	1.5-2.5
113-149	-	until 0.5	32	limit: 0.0	10	1.5-2.5

2.3 Methods

The parameter “**Total suspended solids**” (TSS) is a measure for the biomass concentration in an aeration basin. Values for TSS in the PC were determined by an optical online measuring sensor. The regulation was conducted discontinuously by manual or automatic surplus sludge removal. Additionally TSS was determined by a laboratory method on a weekly basis from both reaction chambers. A defined volume (250-500 mL) of biosuspension is filtered through a paper filter with known weight (MN 615, Macherey-Nagel), dried for 3-4 hours at 105 °C and weighted.

The parameter “**Sludge volume**” describes the settling behavior of sludge and is a first indicator for problems within the complex biological processes. A defined volume of sludge is poured into a graded cylinder and allowed to settle for 30 minutes. After this time the volume of sludge is noted. Measurements were conducted from samples of the PC and FC on a weekly basis.

The design of the pilot plant with the operation of submerged membranes allowed only a limited value of TSS up to 6-8 g/L in the PC and 12 g/L in the FC. The growth of microorganisms and the operational limits for TSS created the necessity to control the biomass concentration. **Surplus sludge** was removed discontinuously either manually or automatically. During the automatic operation a certain amount of biosuspension was

discharged when a threshold value for TSS was reached and when a set time was reached.

“Chemical oxygen demand” (COD) is a sum parameter for all the (organic) substances in a liquid that can be oxidized. The parameter is used to characterize the waste water quality according to its (organic) pollution. Measurements with rapid tests (LCK 414 and 514, Hach Lange) were conducted with samples from the influent and the effluent on a weekly basis. In these rapid tests potassium dichromate ($K_2Cr_2O_7$) is used as oxidizing agent.

“Biological oxygen demand” (BOD_5) (in 5 days) is a sum parameter for all the organic substances that can be degraded by microorganisms under aerobic conditions at 20 °C in a certain period of time. The result of such a measurement is expressed as an oxygen concentration. In BOD_5 measurements only biodegradable substances are oxidized. COD in relation to BOD_5 was used to evaluate the biodegradability of the waste water. BOD_5 was analyzed on days 86 and 108 from homogenized samples of the influent according to DIN 38409-H52. Measurements of BOD_5 in combination with COD resulted in a high ratio of COD to BOD_5 in the range of 4-6 which were not plausible values for this kind of waste water. The results are listed in Tab. 2.2.

Tab. 2.2: BOD_5 measurements.

BOD_5 measurements				
Sample	Day	COD	BOD_5	COD/BOD_5
	[d]	[mg/L]	[mg/L]	[]
Influent	86	744	200	3.7
Influent	108	508	86	5.9
Effluent	108	12.7	<1	-

The **nitrogenous substances** are responsible for a variety of negative environmental effects when released from a WWTP. Paper filtered samples (except measurement of N_{Tot}) from the influent and effluent were used to evaluate an elimination degree and to compare the discharging values with the Jordanian Standard. Rapid tests (NH_4 -N: LCK 302-304; NO_3 -N: LCK 339; NO_2 -N: LCK 341; N_{Tot} : LCK 138 and 338, Hach Lange) were used for measurements on a weekly basis.

Besides nitrogen microorganisms need **phosphorus** as a main nutrient for their metabolism. A release of phosphorus into surface waters must be minimized to avoid growth of algae. The discharging values of the pilot plant were evaluated and compared with the Jordanian Standard (see Tab. 3.2). Additionally the degree of elimination was calculated. Unfiltered samples from the influent and the effluent were used for the

measurements. Total phosphorus (P_{Tot}) was determined with rapid tests (LCK 348 and 350, Hach Lange).

Routine measurements of the influent and the effluent of the **WWTP Eggenstein-Leopoldshafen (WWTP EL)** were carried out by the staff of this facility. COD and P_{Tot} were weekly analyzed from time proportional 24 hour mixed samples of the influent and the effluent. The influent samples were taken at the same position where waste water was extracted for the pilot plant (see Fig. 2.3 for COD values).

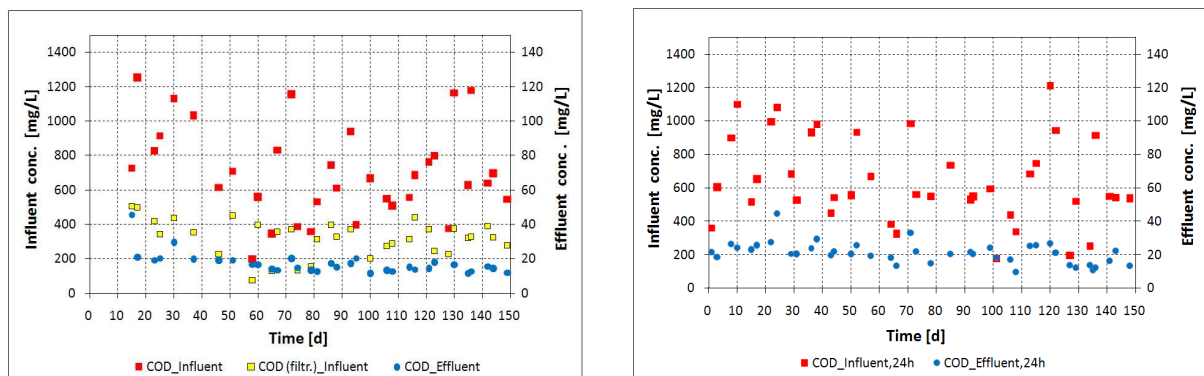


Fig. 2.3: COD – MBR (left) and WWTP EL (right)

2.4 Process parameters

To control the waste water treatment process several parameters were used as given in Table 2.3.

Tab. 2.3: Process parameters used.

Parameter	Unit	Definition
HRT Hydraulic retention time	[h]	$HRT = \frac{V_{PC+FC}}{V_{Permeate}}$
SRT Sludge retention time	[d]	$SRT = \frac{V_{PC+FC}}{V_{SS}}$
SVI Sludge volume index	[mL/g]	$SVI = \frac{SV}{TSS}$
Sludge load	[kg _{COD} /(kg _{TSS} *d)]	$Sludge\ load = \frac{V_{Permeate} * COD_{Inf}}{TSS_{PC}}$
Volume load	[kg _{COD} /(m ³ *d)]	$Volume\ load = \frac{V_{Permeate} * COD_{Inf}}{V_{PC}}$
Permeability	[L/(m ² *h*bar)]	$P = \frac{V_{Permeate}}{A_M} * \frac{1}{TMP}$ with temperature correction $P^{20^\circ C} = P^{T_{\infty}} * \exp[0.0239 * (20^\circ C - T_x)]$

- $\dot{V}_{Permeate}$: Permeate flow [m^3/h or m^3/d]
- V_{PC+FC} : Volume of process and filtration chamber [m^3] ($V_{PC} \approx 6 m^3$)($V_{PC+FC} \approx 8 m^3$)
- $\dot{V}_{SS}$: Surplus sludge removal [m^3/d]
- SV: Sludge volume [mL/L]
- TSS: Total suspended solids [g/L]
- COD_{Inf} : Influent COD [kg/m^3]
- TMP: Transmembrane pressure [bar]
- A_M : Membrane surface [m^2]
- $P^{20^\circ C}$: Normalized Permeability at $20^\circ C$ [$L/(m^2 \cdot h \cdot bar)$]
- T_x : Temperature x [$^\circ C$]
- $P^{T(x)}$: Permeability at $x^\circ C$ [$L/(m^2 \cdot h \cdot bar)$]
- 0.0239: Empirical factor [$1/^\circ C$]

The SVI is an important design parameter for aeration basins in conventional WWTPs and a first indicator to check process stability. SVI Values above 150 mL/g indicate an unstable process with a disturbed biofloc formation.

The evaluation of the sludge load was necessary to monitor and adjust the load in the MBR. A high sludge load could result in incomplete pollutant removal by the biologic system. As a consequence, biofouling on the membrane surface in combination with an incomplete nutrient removal could occur. HUBER SE recommended a sludge load below 0.1 kgCOD/(kg TSS*d) related to the volume of the PC only. Values of TSS were expressed as masses.

Fig. 2.4 demonstrates one treatment cycle in the PC (day 116 as example). The most important operational parameters are shown in the diagram.

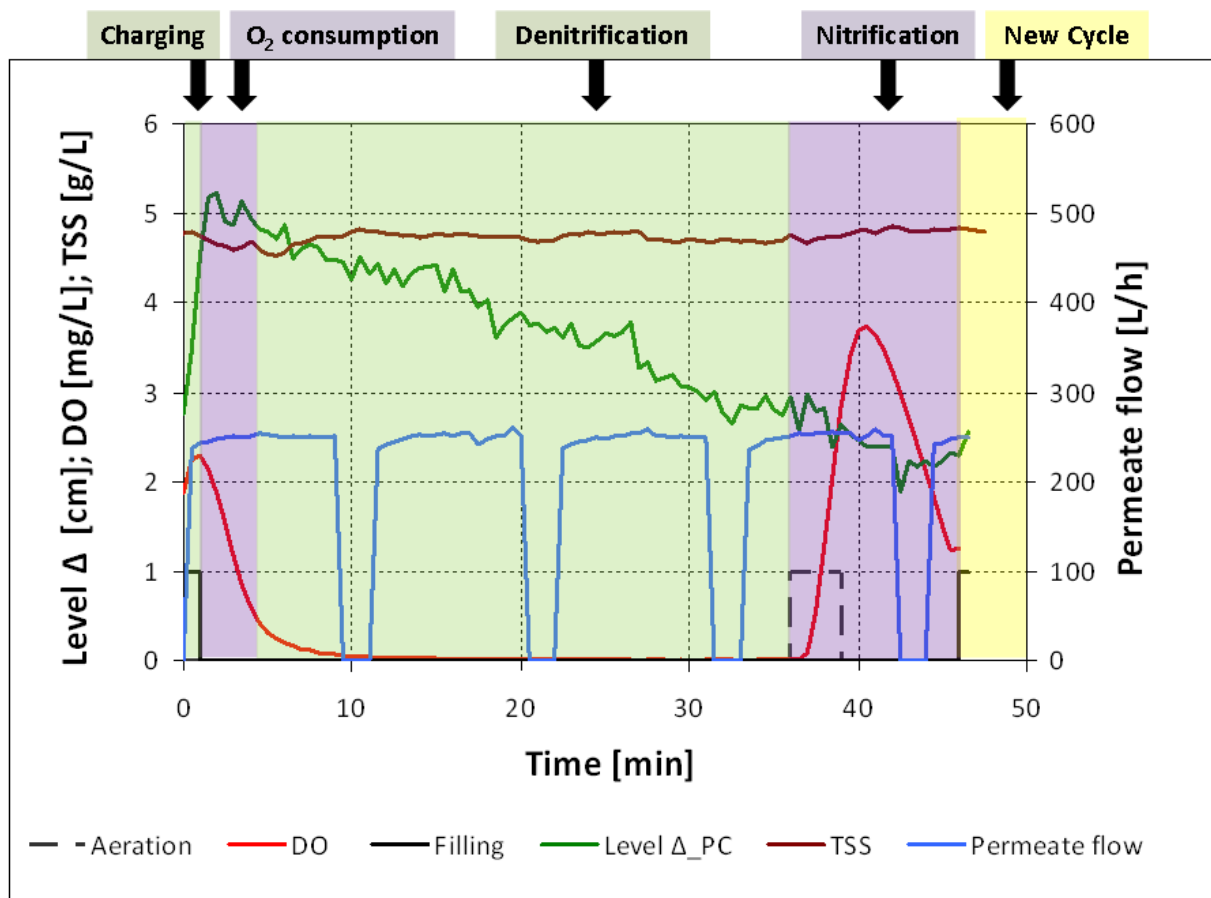


Fig. 2.4: Operation data of a single process cycle.

In the charging phase the PC was filled with waste water from the SBT. The liquid level (green line) was thus raised. It declined due to permeate extraction until the beginning of the next charging phase. Permeate (blue line) was withdrawn at a constant flow rate of 250 L/h with interception by membrane relaxation. During nitrification the aeration (black dotted line) was regulated by the DO content (red line). Although the limiting values were set between 1.5 and 2.5 mg/L the control of DO was not accurate. Peak values up to about 4 mg/L DO were obtained during nitrification. Values well below the set point of 0.5 mg/L were reached during denitrification. Biomass growth and surplus sludge extraction changed TSS during the course of a day. Differences during one cycle (brown line) were too small for a significant change.

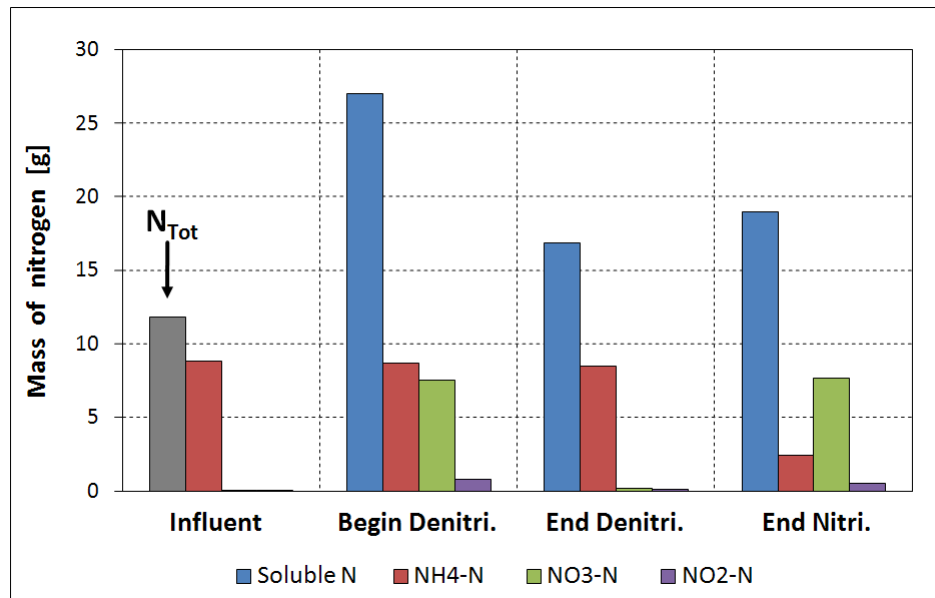
The soluble nitrogenous compounds were analyzed on days 116 and 123 in each phase of one complete cycle in the PC. The measurements should prove that nitrification and denitrification could be realized in the sequential process with the chosen conditions. An additional sample of the influent from the SBT was analyzed for comparison. Results are given in Tab. 2.3.

Tab. 2.3: Nitrogenous compounds – Raw data.

[Day 116] – 1 st measurement					
Parameter	Unit	Influent	Begin Denitri.	End Denitri.	End Nitri.
Time	[Min]	-	0	32	42
N _{dissolved}	[mg/L]	77.20*	4.45	2.78	3.13
NH ₄ -N	[mg/L]	57.40	1.43	1.40	0.40
NO ₃ -N	[mg/L]	0.37	1.24	0.03	1.26
NO ₂ -N	[mg/L]	0.23	0.13	0.02	0.08
Added volume from the SBT during charging phase: 154 L					
[Day 123] – 2 nd measurement					
Parameter	Unit	Influent	Begin Denitri.	End Denitri.	End Nitri.
Time	[Min]	-	0	32	42
N _{dissolved}	[mg/L]	63.30*	2.79	2.15	2.41
NH ₄ -N	[mg/L]	35.10	0.70	0.78	0.04
NO ₃ -N	[mg/L]	0.29	0.76	0.04	0.79
NO ₂ -N	[mg/L]	0.17	0.09	0.01	0.01
Added volume from the SBT during charging phase: 157 L					

* = N_{Tot}

In Fig. 2.5 the results from day 116 are shown as an example. The results of the rapid tests (measured as concentrations) were related to the individual volumes of the SBT (day 116, V_{SBT} = 0.15 m³) and the PC (V_{PC} = 6.1 m³) for comparison purposes. The operation of the recirculation pump was not considered (exchange volume in the PC during on cycle: ≈ 5 %).

**Fig. 2.5: Nitrogen removal during a single process cycle (day 116).**

The amount of NH₄-N (red column) which was added from the influent to the PC and at the beginning of the denitrification phase demonstrated that the measurements were precise

enough for this kind of evaluation. During denitrification $\text{NO}_3\text{-N}$ (green column) and $\text{NO}_2\text{-N}$ (purple column) were completely reduced. The amount of $\text{NH}_4\text{-N}$ remained constant in this phase due to the lack of molecular oxygen. As expected, conversion of ammonium to nitrate and nitrite during nitrification was evident. The amount of soluble nitrogen (blue column) declined in the denitrification phase. It is assumed that nitrogen in the form of nitrate was eliminated from the process as gaseous nitrogen. It can be seen in Fig. 2.5 that the blue columns for soluble nitrogen were higher than the sum of the other three columns. The reason for this difference may be attributed to different detection limits of the rapid tests used. In conclusion, nitrification and denitrification were successfully carried out in the MBR with the chosen operation conditions.

In Fig. 2.6 the time course of the SVI and the $\text{NO}_3\text{-N}$ concentration in the effluent is shown. Both parameters represent a measure for stability of the process cycle. Values of the SVI in the adaption phase decreased constantly suggesting that proper bioflocs were formed. From day 49 values of the SVI were well below 150 mL/g indicating that the sludge was adapted and stabilized during the whole period of investigation. Changes and fluctuations, as shown in the diagram for the SVI, were related to the surplus sludge extraction and the varying sludge loads.

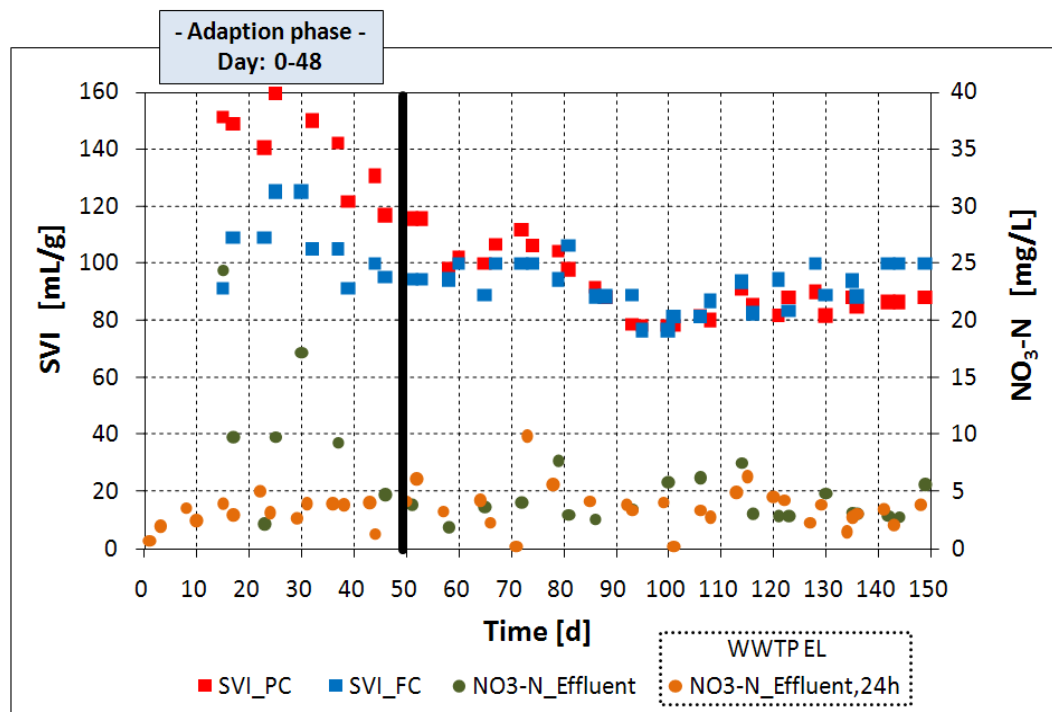


Fig. 2.6: Process stability.

Nitrate as a second parameter for process stability was chosen due to a specialty of the MBR. Permeate was extracted from the FC where aerobic and nitrifying conditions were present at all times. Surplus ammonium from the process cycle would leave the MBR in the form of nitrate.

The missing regulation of the DO content in the adaption phase (days 1-48) with values of $\text{NO}_3\text{-N}$ up to 24 mg/L showed that time control alone was not sufficient. In this phase the limiting value of the Jordanian Standard ($\text{NO}_3\text{-N}$: 6.8 mg/L) was exceeded permanently. During days 49-149 the concentration of $\text{NO}_3\text{-N}$ was higher at 2 measurements (day 79, $\text{NO}_3\text{-N}$: 7.7 mg/L and day 114, $\text{NO}_3\text{-N}$: 7.5 mg/L) than the limiting value. A significant improvement of the effluent values was evident after the modification of operating conditions on day 114. Values of $\text{NO}_3\text{-N}$ from the MBR and WWTP EL were found in the same magnitude (see Fig. 2.7).

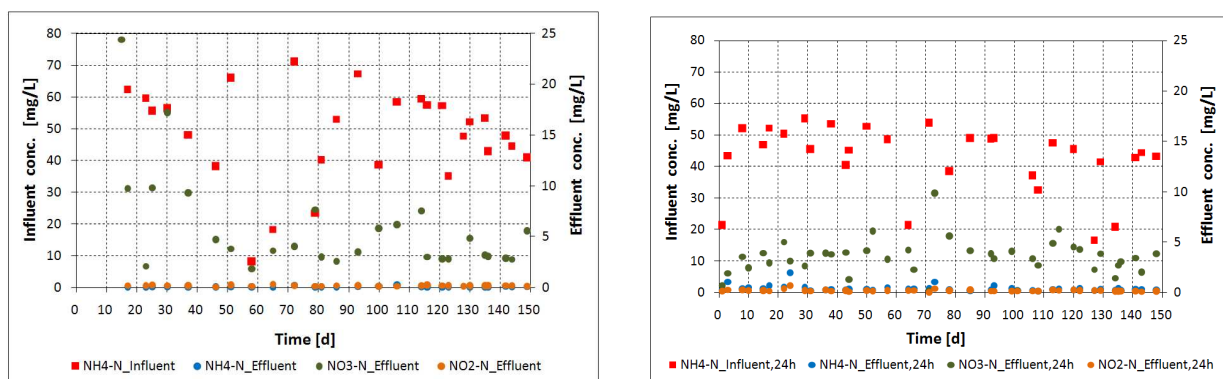


Fig. 2.7: Nitrogenous compounds – MBR (left) and WWTP EL (right).

In conclusion, the process in the MBR was stable in terms of the SVI and nitrate. Monitoring of nitrate and adjustments on the operating conditions are necessary to comply with the Jordanian Standard. Peak values of nitrate caused by the fluctuating loads or the configuration of the process could be buffered by a larger collection tank.

Fig. 2.8 displays the time course of the volume load related to COD from the MBR and WWTP EL. As expected, there were variations to the values of this parameter during the period of investigation in both treatment plants. Rain events, emptying of connected rain overflow basins and fluctuations in load over the course of a day had influence on the volume load.

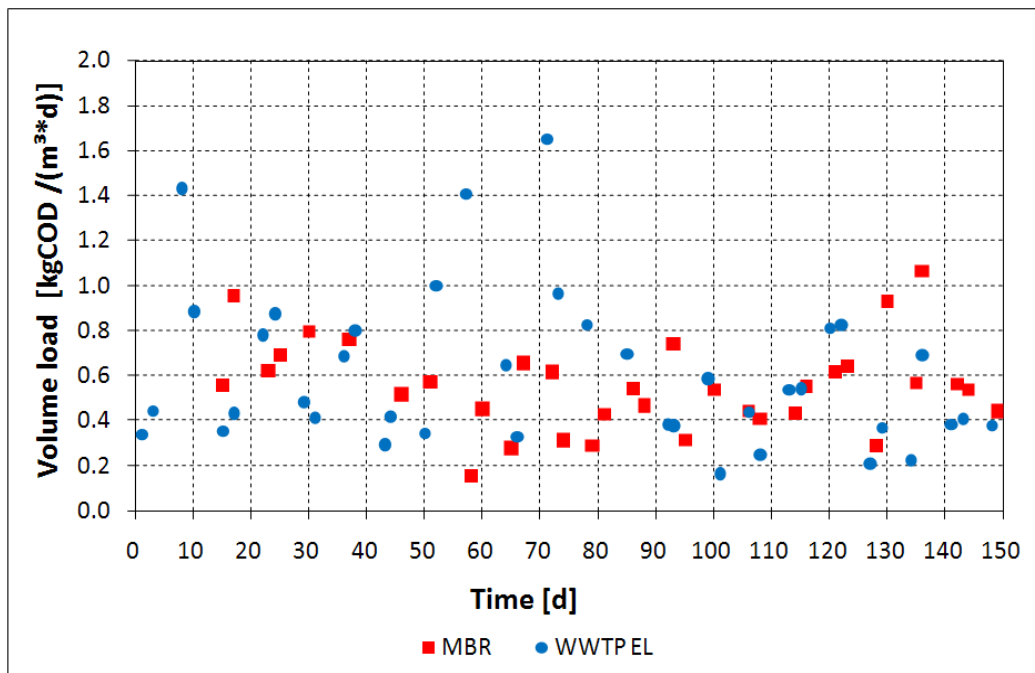


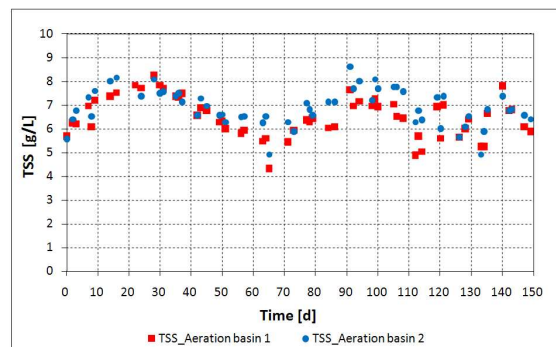
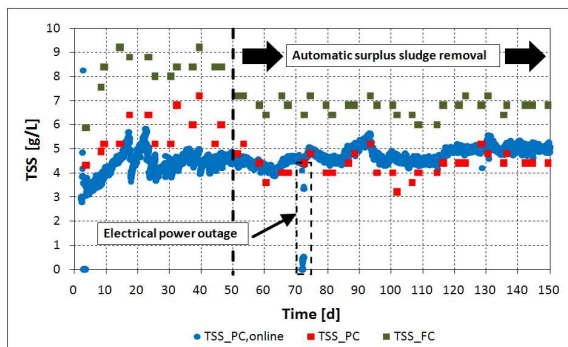
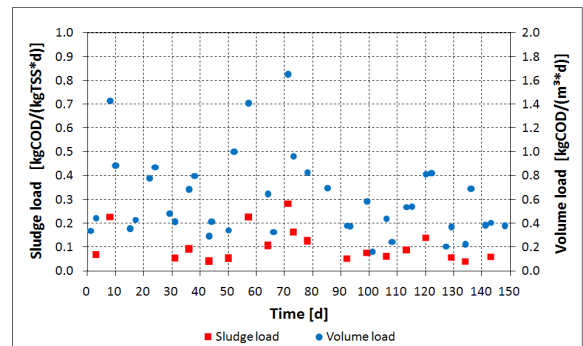
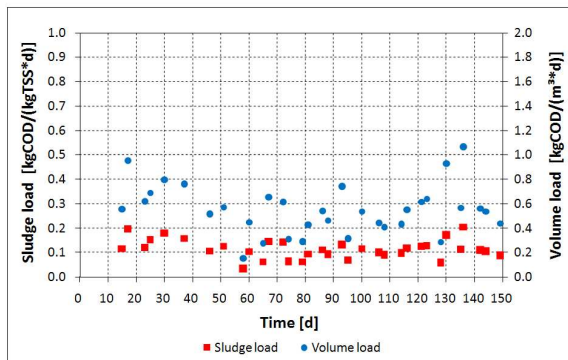
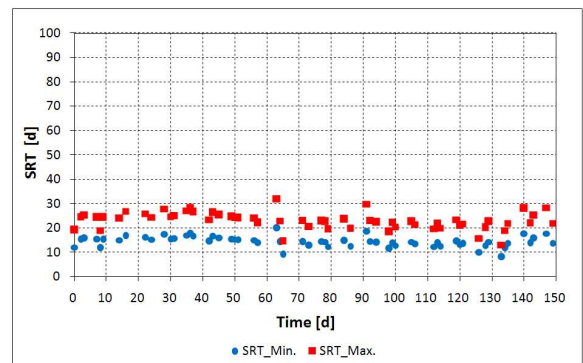
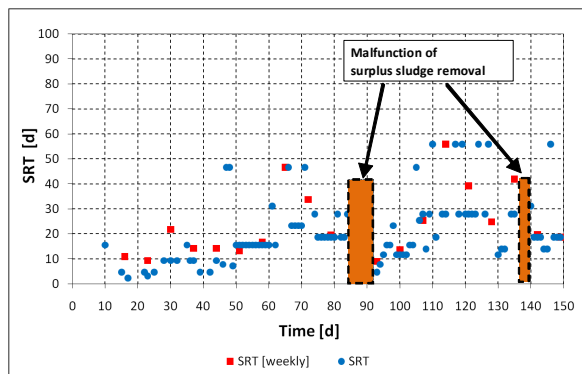
Fig. 2.8: Time course of volume load.

Values of the volume load from the MBR and the conventional WWTP were found in the same range (see Fig. 2.9). The differences in individual values from the two plants on any single day can be explained by different sampling techniques and varying operational conditions. Tab. 2.4 compiles an overview of the most important results related to the volume load, the sludge load and the SRT during the days 49-149.

Tab. 2.4: Volume load, sludge load and sludge retention time.

	MBR	WWTP EL
Volume load [kgCOD/(m³*d)]		
Maximum	1.06	1.65
Minimum	0.15	0.16
Mean value	0.51	0.59
Sludge load [kgCOD/(kgTSS*d)]		
Maximum	0.20	0.28
Minimum	0.03	0.04
Mean value	0.11	0.11
Sludge retention time [d]		
Maximum	56	20-32
Minimum	7	8-13
Mean value	23	14-22

Individual results are shown in Fig. 2.9 for the comparison between MBR and WWTP EL.



MBR

WWTP EL

Fig. 2.9: Individual results – comparison MBR (left) – WWTP EL (right)

From these results it can be concluded that the MBR and WWTP EL were operated under similar conditions. With regard to the SRT, fluctuations in the MBR were significantly higher compared to WWTP EL.

3 Removal efficiencies

3.1 COD and nutrient elimination

The compliance with the limiting values for the effluent set by the public authorities is most important for the successful operation of a treatment plant. In Fig. 3.1 the degree of elimination for COD is shown in relation to the volume load for the MBR and WWTP EL. The combination of these two parameters can be considered as a measure for the performance of a WWTP. On average 649 mg/L (MBR) / 592 mg/L (WWTP EL) of COD were found in the influent and 15 mg/L (MBR) / 19 mg/L (WWTP EL) in the effluent. The elimination of COD in both plants was well above 90% at all measured loads. Between a volume load of 0.25 to 1 kgCOD/(m³*d) 95 to 99% of COD were removed.

From these results it can be concluded that the degree of elimination of COD was comparable high in both treatment plants (see also Fig. 2.3, 2.7. and 2.9). The COD elimination in the MBR and in WWTP EL showed a slight increase with higher loads within the investigated range.

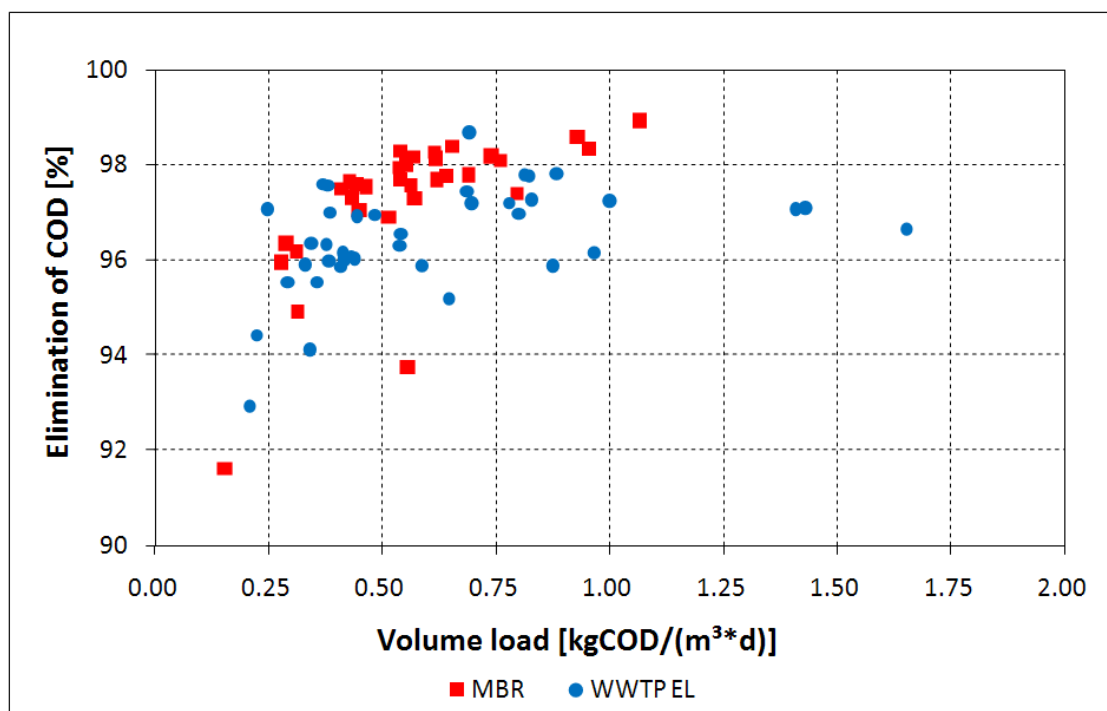


Fig. 3.1: Treatment performance.

An overview on nutrient elimination is shown in Fig. 3.2 including the mean values for COD, P_{Tot}, N_{Tot} and NH₄-N (also compare Tab. 3.1).

Tab. 3.1: Nutrient elimination – Summarized influent and effluent values.

	MBR		WWTP EL	
Parameter [mg/L]	Influent	Effluent	Influent	Effluent
COD (Maximum)	1179	20.2	1210	33
COD (Minimum)	198	11.4	177	9.9
COD (Mean value)	648.6	15.02	592.2	19.01
P _{Tot} (Maximum)	18.0*	6.88*	14.6	0.91
P _{Tot} (Minimum)	2.0*	3.57*	3.5	0.14
P _{Tot} (Mean value)	10.2*	5.13*	8.8	0.57
N _{Tot} (Maximum)	83.0	8.91	82.5	14.50
N _{Tot} (Minimum)	57.9	3.86	23.9	3.76
N _{Tot} (Mean value)	69.7	5.29	59.3	6.78
NH ₄ -N (Maximum)	71.1	0.27	53.8	1.07
NH ₄ -N (Minimum)	8.2	0.04	16.5	0.15
NH ₄ -N (Mean value)	46.8	0.09	40.8	0.34
NO ₃ -N (Maximum)	0.6	7.68	n.m.	9.84
NO ₃ -N (Minimum)	0.2	1.85	n.m.	0.23
NO ₃ -N (Mean value)	0.3	4.03	n.m.	3.71
NO ₂ -N (Maximum)	0.3	0.21	n.m.	0.42
NO ₂ -N (Minimum)	0.1	0.01	n.m.	0.02
NO ₂ -N (Mean value)	0.2	0.02	n.m.	0.18

*=Days 49-139 – Period without FeCl₃ dosing.

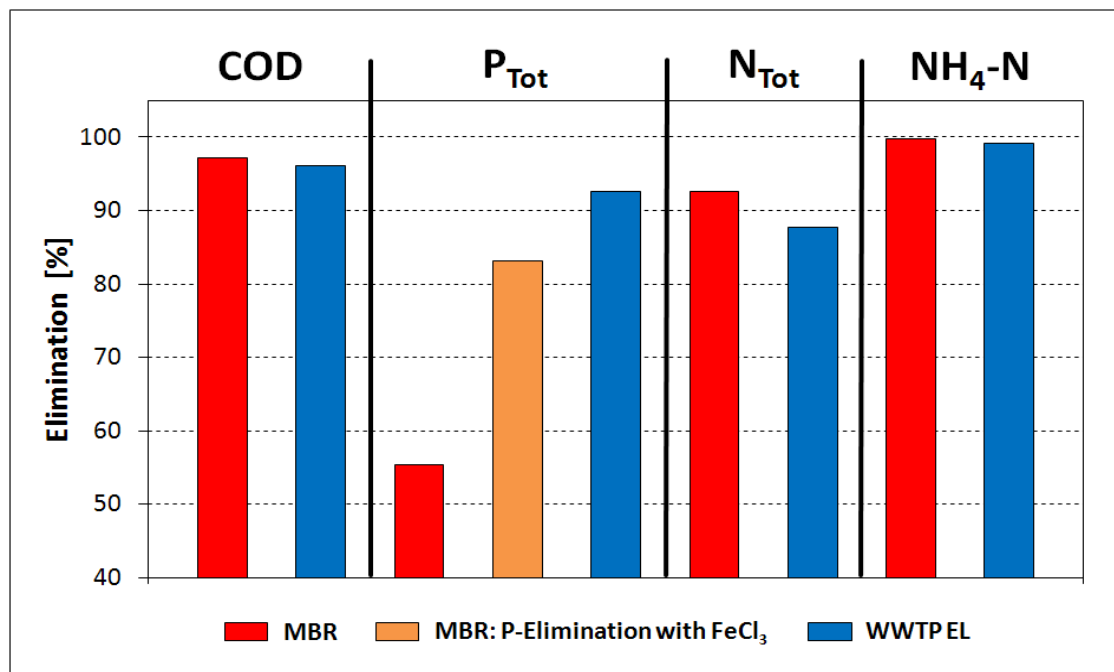


Fig. 3.2: Nutrient elimination.

The diagram shows that the MBR was able to remove more than 90% of all nutrients except for phosphorus. The degree of elimination for COD, N_{Tot} and NH_4-N was similar to the one in WWTP EL. The recorded values demonstrated the good performance of both treatment plants.

On an average, only about 55% of phosphorus was eliminated in the MBR (days 49-140). The reason for this low rate was the absence of a separate removal treatment for this substance. About 5 mg/L of P_{Tot} were released into the effluent exceeding the Jordanian limiting value (4.9 mg/L P_{Tot}). A reduction of the phosphorus concentration to a value of 1.0 mg/L in the MBR was possible by dosing iron(III)chloride ($FeCl_3$) into the FC following the principle of chemical precipitation. This elimination process was also implemented in the full size WWTP. Fig. 3.3 shows the unit for simultaneous precipitation installed in the FC and operated during days 140 to 149. The volume flow of $FeCl_3$ dosage (40%) was 16 mL/h corresponding to 15.6 mg/L Fe.



Fig. 3.3: Experimental setup for phosphorus elimination.

The outcome of this investigation showed that the phosphorus concentration in the effluent could be reduced to a value of 1.5 mg/L resulting in an elimination degree of $\approx 83\%$. The optimization of the $FeCl_3$ dosage or the selection of another precipitating agent could probably further minimize the effluent concentration of phosphorus and increase the elimination rate. A membrane blockage did not occur during this short period of precipitation. However, a long term investigation is needed to analyze the influence of this chemical agent and its byproducts on permeability.

In conclusion, COD, nitrogen and ammonium were successfully eliminated during the investigated period by the MBR. The simultaneous precipitation with iron salts is a possible measure to increase phosphorus elimination to acceptable values.

The operation of the MBR in Jordan for irrigation purposes is connected with stringent requirements [1]. In Tab. 3.2 the limiting values of the current Jordanian Standard for artificial groundwater recharge are displayed along with the results which were achieved during the operation of the MBR. TSS, *E.coli* and Helminthes eggs were not determined in this investigation due to organizational restraints. The values for COD, pH and $\text{NH}_4\text{-N}$ complied with the Jordanian Standard during the whole period of 100 days. However, the concentration measurement of $\text{NO}_3\text{-N}$ exceeded the limiting value only on two days. Phosphorus could not be eliminated with the current design of the MBR.

Tab. 3.2: Jordanian Standard for artificial groundwater recharge and MBR results.

Parameter	Unit	Limiting value (JS:893/2006)	Permeate			Elimination [%]
			Max	Min	Mean	
COD	[mg/L]	50	20.2	11.4	15.0	97.3
TSS	[mg/L]	50	b.d.	b.d.	b.d.	b.d.
pH-value	[]	6-9	8.0	7.7	7.9	-
$\text{NO}_3\text{-N}$	[mg/L]	6.8	7.7	1.9	4.0	-
$\text{NH}_4\text{-N}$	[mg/L]	3.9	0.30	0.04	0.09	99.8
N_{Tot}	[mg/L]	45	8.9	3.9	5.3	92.7
P_{Tot}^*	[mg/L]	4.9	6.9	3.6	5.1	55.4
<i>E.coli</i>	[MPN/100 mL]	<2.2	n.m.	n.m.	n.m.	n.m.
Helminthes eggs	[Eggs/L]	<1	n.m.	n.m.	n.m.	n.m.

*= Values do not include the operation of phosphorus elimination with FeCl_3 .

n.m. = not measured in this study, b.d. = below detection limit

In conclusion, waste water treatment with the MBR was successful. Questions to be solved for future applications should deal with nitrate monitoring, phosphorus removal and surplus sludge dewatering. In addition, the mechanical treatment of the influent by the MBR could be a relevant topic. The preconditioning of the influent during this study was conducted by WWTP EL.

3.2 Removal of microorganisms

A major advantage of MBR technology is its very good removal of particulate matter and microorganisms. Bacteriophages MS2 used as model parameter for viruses as well as total cell count and coliform bacteria were determined in samples from the process tank and the permeate taken on days 56, 107, 121 and 143.

A selection of representative results of the total cell count determination for the evaluation of removal of microorganisms is shown in Fig. 3.4. Further results are summarized in Tab. 3.3.

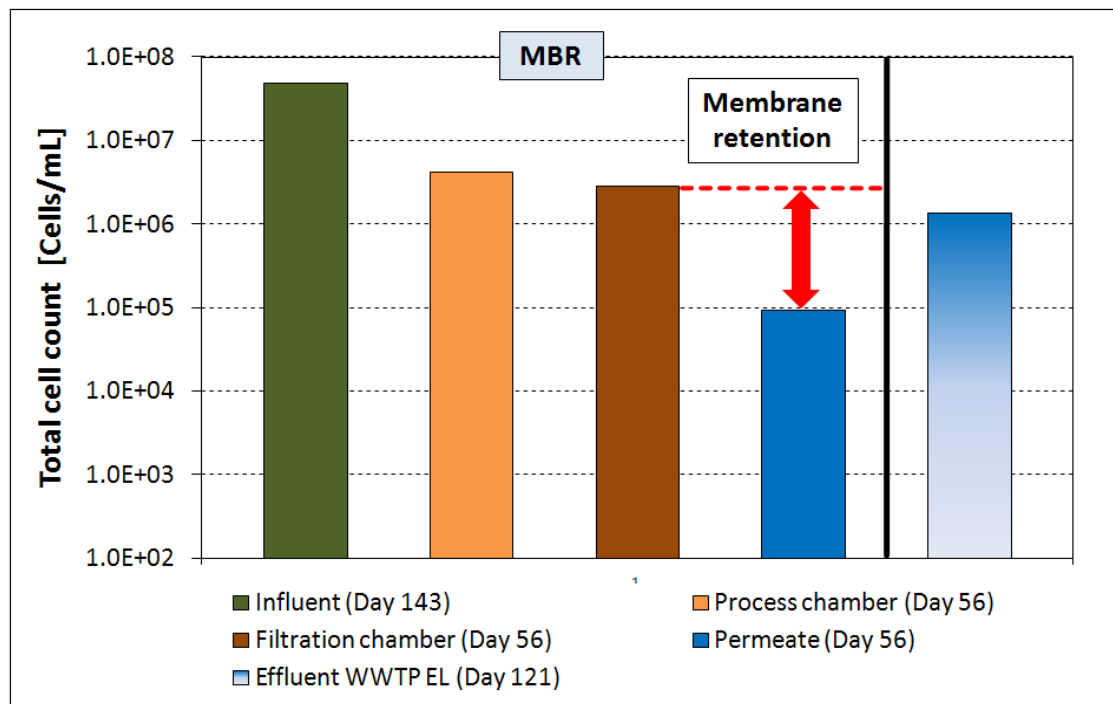


Fig. 3.4: Total cell count.

Tab. 3.3: Removal of microorganisms – Total cell count.

Sample	Total cell count			
	Day 56 [Cells/mL]	Day 107 [Cells/mL]	Day 121 [Cells/mL]	Day 143 [Cells/mL]
Influent	n.m.	3.72E+07	n.m.	4.94E+07
Process chamber	4.24E+06	n.m.	n.m.	n.m.
Filtration chamber	2.94E+06	n.m.	n.m.	n.m.
Permeate	9.53E+04	1.23E+05	1.17E+05	1.35E+05
Permeate (small MBR)*	6.59E+04	n.m.	n.m.	1.15E+05
Effluent WWTP EL	n.m.	n.m.	1.36E+06	n.m.

n.m. = not measured

* small MBR (same membrane, same influent, higher TSS)

At least 97 % of the cells were retained by the membrane on day 56. Retention was probably even higher as many cells (in sample “*Filtration chamber*”) were bound to particles and therefore could not be counted. The overall retention of the MBR for microorganisms was about 99 % on days 56 and 143. The large cell size of microorganisms in the micrometer range in comparison with the smaller membrane pore size of 38 nm justifies these high values. Concentrations from $9.5 \cdot 10^4$ to $1.4 \cdot 10^5$ cells/mL (days 56, 107, 121, 143) were counted as absolute numbers in the permeate. There was a significantly better cell retention in the MBR than in WWTP

EL on day 121 (Fig. 3.4). The total cell count in MBR permeate was about one order of magnitude smaller than in the effluent of WWTP EL.

Results for the determination of MS2-phages are summarized in Fig. 3.5 and Tab. 3.4. The percentage of retention in the overall MBR process is shown on the left of the chart. Samples of influent and permeate were evaluated for this representation. The percentage in membrane retention is shown on the right of the chart. Samples of the FC and permeate were evaluated for this representation.

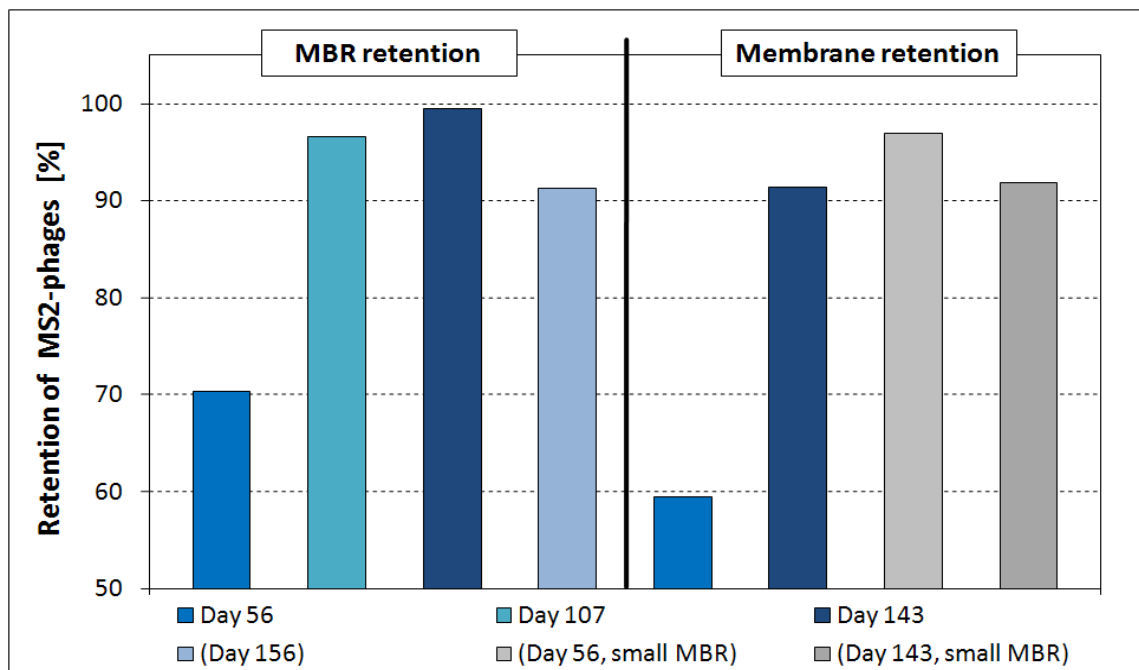


Fig. 3.5: Retention of MS2 bacteriophages.

The numbers of MS2-phages in the permeate were found in the range from $2.5 \cdot 10^3$ to $1.2 \cdot 10^4$ copies/L (days 56, 107, 121, 143). The results demonstrate the relative good retention potential of the MBR and the membrane on days 107 and 143. As a single MS2-phage with a size of about 25 nm is smaller than the membrane pore size of the membrane (38 nm), such good retention can be only explained by the adhesion of MS2-phages to the flocs or to microorganisms which were retained by the membrane.

The retention on day 56 was significantly lower (70 % MBR retention / 60 % membrane retention) than on days 107 and 143. Additional results from day 156 and from another MBR plant (small MBR*) operated with the same membrane and the same influent did not confirm these low values as shown in the diagram.

Tab. 3.4: Removal of viruses – MS2-phages.

Sample	MS2-phages				
	Day 56	Day 107	Day 121	Day 143	Day 156
	[Copies/L]	[Copies/L]	[Copies/L]	[Copies/L]	[Copies/L]
Influent	3.0E+04	9.8E+04	n.m.	5.2E+05	6.8E+04
Process chamber	2.4E+04	n.m.	n.m.	3.4E+04	n.m.
Filtration chamber	2.2E+04	n.m.	n.m.	2.9E+04	n.m.
Permeate	8.9E+03	3.3E+03	1.2E+04	2.5E+03	5.9E+03
Process chamber (small MBR*)	1.5E+05	n.m.	n.m.	2.1E+05	n.m.
Permeate (small MBR*)	4.5E+03	n.m.	n.m.	1.7E+04	n.m.
Effluent WWTP EL	n.m.	n.m.	2.2E+04	n.m.	n.m.

* small MBR (same membrane, same influent, higher TSS)

In conclusion, the MBR was able to reduce microorganisms (> 99.7 %) and MS2-phages (> 90 %) to a relatively high degree. The MBR effluent still contains high numbers of microorganisms and viruses when both parameters are shown in absolute numbers. It has to be mentioned, that these samples were taken during normal operation of the plant, where no further effort has been put on keeping the filtrate side of the MBR system completely sterile. In comparison to the effluent of the conventional WWTP EL the MBR produced water with a one log higher removal of microorganisms.

3.3 Elimination of micropollutants

To investigate the elimination of micropollutants samples were taken at days 107 and 121. 50 single compounds were analyzed which can be divided into different groups depending on the analytical methods applied. The groups are “*Beta blockers and the analgesic phenazone*” (1), “*Anti-inflammatory drugs/Analgesics/Lipid lowering agents and the antiepileptic Carbamazepine*” (2), “*X-ray contrast media*” (3), “*Steroid hormones*” (4) and “*Alkylphenols/ Bisphenol A*” (5). Elimination degrees for the overall process were calculated from samples of the influent and the effluent of the MBR, while a substance with an elimination rate below 10% was defined as persistent.

Time proportional 24 hour mixed samples from WWTP EL were analyzed for comparison. Samples from the influent were taken on days 106 and 120, samples from the effluent on days 107 and 121.

Results are summarized for the MBR in Tab. 3.5 for day 107 and in Tab. 3.6 for day 121 and in Tab. 3.7 for the WWTP EL for both sampling campaigns.

From 50 analyzed substances 24 were detected in both treatment plants.

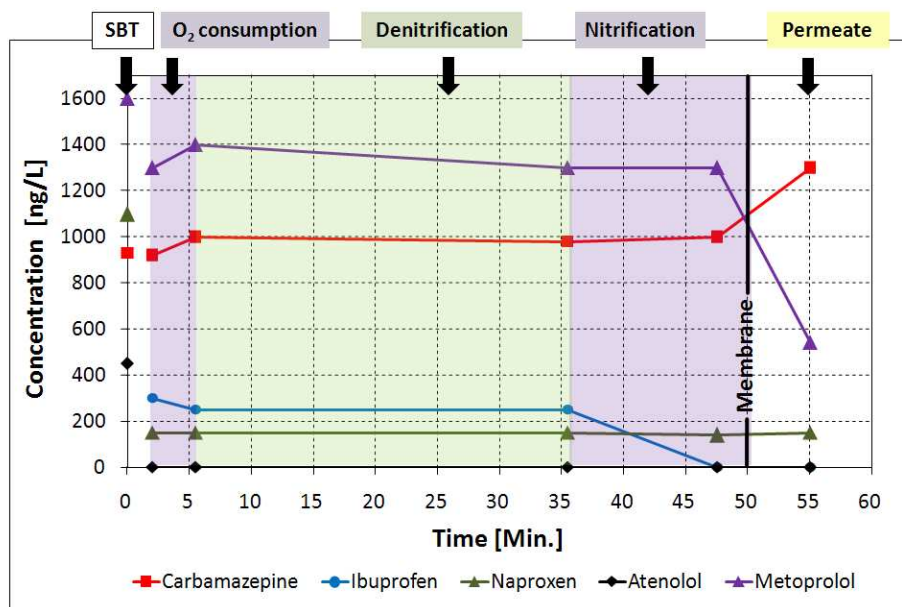
Tab. 3.5: Micropollutant analysis – Samples of the MBR [Day 107].

Samples of the MBR [Day 107]							
Substance [ng/L]	Group	SBT Influent	PC after charging	PC after O ₂ consumption	PC after Denitri.	PC after Nitri.	PST Permeate
Atenolol	1	450	< DL	< DL	< DL	< DL	< DL
Bisoprolol	1	440	190	210	190	200	< DL
Metoprolol	1	1600	1300	1400	1300	1300	540
Phenazone	1	< DL	390	400	490	530	100
Sotalol	1	240	210	200	220	220	170
Bezafibrate	2	3200	160	140	100	< DL	< DL
Carbamazepine	2	930	920	1000	980	1000	1300
Diclofenac	2	1600	310	190	< DL	< DL	2000
Fenofibric acid	2	330	< DL	< DL	< DL	< DL	< DL
Gemfibrozil	2	220	< DL	< DL	< DL	< DL	< DL
Ibuprofen	2	11000	300	250	250	< DL	< DL
Ketoprofen	2	120	< DL	< DL	< DL	< DL	< DL
Naproxen	2	1100	150	150	150	140	150
Pentoxifylline	2	120	< DL	< DL	< DL	< DL	< DL
Phenacetin	2	< DL	< DL	< DL	< DL	< DL	< DL
Amidotrizoic acid	3	1700	3900	4600	4700	5600	4500
Iohexol	3	6600	6300	5300	5100	4800	3100
Iomeprol	3	2700	4700	5200	4700	4600	3700
Iopamidol	3	< DL	< DL	< DL	< DL	< DL	< DL
Iopromide	3	< DL	1300	1300	1200	1200	980
Ioxitalamic acid	3	710	530	580	480	490	500
Estriol	4	120	< DL	< DL	29	< DL	< DL
Estron	4	240	< DL	< DL	< DL	< DL	< DL
Bisphenol A	5	510	< DL	< DL	< DL	< DL	< DL

Fig. 3.6 shows the results of the micropollutant analysis during a process cycle on day 107 in the PC of the MBR. The change of concentrations demonstrates the influence of the individual phases in the process cycle. An additional sample was withdrawn from the SBT prior to this cycle and a permeate sample was taken within 10 minutes after the end of the cycle to evaluate the influence of the sludge separation. Carbamazepine, Ibuprofen, Naproxen, Atenolol and Metoprolol were selected out of 24 detected substances for a better demonstration of the results.

Tab. 3.6: Micropollutant analysis [Day 121] – Samples of the MBR.

Samples of the MBR [Day 121]							
Substance [ng/L]	Group	SBT	PC	PC	PC	PC	PST
		Influent	after charging	after O ₂ consumption	after Denitri.	after Nitri.	Permeate
Atenolol	1	600	< DL	< DL	< DL	< DL	< DL
Bisoprolol	1	570	300	290	280	280	56
Metoprolol	1	4900	1600	1500	1500	1400	590
Phenazone	1	< DL	150	130	< DL	< DL	< DL
Sotalol	1	600	340	340	350	330	270
Bezafibrate	2	2300	110	< DL	< DL	< DL	< DL
Carbamazepine	2	1400	1700	1700	1700	1100	2000
Diclofenac	2	1600	1100	1100	1100	1500	3200
Fenofibric acid	2	170	< DL	< DL	< DL	< DL	< DL
Gemfibrozil	2	170	< DL	< DL	< DL	< DL	< DL
Ibuprofen	2	13000	420	360	350	230	< DL
Ketoprofen	2	250	< DL	< DL	< DL	< DL	< DL
Naproxen	2	710	220	240	220	260	200
Pentoxifylline	2	110	< DL	< DL	< DL	< DL	< DL
Phenacetin	2	< DL	< DL	< DL	< DL	< DL	< DL
Amidotrizoic acid	3	800	1300	1900	1800	2100	2000
Iohexol	3	2500	1900	1500	1900	2200	1400
Iomeprol	3	73000	42000	37000	37000	38000	21000
Iopamidol	3	170	1100	1100	1200	1200	1100
Iopromide	3	< DL	< DL	< DL	< DL	< DL	< DL
Ioxitalamic acid	3	830	490	480	410	490	350
Estriol	4	< DL	< DL	< DL	< DL	< DL	< DL
Estron	4	< DL	< DL	< DL	< DL	< DL	< DL
Bisphenol A	5	650	71	55	94	< DL	< DL



Not shown in the diagram: Ibuprofen [SBT]: 11.000 ng/L.

Fig. 3.6: Micropollutant removal during a single process cycle.

Substances like Carbamazepine, Diclofenac, Amidotrizoic acid, Iopamidol and Iopromide can be defined as very persistent substances. Unchanged concentrations were found in the SBT and the PC. An increase in Carbamazepine levels was observed in the permeate. It is known that some pharmaceutical substances form glucuronic acid conjugates when metabolized in the human body. Enzymatic cleavage of these intermediates during the waste water treatment processes results in reconstitution of the parent compound and has been described for instance as a reason for higher loads of these compounds in WWTP effluents compared to influent concentrations [2]. These considerations could explain the higher concentrations of Carbamazepine in the MBR permeate compared to the SBT.

Atenolol and other substances, such as Fenofibric acid, Gemfibrozil, Ketoprofen, Pentoxifylline, Bisphenol A, Estron and Estriol, were found in the SBT, but neither in the PC nor in the permeate. A fast degradation, an adsorption in the solid phase or a transformation into non-detectable metabolites could explain this result. Ibuprofen and Bezafibrate were additionally eliminated during the treatment itself. Aerobic conditions favoured the elimination of these compounds.

Naproxen, Sotalol and Ioxitalamic acid were not eliminated during the process cycle on both days of measurements. During the individual phases the concentrations remained constant and unchanged.

The main effect is observed in the charging phase, when waste water is pumped from the SBT to the PC. The concentration of Naproxen decreases from 1100 ng/L in the SBT to 150 ng/L in the PC. This decrease may be due to dilution effects but it also can be explained with the partial adsorption of Naproxen to the sludge or with the partial transition into the solid phase.

Metoprolol, similar to Naproxen, was not eliminated in the PC. However, the concentration of Metoprolol in the permeate (540 ng/L) was significantly lower than in the process tank (1300-1400 ng/L). This meant that the retention of sludge and the separation by the membrane had an influence on the micropollutant removal. The results from days 107 and 121 showed consistent results. Bisoprolol, Phenazone, Iohexol and Iomeprol showed the same behavior. Possible effects within the FC on the micropollutant removal were not investigated and cannot be excluded. It has to be mentioned that the TSS is higher by a factor of 2 in the FC compared to the PC. Such conditions may enhance degradation for some substances. In order to elucidate the mechanisms further research is needed.

Tab. 3.7: Micropollutant analysis – Samples of WWTP EL.

Samples of WWTP EL [Day 107]				Samples of WWTP EL [Day 121]	
Substance [ng/L]	Group	Influent,24h (Day 106)	Effluent,24h (Day 107)	Influent,24h (Day 120)	Effluent,24h (Day 121)
Atenolol	1	n.m.	n.m.	880	62
Bisoprolol	1	n.m.	n.m.	690	110
Metoprolol	1	n.m.	n.m.	5400	1100
Phenazone	1	n.m.	n.m.	680	390
Sotalol	1	n.m.	n.m.	580	300
Bezafibrate	2	3500	70	3900	< DL
Carbamazepine	2	750	1100	2000	2100
Diclofenac	2	2100	1500	4100	2400
Fenofibric acid	2	< DL	< DL	170	< DL
Gemfibrozil	2	< DL	< DL	210	< DL
Ibuprofen	2	12000	160	14000	120
Ketoprofen	2	140	< DL	150	< DL
Naproxen	2	530	100	1400	170
Pentoxifylline	2	150	< DL	160	< DL
Phenacetin	2	360	< DL	< DL	< DL
Amidotrizoic acid	3	5000	2500	< DL	1200
Iohexol	3	500	900	< DL	1200
Iomeprol	3	34000	2100	59000	3800
Iopamidol	3	< DL	< DL	2100	1200
Iopromide	3	21000	340	< DL	< DL
Ioxitalamic acid	3	< DL	140	< DL	70
Estriol	4	n.m.	n.m.	< DL	< DL
Estron	4	n.m.	n.m.	< DL	< DL
Bisphenol A	5	n.m.	n.m.	1300	< DL

In Fig. 3.7 a comparison of the MBR and WWTP EL relating to the elimination rates of micropollutants is shown. The results from days 107 and 121 are presented as average values in the diagram. The substances were arranged in groups according to the analytical methods applied. Phenazone, Phenacetin, Estron and Estriol are not displayed for both treatment plants, Iopromide for the MBR and Ioxitalamic acid for WWTP EL due to a missing significance for a comparison.

Both plants in Fig. 3.7 show a similar picture for the elimination rates of single substances. The exceptions were Diclofenac and substances from the x-ray contrast media group. Large fluctuations of the influent concentration of a single substance during the course of a day in combination with different sampling techniques at the MBR and WWTP EL can explain these deviations.

Bezafibrate, Fenofibric acid, Gemfibrozil, Ibuprofen, Ketoprofen, Pentoxifylline, Atenolol and Bisphenol A were fully eliminated in both plants. Bisoprolol, Estron and Estriol were removed completely in the MBR, Iopromide and Phenacetin in the full size WWTP. Naproxen and Metoprolol were eliminated to more than 50 % in both treatment plants, Bisoprolol additionally in WWTP EL. An elimination rate between 10

and 50 % was found in the MBR for the substances Sotalol, Iohexol, Iomeprol and Ioxitalamic acid. The conventional treatment eliminated Diclofenac, Phenazone, Sotalol, Amidotrizoic acid and Iopamidol to the same degree. Carbamazepine, Diclofenac, Amidotrizoic acid and Iopamidol were persistent micropollutants in the MBR, Carbamazepine and Iohexol in WWTP EL.

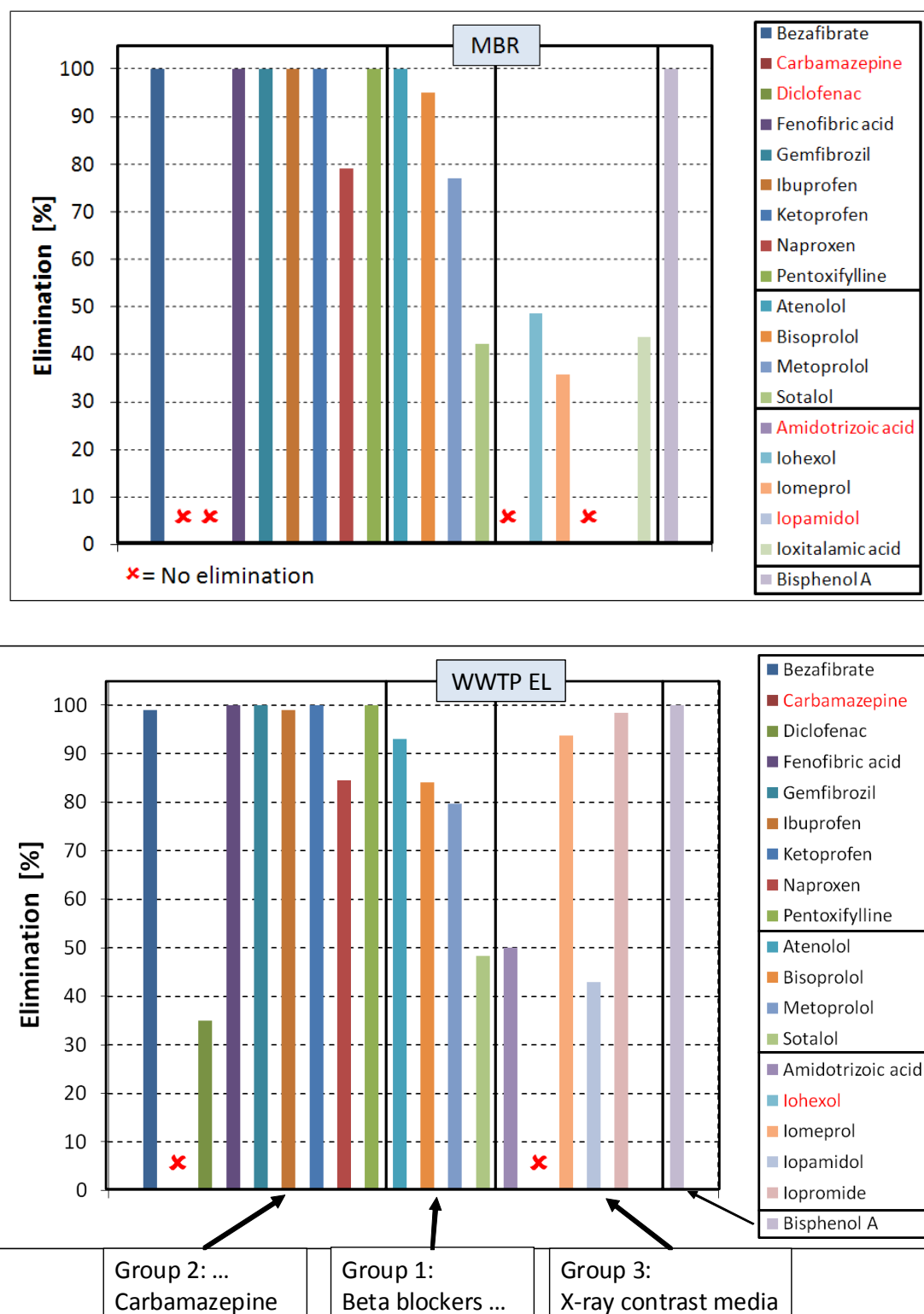


Fig. 3.7: Micropollutant elimination.

In conclusion, micropollutants showed different behavior to the waste water treatment and the influencing factors in the MBR. The elimination rates and the persistency with some exceptions were comparable in the MBR and in the conventional treatment plant. Membrane filtration or the separation of sludge from permeate reduced the amount of some micropollutants significantly.

4 Membrane performance

A critical aspect besides the biological process is the operation of submerged membrane modules. Major disadvantages for the membrane filtration in waste water applications are the loss of permeability and the occurrence of biofouling. Fig. 4.1 shows the long term performance of the three modules over 149 days with respect to permeability.

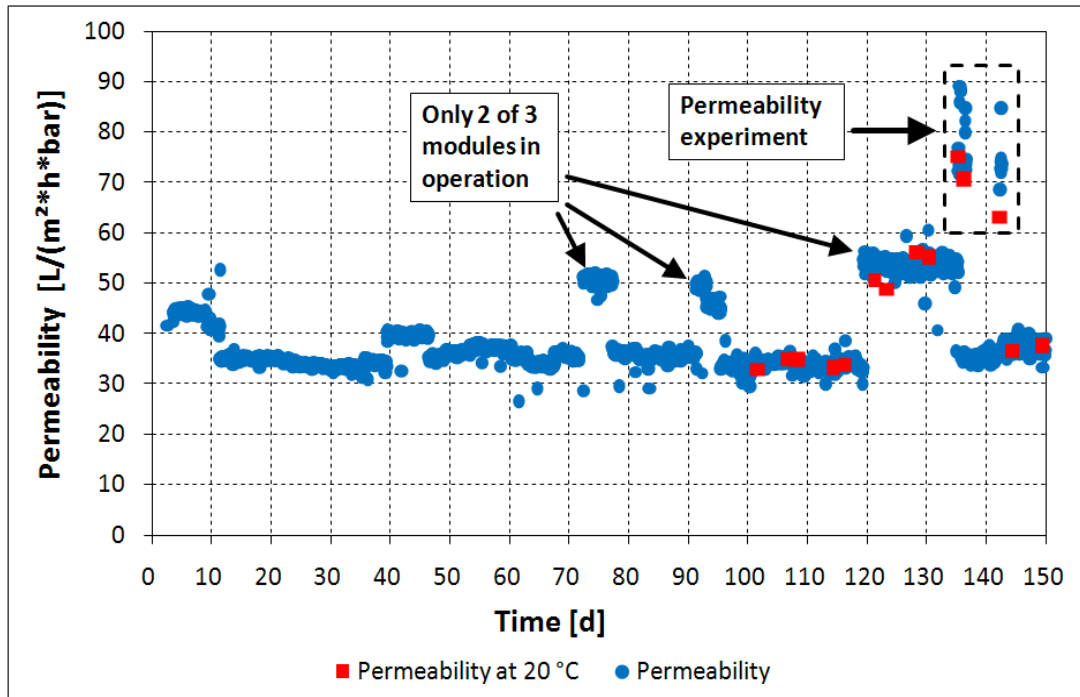


Fig. 4.1: Time course of permeability.

From Fig. 4.1 it can be seen that permeability remained constant over 150 days and only increased when one or two out of three modules were shut down. All modules were operated with the same flux keeping an overall mean throughput of the MBR of 6 m³/d.

During the examined period not all of the three modules were operated continuously. A temporarily decreasing permeate flow of module “Left” and problems with the operation of scouring air required an occasional shut down of the left module. On days 135, 136 and 142 the permeability of each single module was investigated.

In order to achieve a stable performance moderate operation conditions were chosen. As a result transmembrane pressure kept rather constant (0.17 bar) over the total operation time as shown in Fig. 4.2.

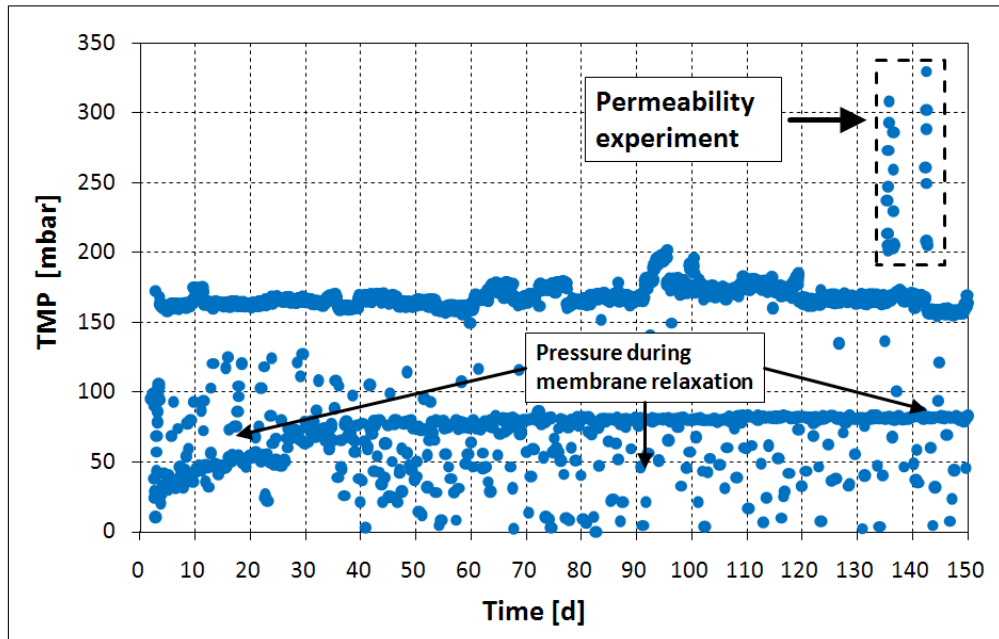


Fig. 4.2: Time course of TMP.

As an effect of the constant pressure, permeability seemed to increase at these low fluxes. The combined connection of all operating modules to a single pressure gauge and a single extraction pump made an evaluation of individual module permeabilities impossible.

In conclusion, membrane operation with a low flux was stable over a period of 5 months. Mechanical cleaning by air and flow rate adjustments were the only maintenance procedures applied. A critical point related to low fluxes to be mentioned is economic feasibility. The energy cost will increase because a larger membrane area is needed for the same permeate output compared to high fluxes. A larger membrane surface requires a higher compressor output for the operation of scouring air.

In order to determine the critical flux of the membrane system the flux step method was applied for an evaluation of permeability on a single module [3]. The permeate flow or the flux was increased stepwise by this method. During a test the two remaining modules were shut down. In Fig. 4.3 the results of an examination on module “*Right*” are shown as an example.

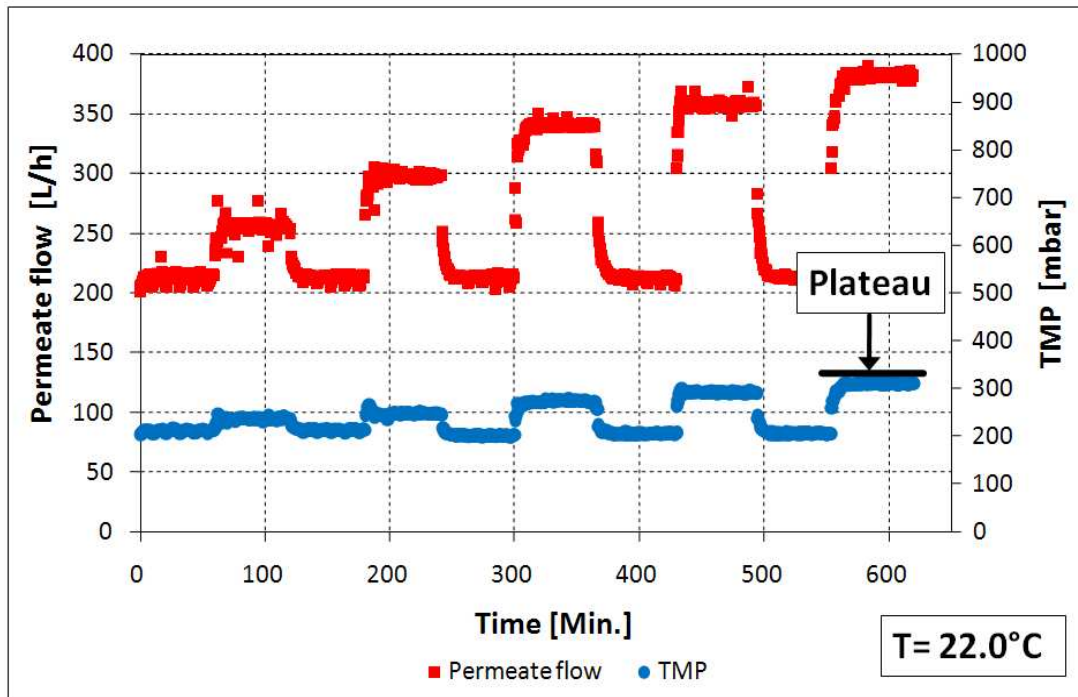


Fig. 4.3: Permeability investigation on module “Right”.

The flow rate to be analyzed ranged from 250 L/h up to 400 L/h during filtration mode with flux values of 15 - 30 L/(m²*h). The maximum flux of 30 L/(m²*h) to be tested was the projected value by HUBER SE. A leakage in a valve on the left module caused a 15 % reduction in permeate extraction over module “Left” when the permeability on modules “Middle” or “Right” was investigated. Thus, 15 % of permeate flow and flux were subtracted from the measured values (see Tab. 4.1).

The TMP values were left unchanged because it was not possible to determine the deviation. A conservative representation of these TMP values allowed the conclusion that permeability could be higher than shown in Fig. 4.4 for modules “Middle” and “Right”.

Effective permeate flows from about 210 to 380 L/h resulting in fluxes from 15 to 27 L/(m²*h) were achieved with modules “Middle” and “Right”. Module “Left” was only operated up to a permeate flow of 350 L/h with an average TMP of 0.33 bar. Limitations by the module manufacturer for the given conditions (TMP_{Max}: 0.35 bar) did not allow a further increase of flux. As expected, Fig. 4.3 shows that the stepwise increase of permeate flow resulted in a stepwise increase of TMP.

Subcritical conditions were present for all modules during the tests because TMP stayed constant at a constant flux which is illustrated in Fig. 4.3 as “Plateau”.

Tab. 4.1: Permeability experiment – Summarized results.

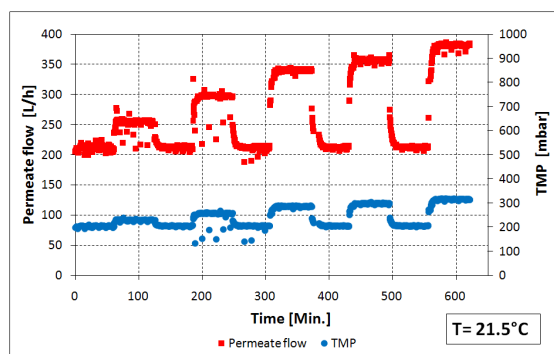
Module „Left“						
Day	Permeate flow	Flux	TMP	P	T	P [20°C]
[d]	[L/h]	[L/(m ² *h)]	[mbar]	[L/(m ² *h*bar)]	[°C]	[L/(m ² *h*bar)]
142	250	17.8	259.1	68.9	23.5	63.3
142	300	21.5	287.4	74.7	23.5	68.7
142	350	25.0	332.9	75.1	23.5	69.1

Module „Middle“							
Day	Permeate flow	Flux with error	Flux	TMP*	P*	T	P [20°C]*
[d]	[L/h]	[L/(m ² *h)]	[L/(m ² *h)]	[mbar]	[L/(m ² *h*bar)]	[°C]	[L/(m ² *h*bar)]
136	250	17.9	15.2	203.8	74.4	21.5	71.8
136	300	21.4	18.2	229.6	79.4	21.5	76.6
136	350	25.0	21.3	257.4	82.6	21.5	79.7
136	400	28.5	24.3	286.1	84.8	21.5	81.8
136	420	30.0	25.5	297.8	85.6	21.5	82.5
136	450	32.1	27.3	315.5	86.5	21.5	83.4
142	250	17.9	15.2	206.9	73.4	23.5	67.5
142	420	30.0	25.5	301.2	84.6	23.5	77.8

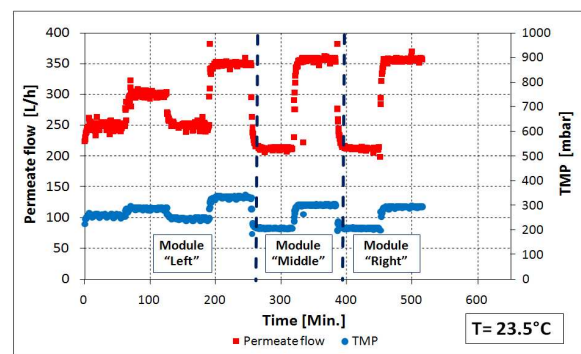
Module „Right“							
Day	Permeate flow	Flux with error	Flux	TMP*	P*	T	P [20°C]*
[d]	[L/h]	[L/(m ² *h)]	[L/(m ² *h)]	[mbar]	[L/(m ² *h*bar)]	[°C]	[L/(m ² *h*bar)]
135	250	17.9	15.2	211.6	71.7	22	68.4
135	300	21.5	18.3	236.7	77.2	22	73.6
135	350	25.0	21.3	247.0	86.1	22	82.1
135	400	28.6	24.3	273.8	88.8	22	84.7
135	420	30.1	25.5	291.9	87.5	22	83.4
135	450	32.1	27.3	310.0	88.1	22	84.0
142	250	17.8	15.2	206.5	73.5	23.5	67.6
142	420	30.0	25.5	293.7	86.8	23.5	79.8

*= values are **not** corrected by a reduction of 15%.

Fig. 4.4 shows the results for module “Left” and “Middle”. A flux beyond the critical flux would not result in a plateau behavior, but in a steady increase of the TMP.



Middle



Left / Middle / Right Module

Fig. 4.4: Permeability experiment [Day 136] – Module “Middle”, [Day 142] – Module “Left”.

The summarized results of this permeability experiment after 135, 136 and 142 days of membrane operation within the MBR are presented in Fig. 4.5. Modules “*Middle*” and “*Right*” achieved normalized permeabilities of 83 and 84 L/(m²·h·bar) at a flux of 27 L/(m²·h). A normalized permeability of 69 L/(m²·h·bar) at a flux of 25 L/(m²·h) was obtained from the left module. As stated before, the operation of module “*Left*” at higher fluxes was not possible.

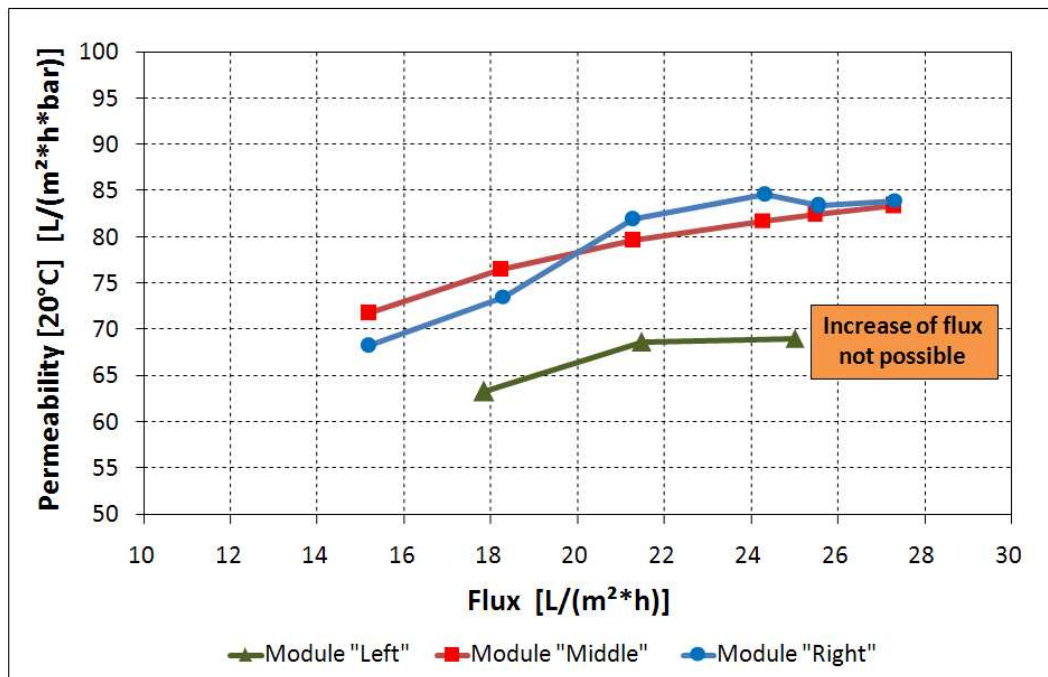


Fig. 4.5: Module permeabilities.

The course of permeability, as charted in Fig. 4.5, shows that module “*Left*” was affected by the operation of the MBR. The permeability was significantly lower compared to modules “*Middle*” and “*Right*” at the same fluxes. In addition, module “*Left*” was in a non-operational mode for longer periods (in sum: ≈ 27 days). Membrane fouling could be an explanation for this result.

Another interpretation of the results for modules “*Middle*” and “*Right*” was found when the error of the TMP caused by the leaking valve was calculated in a different way. Subtracting 15 % of the measured TMP values analog to the values of permeate flow and flux resulted in permeabilities of 98 L/(m²·h·bar) (module “*Middle*”) and 99 L/(m²·h·bar) (module “*Right*”) at a flux of 27 L/(m²·h). This kind of calculation did not indicate an occurrence of biofouling or a loss in permeability. Tab. 4.2 shows the results of this permeability calculation in dependence on flux.

Tab. 4.2: Permeability calculation*

Module " <i>Middle</i> " at 21.5 °C			Module " <i>Right</i> " at 22°C		
Flux	TMP	P [20°C]	Flux	TMP	P [20°C]
[L/(m ² *h)]	[mbar]	[L/(m ² *h*bar)]	[L/(m ² *h)]	[mbar]	[L/(m ² *h*bar)]
15	173	85	15	180	80
18	195	90	18	201	87
21	219	94	21	210	97
24	243	96	24	233	100
26	253	97	26	248	98
27	268	98	27	263	99

*= the TMP reduction of 15 % is related to the measured values.

In conclusion, higher permeabilities were achieved when flux was increased with regard to the long term operation with low fluxes. Module "*Left*" was significantly affected by membrane fouling. The loss of permeability on one module was not an indication for a chemical cleaning of all three modules. Low fluxes and the compensation by the two other modules enabled the continuous and stable membrane filtration. The treatment of municipal waste water with the chosen conditions for the membrane and the MBR operation was successful.

5 Irrigation study

One of the objectives of IWRM projects is to evaluate different possibilities for the use of treated waste water. In the research project presented here a case study for irrigation was carried out in order to investigate the influence of water quality on the growth of tomatoes and on the uptake of micropollutants.

Small tomato seedlings were grown on ordinary flower soil and watered with different water qualities over a period of 102 days parallel to the operation of the MBR.

Three seedlings were planted into one flower box. Two flower boxes were defined as one set of plants irrigated with a defined water quality. Three different water qualities were used for the irrigation (MBR permeate, prefiltered waste water and tap water). The experimental setup on the first day is shown in Fig. 5.1. The flower boxes were located under a roof to avoid an influence by rainfall. The plant and fruit growth over the period was documented with photos. The amount of water used and other remarks were documented in an irrigation protocol.

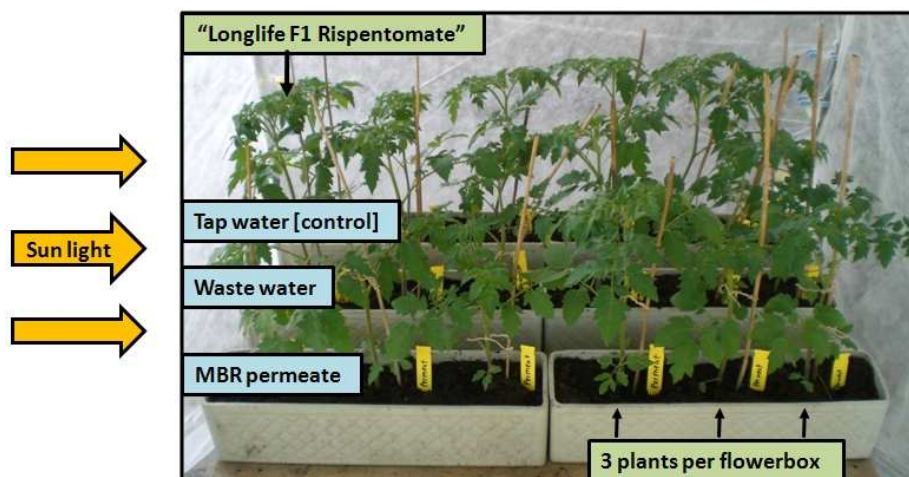


Fig. 5.1: Start of the irrigation study at day 1.

Fig. 5.2 shows that plants watered with "Tap water", "Waste water" and "Permeate" had the same growth pattern after 8 and 27 days of irrigation. Small differences in height of the individual plants for each flower box were related to the sunlight exposure.

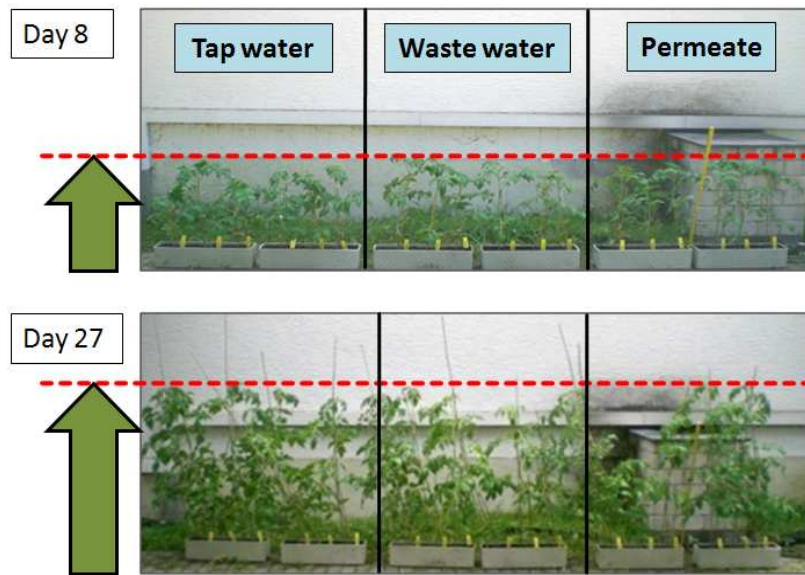


Fig. 5.2: Tomato growth.

The plants were watered with a total volume of about 46 L per flowerbox in 105 days. Ripe tomato fruits were harvested from all plants starting from day 84 until day 105 due to different levels of maturity. Fig. 5.3 shows pictures of mature and immature tomatoes from day 97.

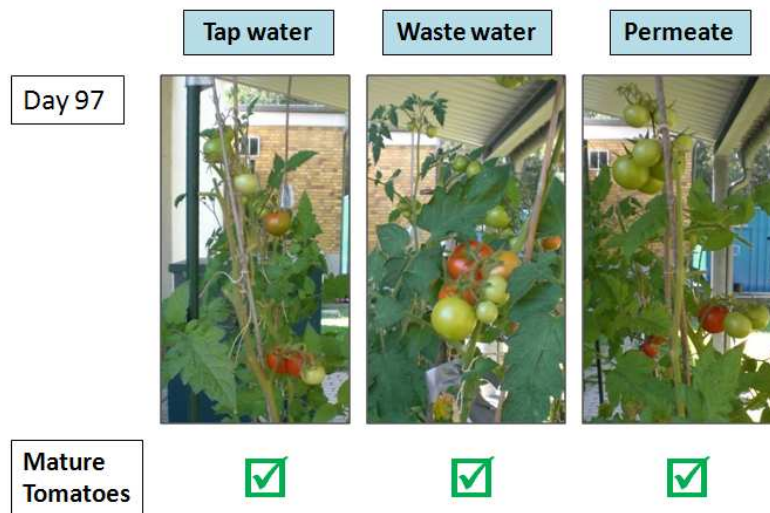


Fig. 5.3: Tomato fruits.

Regarding the growth of tomatoes fruits and plants it can be concluded, that the water quality had no effect on the growth.

After the harvest the tomatoes were stored in a freezer for further analysis. The preparation for the analysis of micropollutants followed a protocol which was developed especially for this investigation. Measurements were carried out for both

mature and immature tomato fruits. Figure 5.4 shows tomato fruits before preparation.



Fig. 5.4: Tomato fruits before preparation for analysis.

If it were assumed that the micropollutants present in the waters used for irrigation were incorporated into the tomato fruits the resulting concentrations of micropollutants would be in a detectable range. For example, Naproxen was found in the permeate in a quite low mean concentration of 175 ng/L compared to other micropollutants like Carbamazepine or Diclofenac. Assuming that 40 % (18.4 L) of the irrigated volume (per flowerbox) including the micropollutants was absorbed by the plants, an amount of approximately 3000 ng of Naproxen would be present in the tomato plants. In a worst case scenario it is assumed that Naproxen is totally accumulated in the edible fruits. Thus, a high concentration (>10000 ng/L) of Naproxen could be expected from the measurements, considering that 300-400 g tomatoes with a liquid content greater 60 % were purified for the analysis of micropollutants.

However, the quantitative analysis showed that no micropollutants were found in the tomatoes for all three tested water qualities. From these results it can be concluded that tomato fruits do not incorporate micropollutants which were analyzed in this study.

The repetition of this experiment and the standardization of tomato preparation have to verify these results in future investigations. In addition, irrigation studies with other plants might be interesting for future research.

6 Conclusion

The operation of a MBR in container size for domestic waste water treatment was investigated with regard to the SMART II project over a period of 149 days. The treatment included mechanical screening, activated sludge process with intermittent denitrification and membrane filtration. The preconditioned influent of a municipal WWTP (5-6 m³/d) was used for the investigation. After an adaption phase of 49 days stable conditions in the biological stage were achieved and maintained for 100 days. Sludge loads of 0.05-0.2 kgCOD/(kgTSS*d), volume loads of 0.2-1.1 kgCOD/(m³*d) and sludge retention times of around 25 days were present in the MBR. These values were comparable with the ones in a neighboring conventional WWTP.

An essential prerequisite for the operation of the MBR in Jordan was the compliance with the Jordanian Standard for artificial groundwater recharge for COD (50 mg/L), N_{Tot} (45 mg/L), NH₄-N (3.9 mg/L), NO₃-N (6.8 mg/L) and P_{Tot} (4.9 mg/L) (3.1.2). The results during days 49-149 showed that the maximum values for COD (20 mg/L), N_{Tot} (9 mg/L) and NH₄-N (0.3 mg/L) were well below these specifications. Nitrate exceeded only on two days (day 79, NO₃-N: 7.7 mg/L and day 114, NO₃-N: 7.5 mg/L) the limiting value. Adjustments on the operation conditions in the process tank reduced the concentration to acceptable values.

The elimination of phosphorus ($\approx 55\%$) was insufficient under the given conditions. On average (days 49-139), 5.1 mg/L P_{Tot} were measured in the permeate. An investigation on chemical precipitation with iron(III)chloride in the MBR (days 140-149) was able to increase the elimination degree up to 83% resulting in a concentration of 1.5 mg/L P_{Tot} in the effluent. The optimization of chemicals and dosage and the adaption to the corresponding influent could probably lead to a higher removal degree, if desired. In conclusion, it can be stated that the MBR had the ability to comply with the limiting values of the Jordanian Standard with some optimization.

The long term operation of membrane filtration with low fluxes allowed a stable and nonstop operation of waste water treatment in the MBR during 5 months. Permeability was used as an indicator for the performance of membrane filtration and the occurrence of fouling. The operation of the three modules in parallel could not give information on individual module permeabilities. In a short term experiment on days 135, 136 and 142 the flux step method was used to investigate single permeabilities in the subcritical flux regime, showing that some fouling occurred especially on module "Left".

The MBR showed a high removal efficiency of microorganisms. The measurements of total cell count showed that at least 99.7 % were retained by the MBR with a remaining number of about $1.2 \cdot 10^5$ cells/mL in the effluent. The size exclusion of microorganisms (micrometer range) by the smaller membrane pores (38 nm) was the reason for this result. The retention for MS2-phages was greater than 90 % with a remaining number of about $6.5 \cdot 10^3$ viruses/mL in the effluent. The good retention in the MBR depended mainly on the incorporation of MS2-phages into the sludge.

Substances from the groups of "*Beta blockers and the analgesic phenazone*", "*Anti-inflammatory drugs/Analgesics/Lipid lowering agents and the antiepileptic Carbamazepine*", "*X-ray contrast media*", "*Steroid hormones*" and "*Alkylphenols/Bisphenol A*" were analyzed for an investigation on the micropollutant removal on days 107 and 121.

A selection of 24 out of 50 possible micropollutants was present in the tested municipal waste water. The elimination degrees in the MBR and in the conventional WWTP were substance specific and in comparison of both plants under equivalent operation conditions similar. Carbamazepine, Diclofenac and substances from the x-ray contrast media group were identified as persistent micropollutants. Degradation by activated sludge, adsorption to biomass and membrane retention were the influencing factors. In conclusion, the MBR and the waste water treatment plant in Eggenstein-Leopoldshafen were able to remove some of the micropollutants. Limitations for some persistent substances require further steps for a complete retention.

MBR permeate was used for the irrigation of tomato plants. For comparison, two further sets of tomato plants were watered with waste water directly or drinking water. Ripe tomatoes harvested from all three irrigation fields were analyzed for micropollutants and showed no indication of uptake from the irrigated water used. The results demonstrate that tomatoes do not incorporate these substances. However, as tomato preparation for analysis and analytical methods are not standardized for such conditions yet, further measurements have to be made to verify this finding.

In the present study fluxes and the value for the total suspended solids in the filtration chamber were chosen rather low in order to achieve a stable performance. The main objective of the MBR operation was to successfully demonstrate this for a rather unknown site. The choice of the operation conditions was conservative in order to be

on the safe side. The results showed that the operation was successful regardless of fluctuations in the influent quality.

At the WWTP EL a small MBR (40 L/h) was operated with the same influent as the MBR pilot plant but with higher fluxes up to 15 L/m²/h and TSS values in the process tank of 10-12 g/L. The results demonstrate that also under such challenging conditions a stable operation of the MBR is achievable. Permeability of the small MBR was in the range of 80-120 L/m²/h/bar for a period of 12 months and therewith higher than the permeability of the MBR pilot plant in the container which was only 35 to 45 L/m²/h/bar.

From the results presented above, it was said that WWTP and MBR performed similarly with regard to elimination rates. However, it has to be pointed out that the effluent of the MBR is definitely of higher quality than the effluent of the WWTP, because the MBR has a more than one log higher removal of microorganisms and its effluent is free of particles with a very low turbidity. From this point of view it is suitable for groundwater recharge or irrigation purposes.

Moreover it may be used as feed for further treatment steps like activated carbon filtration for further removal of micropollutants.

Another advantage of the MBR compared to the WWTP that can be named is the footprint. Because MBR can be operated at higher biomass concentration the process tanks can be smaller designed. MBR plants only need half of the footprint for process tanks than conventional waste water treatment plants.

7 References

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8 Abbreviations

ASP	Activated sludge process
BOD	Biological oxygen demand
COD/	Chemical oxygen demand
DL	Detection limit
DO	Dissolved oxygen
FC	Filtration chamber
HRT	Hydraulic retention time
IWRM	Integrated water resources management
MPN	Most probable number
PC	Process chamber
PES	Polyethersulfone
PST	Permeate storage tank
SBT	Screening and buffer tank
SMART	Sustainable management of available water resources with innovative technologies
SRT	Sludge retention time
SV	Sludge volume
SVI	Sludge volume index
TMP	Transmembrane pressure
TSS	Total suspended solids
TZW	Technologiezentrum Wasser
WWTP EL	Waste water treatment plant Eggenstein-Leopoldshafen

