SANASA Capivari II – the first full-scale municipal membrane bioreactor in Latin America

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ABSTRACT

The macro region of Campinas (Brazil) is rapidly evolving with new housing developments and industries, creating the challenge of finding new ways to treat wastewater to a quality that can be reused in order to overcome water scarcity problems. To address this challenge, SANASA (a publicly owned water and wastewater concessionaire from Campinas) has recently constructed the 'EPAR (Water Reuse Production Plant) Capivari II' using the GE ZeeWeed 500D® ultrafiltration membrane system. This is the first large-scale membrane bioreactor (MBR) system in Latin America with biological tertiary treatment capability (nitrogen and phosphorus removal), being able to treat an average flow of 182 L/s in its first phase of construction. The filtration system is composed of three membrane trains with more than 36,000 m^2 of total membrane filtration area. The membrane bioreactor (MBR) plant was commissioned in April 2012 and the permeate quality has exceeded expectations. Chemical oxygen demand (COD) removal rates are around and above 97% on a consistent basis, with biochemical oxygen demand (BOD_5) and NH_3 (ammonia) concentrations at very low levels, and turbidity lower than 0.3 nephelometric turbidity unit (NTU). Treated effluent is sent to a water reuse accumulation tank (from where will be distributed as reuse water), and the excess is discharged into the Capivari River.

Key words | large-scale MBR, municipal wastewater, nutrient removal

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INTRODUCTION

Water is becoming a scarce resource in important developed areas of Brazil, being critical in the São Paulo state region due to the high concentration of people and industries. Appropriate wastewater treatment is hence required, with a high level of contaminant removal that will allow water reuse operations for non-potable applications.

This is the case with Campinas City – located 100 km from São Paulo City – a bustling city with over a million inhabitants. As the macro region of Campinas continues to evolve with new housing developments and industries, the community faces the following complex problems:

- The existing wastewater treatment plants are distant from new developments (southeast region of Campinas).
- Treated effluent is discharged into an increasingly sensitive environment (Capivari River), where nutrient reduction and pathogen removal have become critical requirements.
- Freshwater resources are scarce in heavily populated and industrialized Piracicaba, Capivari and Jundiai River basins, to the extent that initiatives to reduce water consumption and promote the recycling of water for diverse uses are warranted.
- Simple, automated, reliable and easy-to-maintain solutions are required by operation personnel.

To address these issues, and in an effort to provide full access to sanitation for Campinas City, SANASA (a publicly owned water and wastewater concessionaire) has recently constructed the 'EPAR (Water Reuse Production Plant) Capivari II' facility, which is the first large-scale membrane bioreactor (MBR) to treat municipal sewage in Latin America (Figure 1). This facility will provide domestic sewage treatment for a population of 350,000 inhabitants once construction of Phase II is completed. The basic and detailed engineering for this facility was conducted by the Brazilian engineering company EMA – Engenharia de Meio Ambiente. The equipment supply, construction, installation and commissioning works were executed by a consortium formed between Construtora Norberto Odebrecht Brazil SA and GE Water & Process Technologies Brazil.

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Figure 1 | Aerial view of the SANASA Capivari II Wastewater Treatment and Reuse Facility in Campinas, Brazil.

Figure 2 | View of the membrane cassette ZeeWeed® 500D applied in EPAR Capivari II.

While MBR technology is a relatively recent approach for wastewater treatment solutions in Brazil, it has been applied extensively throughout North America, Europe and Asia for many years. In the last two decades, MBR technology has grown exponentially because of the advantages it offers over conventional treatment processes, such as: smaller footprint, improved effluent quality (suitable for several direct reuse applications such as make-up water for cooling systems) and better process control (Buer & Cummin 2010). It is expected that the demand for MBR systems will further increase with more than double-digit growth annually over the next decade due to increasingly stringent regulations and the huge demand in water reuse applications (Cote *et al.* 2012).

This paper presents key information related to the EPAR Capivari II MBR system design, start-up, operation and system performance for the generation of high quality treated effluent for potential reuse.

The EPAR Capivari II MBR solution with hollow fiber ultrafiltration membrane

The MBR system can be defined as the combination of a reliable ultrafiltration (UF) membrane with an activated sludge process. At the heart of the system is the immersed ZeeWeed® 500D UF membrane with the following features:

- The UF membrane is an immersed, suction-driven, hollow fiber membrane built in a rectangular frame of hollow fiber bundles (Figure 2), immersed directly in the mixed liquor of an aerobic reactor, and connected to the suction side of a positive displacement pump. Under gentle suction of 20–55 kPa, treated water (permeate) is drawn through the pores of the membrane in an 'outside-in' fashion into the hollow core of each fiber, and discharged from the system.
- The UF membrane has a nominal pore size of 0.04 μm and rejects all suspended and colloidal solids, including bacteria and most viruses. Any solids larger than this – including the bacteria in the biomass – are unable to pass through the pores and always remain on the outside of the hollow fiber.
- The hollow fiber is actually a composite membrane, where the permeable membrane is cast over a porous, but tough, structural core to create the most robust membrane available. This construction confers high durability that may render a membrane lifetime of more than 10 years (Cote *et al.* 2012).

As the solids are completely separated from the treated wastewater by the membrane, there is no need to settle sludge, which brings the following benefits:

- The MBR system operates at mixed liquor suspended solids (MLSS) concentrations between 8 and 10 g/L. This is almost three times higher than a conventional activated sludge system; therefore, reactor volumes are approximately one-third.
- Highly variable wastewater (flow and/or concentration due to industrial discharges into the sewer pipes), a condition that causes serious biological process upset problems in a conventional system, has little, if any, effect on the smooth and reliable operation of an MBR system.

The MBR and ancillary equipment installed at the EPAR Capivari II is represented by the arrangement shown in

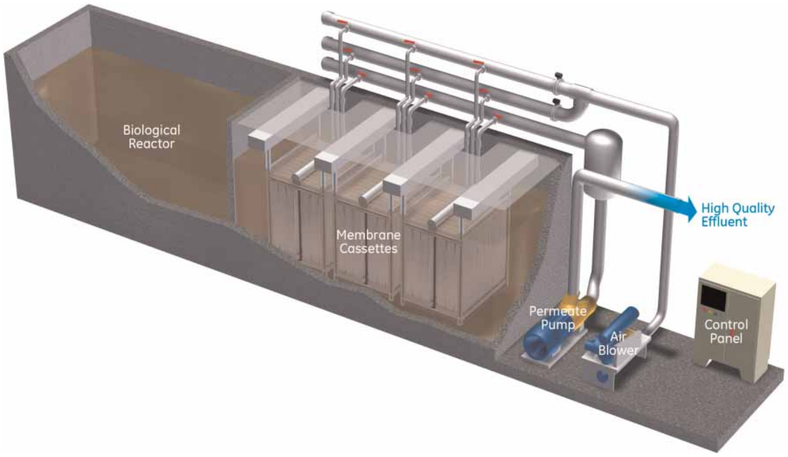

Figure 3 | Generic schematics of an MBR system containing bioreactor units, membrane tank and associated equipment.

Figure 3. Pretreatment comprises coarse screening (15 mm), followed by fine screens (2 mm) and grit removal chambers.

In its first phase, the plant has been designed to treat an average daily flow (ADF) of 182 L/s and a peak hourly flow of 294 L/s. The biological system is comprises tandem deoxygenation (DeOx), anaerobic, anoxic and aerobic zones (Table 1), being the first large-scale system in Brazil with biological tertiary treatment capability, designed to remove nitrogen, and to partially remove phosphorus.

The deoxygenation zone receives the mixed liquor that returns from the membrane tanks by gravity. As the membrane tanks are aerated to control membrane fouling (dissolved oxygen can be as high as 5 mg/L from a membrane tank), the deoxygenation zone brings the benefit of depleting the dissolved oxygen before the mixed liquor is mixed with the incoming influent in the anaerobic zone. In the anaerobic zone, conditions are provided for the fermentation of organic matter producing acetate, which in turn theoretically favors the growth of phosphorus accumulating organisms (PAOs) under specific conditions. The effluent then flows to the denitrification zone, where heterotrophic bacteria reduce nitrate into nitrogen gas, resulting in effective nitrogen removal. The organic carbon and ammonia not oxidized in the previous biological systems are consumed in the aerated zone, thus completing the required bioprocess for the biological removal of carbon, nitrogen and phosphorus.

Table 1 | Summary of reactor volumes and hydraulic retention time of each biological reactor zone for SANASA EPAR Capivari II MBR plant

	Tank volume (m^3)	Hydraulic retention time (HRT) at average flow (h)
Deoxygenation zone	720	1.1
Anaerobic zone	1,685	2.6
Anoxic zone	1,685	2.6
Aerobic zone	4,278	6.5

After flowing through the biological reactor system, the mixed liquor is pumped to three membrane trains (Figure 4). Each train has eight GE ZeeWeed® 500D membrane cassettes, which provides more than 36,000 m^2 of membrane surface area (Table 2).

The membrane trains were designed for independent operation. Each membrane train features dedicated equipment, including permeate/backwash and recirculation pumps, aeration blowers, priming system and all required instrumentation and controls, including dedicated low-range permeate turbidity meters for continuous online quality monitoring. Therefore, even if one train is taken off duty, e.g., for cleaning purposes, the other two remaining trains

Figure 4 | View of the three membrane trains and ancillary equipment at the SANASA EPAR Capivari II MBR plant.

Table 2 | Summary of membrane system design for SANASA EPAR Capivari II MBR plant

Number of membrane trains	3
Number of cassettes per train	8
Number of cassette spaces per train	10
Total number of installed cassettes	24
Total number of installed ZeeWeed 500D modules	1,152
Total membrane area supplied	~ 36,400 m2
MLSS in biological system	Up to 10,000 mg/L
MLSS in membrane tank	Up to 12,000 mg/L
Membrane tank useful dimensions (L × W × H)	10.0 m × 6.4 m × 3.3 m (useful)

are able to treat the totality of the flow. A common tank drain pump, a sludge wasting pump and membrane chemical cleaning systems complete the arrangement.

Treated effluent, filtered by membranes, is sent to an intermediate tank, which overflows to a water reuse accumulation tank before its discharge to the Capivari River.

The plant is controlled by a GE programmable logic controller PAC Systems RX3i, with high speed I/O cards and human-machine interface. The SCADA software is based on the GE Proficy Process System® with an Industrial Historian for data storage and plant operation history.

PLANT OPERATION AND PERFORMANCE

Plant start-up

The MBR plant started up in April 2012 treating about 30–50 L/s of domestic sewage produced in the northwest region of Campinas City. The biological system was seeded with about 300 m^3 aerobic sludge from an existing conventional activated sludge system from SANASA. To safeguard membrane operation due to the presence of fibers and other debris, proper care was taken by launching the seed sludge into the fine screen channel in order to remove any material that could be detrimental to the membranes.

The growth of sludge was carefully followed so as to reach the appropriate loading rate for optimal bioconversions (target F/M of 0.15 kgBOD/kg volatile suspended solids (VSS).day). Start-up went smoothly and the sludge concentration was kept at lower levels of 3–4 g/L. Even though the MBR system can operate with MLSS concentrations as high as 10 g/L in the bioreactor zone, operation is currently geared toward finding the optimal sludge concentration, thus minimizing energy consumption without penalizing the performance of the plant.

Only one membrane train operated during the first year of operation, whereas the other two trains remained in stand-by. However the trains were still alternated so that all trains were engaged in operation and cleaning routines.

Membrane bioreactor operation and performance

The membrane aeration is based on a 10:10 pattern, i.e., the modules are alternately aerated every 10 seconds. The plant operates with both membrane backwash or relaxation modes, and the frequency of one or the other is selected by the operator. Maintenance chemical cleanings are also applied weekly to maintain membrane permeability over time, using sodium hypochlorite (200 ppm) for organic material or citric acid solution for inorganic. Recovery cleanings, at a higher chemical concentration and soaking time, are used when membrane permeability is significantly reduced.

Table 3 summarizes influent and effluent characteristics as well as overall removal performance. The analytical results of raw sewage and treated effluent correspond to the operation of the MBR system for the period from April 2012 through May 2013.

Table 3 shows that the MBR plant generated permeate of excellent quality throughout the first year of operation. The BOD_5 permeate concentrations were, for the vast majority of time, below 1 mg/L, thus irrevocably indicating that little, if any, residual biodegradable organic pollution remained in the treated effluent.

With respect to nitrogen compounds, the results also exceeded expectations, as the removal efficiencies for total Kjeldahl nitrogen (TKN), NH_3 and total nitrogen (TN) were very high, despite unusually high inlet nitrogen concentrations, with inlet TKN concentration as high as 96 mg/L. The high degree of TN removal can be attributed to several factors: (i) intensive recirculation rates (exceeding five times the inlet flow), which are normally applied in MBR design; (ii) the actual inlet flow is still lower than design flow, so actual loads are lower than design values (actual values equal to or below 0.02 kg NH_3-N/kgVSS.day) despite operating the system at lower MLSS concentration; (iii) the anaerobic zone also acts as an anoxic zone, which further increases the reaction volume for heterotrophic denitrification activity; and (iv) the high temperatures in the mixed liquor all year round. The observed high denitrification efficiency, as indicated by the very low permeate nitrate

Table 3 | Summary of feed and effluent quality, as well as membrane performance for the SANASA EPAR Capivari II MBR plant, with samples collected and analyzed on a weekly basis. Legislation requirements are based on Brazilian Ministry of Environment (2011) and São Paulo State Government (1976)

	Feed (raw sewage)		Permeate (treated effluent)			
Parameter	**Range**	**Average**	**Range**	**Average**	**Average removal (%)**	**Legislation requirement**
COD (mg/L)	650–770	725	17–30	23.4	96.9	
BOD_5 (mg/L)	324–390	360	0.5–2	0.92	99.8	60 and minimum 60% removal
TKN (mg/L)	66–96	83	0.01–1.80	0.74	98.6	–
NH_3-N (mg/L)	32–69	54	0.01–0.29	0.15	99.7	< 20
TN-N (mg/L)	68–97	85	4.5–6.9	5.3	93.8	–
NO_3-N (mg/L)	1.0–2.1	1.9	2.1–5.3	3.9	–	–
TP (mg/L)	8.2–10.0	9.1	0.98–7.35	3.05	73.0	–
TSS (mg/L)	276–332	307	0.6–2.0	1.1	99.7	1 mL/L (as settleable material)
Turbidity (NTU)	–	–	0.18–0.28	0.23	–	
Temperature (°C)	–	–	18–31	26.4	–	< 40
pH	6.9–7.4	7.1	7.2–7.9	7.5	–	6.0–9.0
Flux (LMH)	–	–	15–18	17	–	–
Permeability, initial (LMH/bar)	–	–	–	330	–	–
Permeability after 1 year (LMH/bar)	–	–	–	270	–	–

concentrations (Table 3), also brings the benefit of high alkalinity recovery, which means an important saving in operation costs. Throughout the reported operation period, there was no requirement for dosing soda ash or any other alkalinity source, with permeate alkalinity typically higher than 60 mg $CaCO_3$/L.

The removal efficiency of phosphorus varied greatly during the reported period, and permeate total phosphorus (TP) values ranged from 0.98 to 7.35 mg/L (Table 3). This broad variation indicates that the required conditions for the growth of PAOs are not fully met. It is well known that the biological removal of phosphorus by its uptake is a sensitive process and one affected by several factors, such as wastewater characteristics, temperature, presence of dissolved oxygen and pH (Metcalf & Eddy 2002). In the specific case of the Capivari II MBR plant, the reasons for unstable biological P removal may be related to the presence of nitrate in the anaerobic zone. One condition for the growth of PAOs is the need to assimilate acetate to produce intracellular polyhydroxybutyrate with concurrent release of orthophosphate O-PO_4 (Metcalf & Eddy 2002). This acetate is produced by fermentation of the organic matter present in the raw sewage. However, acetate is also the perfect substrate for the heterotrophic denitrifiers. As the mixed liquor that flows to the anaerobic zone is likely to be laden with nitrate (the mixed liquor comes from highly aerated zones), we believe that the acetate produced is being readily consumed by the denitrifiers. In other words, the denitrifying bacteria are probably outcompeting the PAOs for the acetate, which in turn reduces the removal of phosphorus via the biological path.

In case the abovementioned hypothesis (that the presence of nitrate in the anaerobic zone is deleterious for the BioP removal is confirmed), one can consider implementing a second sludge loop, recirculating mixed liquor from the end of the aerobic zone back to the beginning of the anoxic zone. This second sludge loop would enable the removal of nitrate to a level where residual concentrations reaching the membrane tank, and in consequence, reaching the anaerobic zone, would not be detrimental for the growth of PAOs. In any case, the dosing of coagulant for the chemical abatement of phosphorus will be implemented in Phase II of the project, so that very low TP concentrations in the permeate will be possible, irrespective of BioP process sensitiveness.

The results for the removal of thermotolerant coliforms and key parasites were also excellent for MBR permeate with a concentration of faecal coliforms <2 most probable number (MPN)/100 mL and non-detected parasites (Table 4). The excellent removal of bacteria and viruses that can be achieved by ZeeWeed® 500D membrane with turbidity consistently <0.3 NTU and completely free from

Table 4 | Summary of the microbiological quality for the permeate for the SANASA EPAR Capivari II MBR plant

Date	Thermotolerant coliforms (MPN/100 mL)	*Escherichia coli* (MPN/100 mL)	*Giardia* spp. (cysts/L)	*Cryptosporidium* spp. (oocysts/L)
May/14-15/12	< 2	N.A.	N.D.	N.D.
Jun/11-12/12	< 2	N.A.	N.D.	N.D.
Jul/16-17/12	< 2	N.A.	N.D.	N.D.
Aug/06-07/12	< 2	N.A.	N.D.	N.D.
Oct/15-16/12	< 2	< 2	N.D.	N.D.
Nov/05-06/12	< 2	< 2	N.D.	N.D.
Jan/29-30/13	< 2	< 2	N.D.	N.D.
Apr/01-02/13	< 2	< 2	N.D.	N.D.
May/20-21/13	N.A.	< 2	N.D.	N.D.

N.D.: Not detected.
N.A.: Not analyzed.

odor, irrevocably demonstrates the superior performance of MBR systems compared to other conventional technology treatment systems. The permeate characteristics meet commonly adopted standards for industrial and domestic uses, such as make-up water for cooling towers and for non-potable uses (e.g., flushing toilets). In addition to the environmental protection benefits, the consistent generation of reuse water quality by the EPAR Capivari II MBR plant offers the opportunity for additional revenue to SANASA.

The membranes performed within specification on a constant basis. The permeability after 12 months of operation still remains at values around 300 lmh/bar. Chemical cleans with hypochlorite (for biological fouling) and citric acid (for inorganic fouling) are regularly and automatically executed (two cleanings with hypochlorite per week and one cleaning with citric acid every 2 weeks), so that SANASA's recognized high standard of operation and maintenance will probably be rewarded with a long membrane lifetime, thus reducing lifecycle costs.

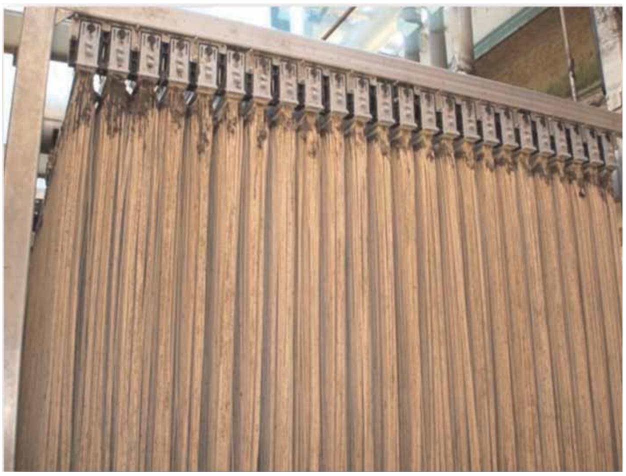

Figure 5 | Membrane fibers after 1 year of uninterrupted operation: absence of broken fibers and sludge/solids accumulation among them.

After 1 year of operation, membrane trains were drained and inspected. No unusual sludge or other solid accumulation in membrane fibers were detected, as shown in Figure 5.

CONCLUSIONS

The robust and reliable operation of the first large-scale MBR treating domestic sewage elevates SANASA to one of the leaders of the Latin American sanitation sector. The MBR plant produced an effluent with COD values consistently lower than 30 mg/L, with BOD_5 and NH_3-N at very low levels, and turbidity lower than 0.3 NTU, with no odour nuisance. This excellent permeate quality and smooth MBR plant operation clearly demonstrates the technical and economic feasibility of hollow fiber based MBR in treating domestic sewage. SANASA's focus on planning, execution and personnel training and commitment were key for the success of this project, which will open the path for the implementation of modern MBR systems in other cities in Latin American countries.

The treated wastewater surpasses the most stringent standards for industrial and domestic uses, which offers the opportunity for reducing the demand for fresh water via the implementation of water reuse, e.g., in the industrial park of Campinas. Treated water is being currently launched into the Capivari River, which will likely impact positively in the quality of the receiving water body.

Operational costs can be lowered by adjusting the sludge inventory to actual pollutant load, demonstrating that MBR is a competitive system for the generation of high-quality water. Finally, trained personnel have been operating UF systems according to best practice recommended by the membrane manufacturer, as indicated by the high membrane permeability (300 lmh/bar) after 12 months of operation. Proper operation, and attentive and scheduled maintenance will be rewarded by extending membrane life. The EPAR Capivari II has been a success – both operationally and from a performance perspective – showing that the use of hollow fiber membranes as the core unit was the right choice.

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