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An integrated wastewater treatment and reuse concept for the Olympic Park 2008, Beijing

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Abstract

In a Sino-German research project, a joined developed sustainable water reclamation concept was developed for different applications of municipal water reuse at the Olympic Green 2008. The concept combines advanced technological processes like membrane bioreactors, specific phosphorus (P) adsorption columns and ultra-filtration (UF) with nature-based treatment processes like wetland and bank filtration mechanisms. The project's approach is not only to comply with the reclamation requests of the Olympic Green 2008, but also to give an example for better, adapted and energy efficient reuse applications throughout China. The study shows that fixed-bed granular ferric hydroxide (GFH) adsorbers after a membrane bioreactor (MBR) can maintain a total phosphorus (TP) concentration of <0.03 mg L^{-1}. A low P concentration will be necessary to control eutrophication in the artificial Olympic Lake filled with treated wastewater. With an adsorption capacity of approx. 20 mg g^{-1} d.m. at a corresponding equilibrium concentration of 1 mg L^{-1} P, GFH reaches long operation times and can be repeatedly regenerated by caustic solutions with an efficiency of 50%. Apart from scenic impoundments, treated wastewater will be used for irrigation and toilet flushing. The latter requires a superior quality that will be delivered by low pressure UF treatment after lake (bank) filtration. A crucial reduction of fouling potential for dead-end UF is expected.

Keywords: Sustainable water reclamation; Eutrophication control; Metal oxide adsorption; Water reclamation standards; Urban reuse applications

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1. Introduction

The Olympics 2008 will be held in the capital of China, Beijing. The games will run under the motto “Green Games — Sustainable Development”. However, the environmental problems of the Mega-City Beijing are still tremendous. Above all the water sector is struggling with quality problems and sinking groundwater levels. As a consequence the City of Beijing is striving for long term solutions for wastewater treatment and its reuse with a challenging and Olympic-oriented water program. Until the year 2007, 12.2 billion USD are to be invested in the environmental sector; substantial contributions will be made for water infrastructure. 14 new wastewater treatment plants will be constructed to collect and treat 90% of the produced wastewater of the City. Higher rates of wastewater reclamation in all areas of reuse applications are planned, so that 50% of the treated wastewater will be reused by the year 2008. Especially in the “Olympic Green”, the centerpiece for the Olympic Games, all qualities of recycled wastewater will be applied. The Park covers a total area of 1215 ha, located north of the city center. It will consist of stadiums, apartments for athletes and artificial surface waters for scenic impoundments. According to Beijing Officials and the Olympic Organizing Committee, a 60 ha large shallow lake will be filled with treated wastewater in the northern area of the Park. In the central area, a smaller lake of 20 ha with superior water quality will be operated with fountains; all waters supplied will be advanced treated municipal wastewaters. Further reuse applications are envisaged, including water for irrigation (not only in the Park, but also in neighboring areas) and urban water applications like toilet flushing and washing waters. Table 1 shows the envisaged quantities of recycled municipal effluents in the different sectors.

Table 1
Planned sectors and quantities for reuse of municipal wastewater in the Olympic Park 2008 [1]

	Quantity ($m^3\ d^{-1}$)
Olympic Lake	29.800
Central Olympic Lake + fountains	10.000
Irrigation	17.000
Urban reuse (street cleaning and car washing)	14.000
Urban reuse (toilet flushing)	19.000

The hygienically safe application of treated municipal wastewater for car washing, toilet flushing and fountains in the Olympic Park requires high treatment standards that need to be defined and further security measures that can only be realized effectively by new technical approaches based on the multi-barrier principle utilizing membranes. Landscape reuse, e.g. impoundments in lakes, requires a reliable and cost effective eutrophication control involving both natural attenuation capacities (wetlands, bank filtration) and technological measures (membrane treatment, specific adsorption, optimized process parameters).

The present study summarizes preliminary results of the Sino-German research cooperation project on Sustainable Water Concept and its Application for the Olympic Games 2008 in the subproject “Wastewater Treatment and Reuse”. Sub-project partners are the reporting Beijing Drainage Group, the Tsinghua University in Beijing and the Technical University of Berlin. Moreover, a German small and medium-sized enterprise (SME) and a consulting company are involved. The Beijing Drainage Group is requested to suggest reliable processes for the envisaged water usage in the Olympic Park to the Olympic Organizing Committee. Consequently, a joint Sino-German research program was developed to apply advanced water treatment and nature-orientated technologies in a combined approach at the sewage treatment plant Beixiaohe (STP BXH). The common objective was to estimate the stability and approximate costs of the treatment prior to a large-scale setup for the Olympics. The project is funded by the Chinese and German Research Ministries (MOST and BMBF) and is highly supported by Beijing Officials.

2. Methods

The STP BXH, located east of the Olympic Park, is intended to be one of two treatment facilities that will supply the Olympic Park with approximately 125,000 $m^3\ d^{-1}$ of treated wastewater. Qinghe STP, located North of the Olympic Park, will be the second source of water. Planned recycling treatment capacities for 2008 are 60,000 $m^3\ d^{-1}$ for BXH (out of a total of 100,000 $m^3\ d^{-1}$, including 40,000 $m^3\ d^{-1}$ conventional activated sludge treatment) and 65,000 $m^3\ d^{-1}$ for Qinghe STP. The final decision regarding the envisaged reuse treatment scheme and involved technologies has not been made yet. However, a partial choice of the implementation of membrane bioreactor (MBR) technology at BXH and submerged microfiltration systems at Qinghe STP has been made.

2.1. Suggested treatment scheme and pilot-scale investigations

In order to cope with the given boundary conditions the joint partners decided to set up a pilot plant system consisting of the following subsequent treatment steps: (i) MBR system with biological phosphorus (P) removal and optional in situ P-precipitation for particle free effluent (a total phosphorus (TP) concentration of <1 mg L^{-1} is expected), (ii) fixed-bed adsorption columns filled with granular ferric hydroxide (GFH), (iii) small artificial lake equipped with two types of sediments (silicates, calcium carbonates) to simulate removal mechanisms by bank- (lakebank-) filtration in natural processes, (iv) tight ultra-filtration (UF) pilot plant for a final polishing step to produce recycled water of superior quality (Fig. 1). The actual treatment capacities of the pilot scheme are 20 $m^3\ d^{-1}$ for the MBR system, for the GFH column 10 $m^3\ d^{-1}$, for bank filtration and subsequent dead-end UF 5–10 $m^3\ d^{-1}$.

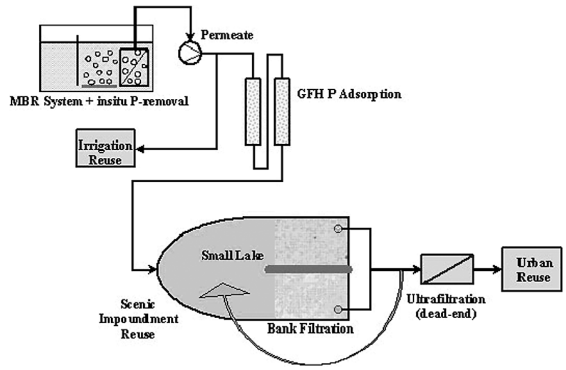

Fig. 1. Pilot treatment and reuse scheme, Beixiaohe STP, Beijing.

A great challenge is the operation of the shallow (2 m) artificial lake (36 m^2) without algae, hygienic or odor problems. For predicting phytoplankton density from total phosphorus concentrations, a cooperative study organized by the Organisation for Economic Co-operation and Development (OECD) developed a widely accepted model, establishing quality criteria for determining the trophic state of water bodies [2]. The partners in this project consider a total phosphorus concentration (TP) of <0.03 mg L^{-1} P necessary to maintain good quality conditions in the artificial lake, corresponding to mesotrophic conditions. MBR biological P removal is possible [3], but will not be able to reach the desired TP limits. Adsorption onto GFH, originally designed for arsenic removal in drinking water [4], is able to completely remove ortho-P due to its properties that are comparable with those of arsenate. After exhaustion, GFH filters can be regenerated by caustic solution. Optimization, performance and costs of GFH regeneration is a matter of the joint research. The GFH column effluent will fulfill the limiting value for TP; the water will subsequently supply the artificial lake. The hydraulic residence time is approximately 10 days. During artificial bank filtration, bio-augmentation and particle (bacteria) removal will occur depending on the adjusted operational conditions (applied sediments, particle size, filtration velocity, redox conditions). According to the removal mechanisms of bank filtration, the content of biodegradable organic matter but also trace organic compounds and microorganisms can be reduced [5–7]. Bank filtration is comparable with soil aquifer treatment (SAT) which is known to be an effective pre-treatment for fouling control in membrane filtration [8]. The UF permeate can be used as a source for urban reuse applications.

2.2. P-adsorption onto GFH

To estimate the adsorption capacity of GFH material, laboratory-scale experiments with both model solutions and MBR effluent were performed at the Technical University of Berlin. GFH is predominantly akaganeite, a poorly crystallized iron oxide. The specific surface area is reported to be 280 m^2 g^{-1}, the point of zero charge (pH_{PZC}) is between 7.5 and 8.0 [9], the water content is 50% by weight. According to the manufacturer's references (GEH Wasserchemie, Osnabrück), the applied material had a grain size range of 0.32–2.0 mm. For isotherm experiments, the GFH material was grounded to <63 μm, for column tests it was sieved to defined grain size ranges between 0.1 and 1.0 mm.

Equilibrium adsorption isotherms were developed for different initial concentrations of phosphate in four different water matrices: (i) an MBR effluent of a pilot at BXH STP, (ii) an effluent from a microfiltration system (MF) being applied in BXH STP after conventional treatment (Table 2), (iii) an effluent from a Berlin small-scale MBR system being operated

Table 2
Water quality of the recent conventional activated sludge process, STP Beixiaohe, annual average values [1]

	BXH influent (mg L^{-1})	BXH effluent (mg L^{-1})
BOD_5	258	12
COD	511	41
SS	277	17
TN	62	33
NH_3-N	43	20
TP	6–7	2–3

in an EU project on persistent polar pollutants [10] as well as ultra-pure water with a spiked P concentration of 100 mg L^{-1} P, (iv) model solutions were prepared by adding sodium phosphate (Na_2HPO_4, Merck) to d.i. water. An ionic strength of 15 mmol L^{-1} was set by adding NaCl. To maintain a constant pH, 2 mmol L^{-1} of a non-adsorbing biological buffer (*N*,*N*-bis(2-hydroxyethyl)-2-aminoethanesulfonic acid, BES) was added. Water quality data are summarized in Table 3. Different masses of a ground GFH fraction (<63 μm) were added to a constant volume of solutions and agitated for an equilibration time of 96 h at an average temperature of 20°C, and a pH of 7.0–7.2.

The regeneration efficiency of GFH was derived by two different column experiments. First, a sequential loading experiment was performed. Three differential column batch reactors (DCBRs, diameter 2.5 cm, height 5 cm) were operated with the model solution at high initial phosphate concentrations of 100 mg L^{-1} PO_4-P and pH of 7.0 and 4.0, respectively (Table 3). The differential bed consisted of 0.4 g dry matter GFH of a defined particle fraction (0.8–1.0 mm). After approx. 120 h operation, the GFH material was regenerated by circulating sodium hydroxide solution (0.1 M NaOH) through the column for another 120 h. In a

Table 3
Characteristics of samples for adsorption isotherm and column experiments

	MBR pilot BXH (mg L^{-1})	Microfiltered effluent BXH (mg L^{-1})	MBR effluent (P-Three Berlin)*** (mg L^{-1})	Artificial model solutions (mg L^{-1})
COD	24.6	25.5	34	n/a
DOC	6.4	8.3	11	~144*
NH_3-N	45.6	45.6	n.d.	–
NO_3-N	0.61	0.48	39	–
PO_4-P	2.5	0.25	2.5–4.0	4/100**
Cl^-	n/a	226	n/a	877.5
pH	8.8	8.6	7–8	7.0–7.2

*As biological, non-adsorbable buffer BES.
**DCBR experiment.
***[13].

control set-up, one column was rinsed with d.i. water instead of NaOH. Subsequently, the GFH was reloaded with model solution.

To investigate adsorption onto GFH under more realistic conditions, a laboratory-scaled column was operated with MBR effluent from a Berlin pilot-plant (iii). The column was scaled using the rapid small-scale column test concept (RSSCT). The RSSCT have been developed for the adsorption of organic micropollutants onto granular activated carbon [11], but moreover have shown to successfully predict arsenate breakthrough of a GFH fixed-bed column [12]. In the RSSCT concept, mathematical methods are used to scale down the full-scale adsorber to an RSSCT maintaining performance similarity, resulting ideally in an identical breakthrough curve. In this study, the RSSCT was scaled-down from the pilot-scale GFH adsorber columns at the BXH STP. The proportional diffusivity approach was used (PD), resulting in an empty-bed contact time (EBCT) of 1.1 min, a bed height of 9.4 cm, an average particle diameter of 0.15 mm (grain size range 0.1–0.2 mm), and a hydraulic loading rate of 5 m h^{-1}. Influent P concentrations were significantly higher than to be expected in future pilot operation at BXH STP (Table 3).

3. Results and discussions

3.1. Equilibrium P-adsorption isotherms

The resulting isotherms for low range concentration experiments are shown in Fig. 2. The solid-phase concentration of phosphate (loading) was calculated from the mass balance and is given per dry matter GFH. Despite different initial concentrations ranging from 0.25 to 4 mg L^{-1} P, comparable equilibrium loadings are achieved. The adsorptive behavior of water from different MBR effluents, as well as pure phosphate solution is highly comparable, which is remarkable

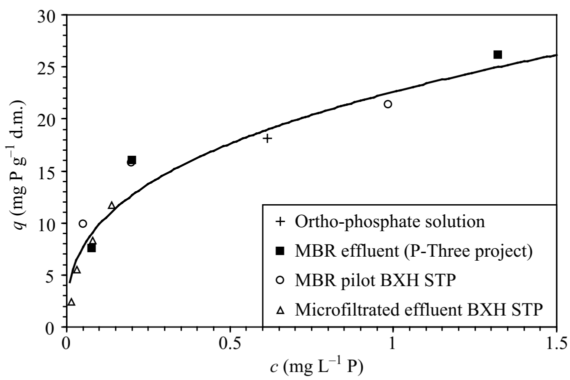

Fig. 2. Adsorption isotherms of real membrane effluents and a model solution pH 7–8, Freundlich fit for MBR effluent (P-Three project).

and suggests that the water matrix does not considerably interfere with orthophosphate adsorption mechanisms. This implies that competitive adsorption of other wastewater constituents (e.g., DOC) is negligible due to the high affinity of phosphate to GFH. At equilibrium concentrations ranging between 1 and 1.5 mg L^{-1} and pH 7–7.2, accumulated loadings of 20–25 mg g^{-1} d.m. were determined.

3.2. Laboratory-scale column tests: regeneration of GFH

The accumulated loading capacities of the DCBR experiment are given in Fig. 3. Depending on the adsorption governing pH, loadings of 32 and 65 mg g^{-1} d.m. are reached at pH 7 and 4, respectively. A subsequent regeneration step using 0.1 M NaOH could successfully desorb the majority of the adsorbed phosphate, whereas no significant change in solid-phase concentration was observed in the control experiment (rinsing with d.i. water). Regeneration efficiency at pH 4 and 7 was 89 and 91%, respectively.

A breakthrough experiment performed at conditions closer to full-scale applications, showed different results (Fig. 4). Whereas regeneration was possible after up to three reloading cycles, the average regeneration efficiency was

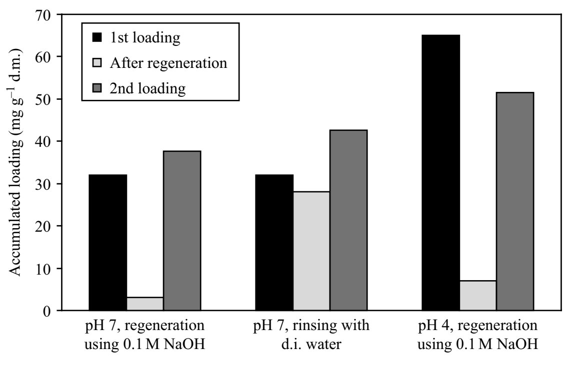

Fig. 3. Accumulated loadings for regeneration of GFH in model solutions.

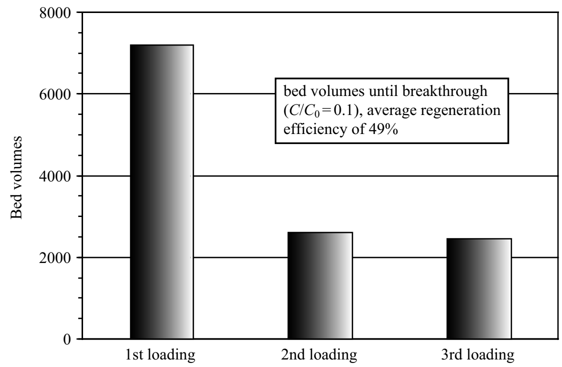

Fig. 4. Breakthrough experiments using RSSCT columns: bed volumes until breakthrough (defined as $C/C_0 = 0.1$).

estimated to be reduced to approximately 50% compared to 90% in the experiment with model solutions at higher initial P-concentrations. At pH values ranging between 6.8 and 8.2 and phosphorus concentrations in the MBR effluent ranging between 2.5 and 4 mg L^{-1} P, breakthrough of the RSSCT column (defined as a normalized effluent concentration $C/C_0 = 0.1$) was observed after 7200 (initial loading), 2600 (2nd loading), and 2455 (3rd loading) bed volumes. The regeneration of the GFH fixed-bed column hence led to newly available adsorption capacity; however, not the total adsorption capacity could be recovered. Nevertheless, column operation in multiple, subsequent loading cycles appears to be possible, facilitating a longer usage of the GFH material.

3.3. Required water quality vs. reuse application

Besides suitable treatment suggestions the consortium is requested to give recommendations for necessary water quality standards and user safety. Table 4 summarizes the existing Chinese standards for municipal wastewater reuse in lakes for restricted and unrestricted applications as well as for urban reuse applications (extract).

An analysis and comparison with international standards like the U.S. EPA recommendations [14] shows that the given parameters in both regulations are closely related but not alike. Limits in the U.S. for BOD5 are <30 (restricted reuse) and 10 (unrestricted reuse) mg L^{-1} respectively, here Chinas standards are more strict. For fecal coliforms (fc), the picture is different, as U.S. EPA recommends <200 (restricted reuse) and 0 (unrestricted reuse) fc counts per 100 mL, which requires mandatory chlorine disinfection to a minimum concentration of 1 mg L^{-1} residual chlorine. With respect to eutrophication control and related P concentrations, U.S. EPA does not give limiting values in contrast to China. Nevertheless the consortium considers the given Chinese wastewater reclamation standards for TP (and also for TN, but not limiting value) as too high for scenic lake impoundments in the Olympic Green, as the comparable Chinese surface water standard III requires TP < 0.05 mg L^{-1} TP for sensitive lakes (Table 4). According to the consortiums experiences and to literature even lower values for TP (<0.03 mg L^{-1}) are considered to be necessary. The lake will be completely filled with advanced treated wastewater and therefore the categorization of surface water standard III must be considered as an upper threshold value. Moreover, the lake will be accessible for athletes and visitors of the Olympic Green and must at least fulfill the limits for unrestricted reuse with respect to pathogen indicators (fc < 500 mg L^{-1}). A final recommendation of the consortium related to the necessary water quality standards will be the output of ongoing experiments at BXH and discussions with international water quality experts.

Table 4
Chinese water quality standards for reclamation (GB/T18920-2002, GB/T18921-2002) and surface water standard III (GB3838-2002) (extract from National Standards)

Parameter (mg L^{-1})	Scenic impoundments, lakes		Urban reuse			Surface water standard
	Restricted reuse	Unrestricted reuse	Toilet flushing	Irrigation of green	Washing purpose	III (f. lakes)
BOD5	<6	<6	<10	<20	<10	<4
TDS			<1500	<1000	<1000	n.r.
Turbidity (NTU)	n.r.	<5	<5	<20	<5	n.r.
TP-P	0.5	0.5	n.r.	n. r.	n.r.	0.05
TN	15	15	n.r.	n. r.	n.r.	1.0
NH_4-N	<5	<5	<10	<20	<10	<1
Fecal coliform (<counts 100 mL)	10,000	500	3	3	3	1000
Residual chlorine			>1 mg L^{-1} after 30 min, >0.2 mg L^{-1} at point of use			n.r.
Color (m^{-1})	30	30	30	30	30	n.r.
Detergents (anionic)	0.5	0.5	1	1	0.5	n.r.
Fe	n.r.	n.r.	0.3	n.r.	0.3	0.3
Mn	n.r.	n.r.	0.1	n.r.	0.1	0.1
Dissolved O_2	>1.5	>2		>1		>5

4. Conclusions

The present paper summarizes the concept and preliminary results of the Sino-German project “Wastewater Treatment and Reuse for the Olympic Park 2008”. A combination of advanced technological approaches and natural treatment processes was developed jointly to account for the necessities of water quality requirements for different water reclamation uses. Irrigation of lawn and crops, urban reuse like toilet flushing and car washing and last but not least scenic impoundment reuse for the Olympic Lake require adapted treatment processes to cover not only the needs for the Olympics, but give examples for sustainable reuse technology throughout China. For shallow artificial lakes filled with treated municipal wastewater, pathogen indicators and TP are critical parameters. TP can be reduced to values <0.03 mg L^{-1} by bio-P MBR systems and subsequent orthophosphate adsorption onto GFH material. The granular media shows high loading rates for phosphorus (>20 mg P g^{-1} d.m. at initial P concentration >1 mg L^{-1} and pH ≈7) relatively independent on the water matrix and competing ion concentrations. In laboratory-scale column tests with real MBR effluents, GFH could be repeatedly regenerated by caustic solutions with an efficiency of 50%. According to the consortiums preliminary results, the existing water reuse regulation for nutrients (TP and TN) does not seem to be sufficient if treated municipal effluents are to be used as the only source for an artificial lake in the Olympic Green. Further pilot-scale tests are in progress.

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References

[1] BDG, Research on Environment Safety and Technology of Reclaimed Water Supply for Olympic Park, Beijing Drainage Group Co., Ltd, Beijing, China, 2005.

[2] R. Vollenweider and J. Kerekes, Eutrophication of Waters, Monitoring, Assessment, Control, Organisation for Economic Co-operation and Development (OECD), Paris, 1982.

[3] B. Lesjean, R. Gnirss, et al., Enhanced biological phosphorus removal process implemented in membrane bioreactors to improve phosphorous recovery and recycling, Water Sci. Technol., 48 (2003) 87.

[4] M. Jekel and R. Seith, The removal of arsenic: comparison of conventional and new techniques for the removal of arsenic in a full-scale water treatment plant, Water Sci. Technol.: Water Supply, 18 (2000) 628.

[5] S. Gruenheid and M. Jekel, Fate of bulk organics during bank filtration and groundwater recharge of wastewater-impacted surface waters, in: ISMAR5 5th International Symposium on Management of Aquifer Recharge, 2005, Berlin, Germany.

[6] C. Ray, T. Grischek, et al., A perspective of riverbank filtration, J. Am. Water Work Assoc., 94 (2002) 149.

[7] E. Holzbecher, H. Dizer, et al., Simulation of bacteriophage populations during sub-surface passage, in: ISMAR5 5th International Symposium on Management of Aquifer Recharge, 2005, Berlin, Germany.

[8] C. Jarusutthirak, G. Amy, et al., Potable reuse of wastewater effluent through an integrated soil aquifer treatment (SAT)-membrane system, Water Sci. Technol.: Water Supply, 3 (2003) 25.

[9] A. Genz, A. Kornmüller, et al., Advanced phosphorus removal from membrane filtrates by adsorption on activated aluminium oxide and granulated ferric hydroxide, Water Res., 38 (2004) 3523.

[10] J.B. Quintana, S. Weiss, et al., Pathways and metabolites of microbial degradation of selected acidic pharmaceutical and their occurrence in municipal wastewater treated by a membrane bioreactor, Water Res., 39 (2005) 2654.

[11] J.C. Crittenden, P.S. Reddy, et al., Predicting GAC performance with rapid small-scale column tests, J. Am. Water Work Assoc., 83 (1991) 77.

[12] A. Sperlich, A. Werner, et al., Breakthrough behavior of granular ferric hydroxide (GFH) fixed-bed adsorption filters: modeling and experimental approaches, Water Res., 39 (2005) 1190.

[13] P. Bauer, Inbetriebnahme und Optimierung eines Membranbioreaktors zur Behandlung von kommunalem Abwasser, Department of Water Quality Control, 2004, Technical University of Berlin, Berlin.

[14] US-EPA, Guidelines for Water Reuse, United States Environmental Protection Agency, Washington, DC, 2004.