Treatment of Toilet Wastewater for Re-use in an MBR

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Abstract. Toilet wastewater is treated and re-used on-site at Europe's highest membrane bioreactor (MBR), located in a cable car mountain station in the ski resort of Zermatt. Negative impacts on the sensitive mountain environment are minimized by re-using close to 100% of the treated wastewater for toilet flushing. Besides 100% nitrogen removal, 80%of phosphorus was also eliminated. This paper presents operational results, optimisations of sludge management, decolouration and long term maintenance of biomass in very low loaded summer season. In a global view the experiences and results of the project are of great importance, proposing a solution to a problem existing hundredfold in the Alps as well as in arid regions all over the world: reducing water consumption for sanitation by re-use.

Keywords: water re-use, MBR, toilet waste water, nutrient removal, sludge management, decolouration, seasonal load variation, maintenance of low loaded biomass

Introduction and Background

In the last century, the upper alpine region experienced a major change in activities, from a pure agricultural land use towards an increased use for tourism. Because of the special location of the tourist infrastructures (high altitudes and mountain tops with sensitive environments and water scarcity) innovative solutions are needed for wastewater management and sludge disposal.

One example is Europe's highest biological wastewater treatment plant (WWTP) in the ski resort of Zermatt (Boehler et al., 2006). The membrane bioreactor (MBR) is located in the basement of a cable car mountain station, 3300 m above sea level. The treated wastewater is re-used for toilet flushing. Before operating the WWTP, dry toilets with tubular bags were used for excrement disposal, which were difficult to maintain and generated odours. Altogether, the installations did not meet the needs of increased hygiene and comfort for the tourists.

In a global view the project is of great importance because it proposes a solution to a problem that exists in hundreds of locations in the Alps as well as in arid regions all over the world. The project was a joint venture of Zermatt Bergbahnen AG, terraLink Gmbh and of Eawag. The project was financially supported by the Swiss Federal Office for the Environment (BAFU).

Material and methods

Wastewater composition and plant configuration

The wastewater at the mountain cable car station contains mainly urine, faeces and toilet paper. Wastewater dilution takes place only via toilet flushing (4 l flush^{-1}), which results in high BOD, nutrients and salt concentrations. Because the treated waste water is recycled as flushing water and water for sinks, salts and refractory organic compounds accumulate in the system. The average ammonium concentration in the equalization tank was about 130 mg NH_4-N l^{-1}. Phosphate and inert COD increased in the winter season during 5 months of continuous operation. The daily wastewater flow depends strongly on the number of tourists (weather conditions) and varies between 0 to 2 m^3 d^{-1}, which is equivalent to a maximum of 500 toilet flushes per day). In summer, when the cable car is not open for the public, the toilets are used only by the maintenance personnel of the cable car company, therefore the wastewater load is drastically reduced.

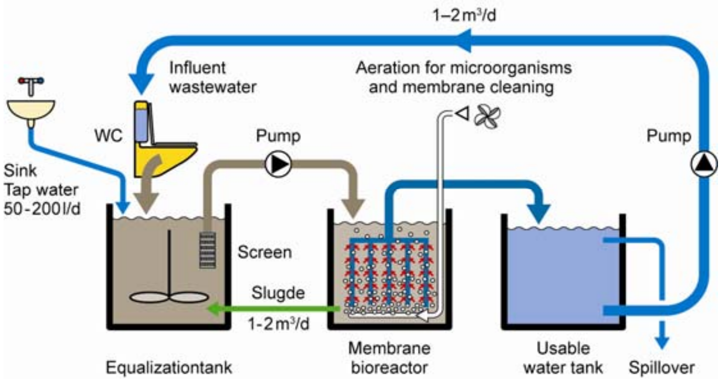

Figure 1. Optimised configuration of the toilet wastewater treatment plant (autumn 06)

The first reactor (figure 1: filling level varies from 2 to 3.5 m^3) serves as a flow buffering tank, disintegration, hydrolysis and separation (2.5 mm screen) of faeces and toilet paper as well as for the ammonification of urea. The ratio of inlet to sludge recycle from the membrane chamber (MBR) was about 1. If a defined level in the primary reactor is reached, wastewater is pumped batch-wise into the MBR (the volume varied from 3 to 3.4 m^3). The MBR is equipped with 2 to 3 standard flat sheet membrane modules (each 6.2 m^2, pore size 0.04 µm, Martin System AG). During intermittent aeration ammonium is mainly nitrified to nitrite that is nearly completely denitrified during the anoxic phase. The pH in the MBR varied between 7.0 and 7.5. Excess sludge was removed from the MBR two to three times per week. Permeate storage for covering daily peak flows takes place in a third tank.

Result and discussion

Accumulation of salts and refractory organic substances in recycled waste water

Due to complete water recycle and evaporation of urine liquid (net input 0.1 l per toilet flushing) during aeration, nearly no spillover was observed and salts accumulated in the system. In the winter season of 2005/06, the permeate conductivity increased from 3 to 9 mS cm^{-1} after 5 months of operation (urine has 20 mS cm^{-1}, Figure 2).

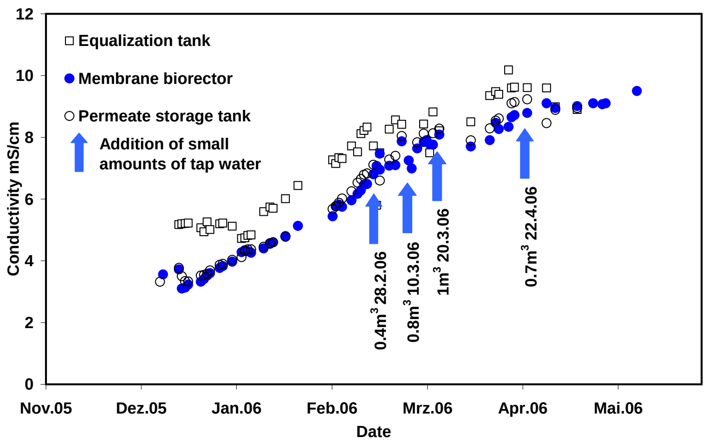

Figure 2. Increasing conductivity due to recycle of cleaned toilet water as toilet flushing water. About 3 m^3 fresh water were added in March and April due to operational problems.

The increasingly saline conditions (greater than 10 mS/cm) may cause salts to precipitate in the plant (e.g. on the membrane surfaces) or inactivate the biomass. To prevent these effects the sink will be operated with a limited amount of fresh water during next winter seasons.

Along with the salts, non biodegradable organic compounds accumulated in the flushing water. Due to by-products of biological decomposition of organic substances an intensive colouration of permeate similar to urine was observed. Figure 3 shows an increase in the absorbance of the permeate proportional to the amount of wastewater treated, during phases without dosage of powder activated carbon (PAC). To prevent multiple toilet flushing (i.e. prevent users from assuming that the off-coloured water meant that the toilet hadn't been flushed), decolouration was achieved with about 100 g PAC per m^3 of treated toilet wastewater, added into the MBR (ca. 30 mgPAC per cable car passenger; assuming that 10% of the passengers visited the toilet). Compared with PAC, trials with a granulated activated carbon (GAC) filter after the MBR also showed a strong decrease in colour but were correlated with a high consumption of GAC (circle, Figure 3).

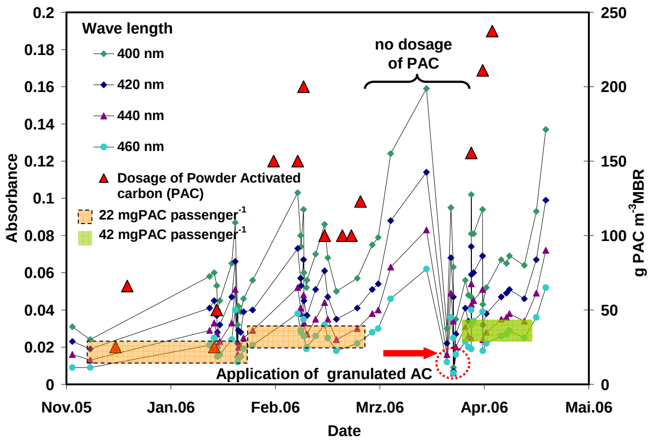

Figure 3. Absorbance profile of the permeate in ski season 2005/06 and decolouration due to PAC and GAC dosage

Nitrogen removal

In spite of the continuously increasing salinity, complete nitrification and denitrification by intermittent aeration (30 min aerobic / 30 min anoxic phase) was observed (Figure 4). The reactor was inoculated with sludge from digester supernatant treatment sludge of the WWTP Buelach (Switzerland). Before the main ski season, the nitrification capacity of the activated sludge was built up to 50 gN $kgCOD^{-1}$ d^{-1} by adding NH_4HCO_3 and sugar (Figure 5A). This specific nitrification rate (r_{nit}) remained almost constant during the whole ski season. Samples were taken from the reactors every morning. About 20 to 30 g m^{-3} of ammonium were found as a result of residual ammonification of urea in the MBR overnight.

A recycle ratio ≥ 1 generated an efficient hydrolysis of suspended solids (faeces and toilet paper) to readily biodegradable compounds in the equalization tank. By pumping the raw toilet wastewater into the MBR during the anoxic phase, denitrification took place mainly in the MBR and only marginally in the equalization tank.

During the operation of the MBR the composition of the nitrifying bacteria population changed in such a manner that the oxidation of ammonium to nitrate decreased from 100% to about 20%; the remaining 80% being oxidized only to nitrite

(Figure 5B). Due to a reduced carbon demand for denitrification via nitrite external additions of C-sources were only needed during the start up phase and when sludge recycle ratios were significantly below 1. Complete denitrification stabilized the pH between 7 and 7.5 in the MBR during the whole season.

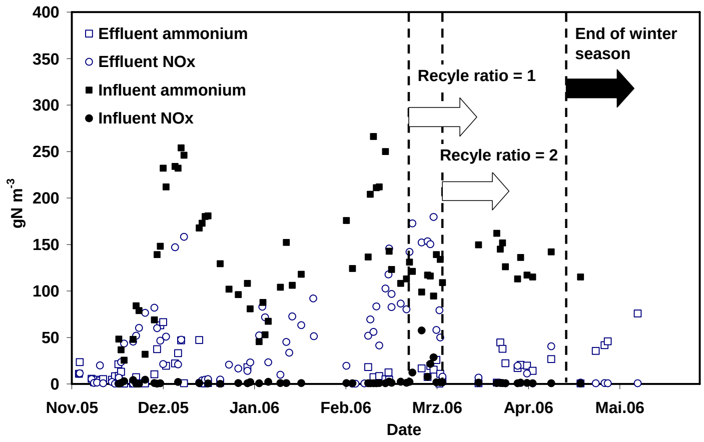

Figure 4. Nitrification and denitrification in MBR (NOx = NO_2-N + NO_3-N)

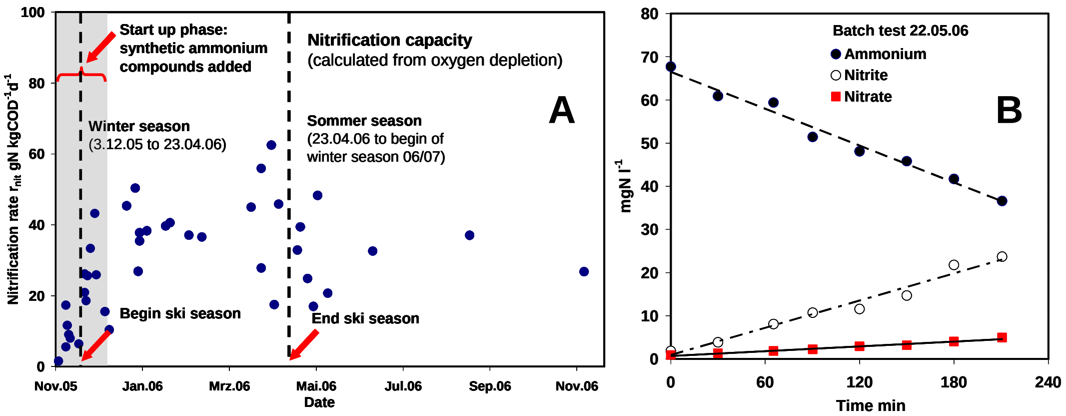

Figure 5. Nitrification capacity of MBR sludge and change of activity of nitrifiers. Graph A: observed activity over the whole year; graph B: results of a single activity test performed to obtain each single data point of graph A.

Phosphorus removal

Up to the end of February the phosphate concentration in the equalization tank and MBR did not increase (Figure 6). We assume that the inoculation sludge from the digester supernatant treatment plant of the WWTP Buelach contained some iron from P-precipitation. Apart from P incorporation by biomass growth, the predominant part of the polyphosphate possibly precipitated with the iron in the first 3 month of operation (about 15% of the total P load).

At the end of the ski season, the phosphate concentration in the plant reached about 40 mgPO_4-P l^{-1} which corresponds to 0.4 kg P (about 20% of total P load). About 1.9 kg P was incorporated into the sludge that was partly removed as excess sludge (0.5 kg, contained about 0.022 kgP $kgCOD^{-1}$). In batch tests polyphosphate storage was observed, corresponding to about 0.3 kg P. Thus, about 65% of the P-load was biologically bounded in sludge or eliminated by excess sludge respectively.

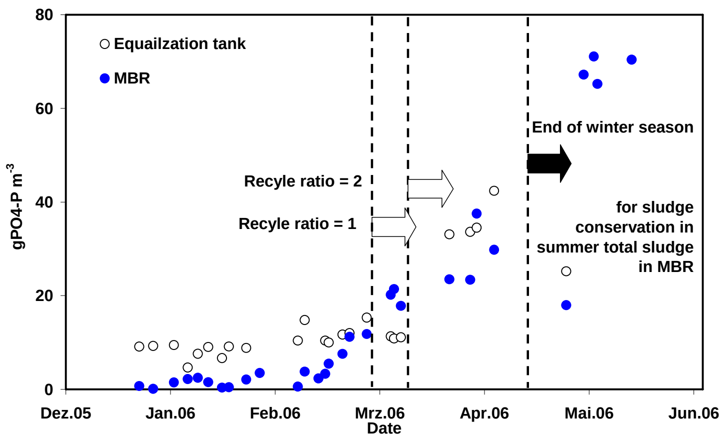

Figure 6 Accumulation of phosphate in the plant

Polyphosphate storage and denitrification strongly depend on the sludge recycle ratio and intermittent aeration cycle. This was documented by mathematical modeling of the wastewater treatment (Buetzer et al., 2006). The biological part was simulated with the calibrated Activated Sludge Model 3 (Koch et al., 2000) supplemented with the Bio-P-Modul (Rieger et al., 2001) designed by Eawag. The simulation results showed substantial ingrown of polyphosphate accumulating organisms (PAO) by introducing a sludge recycle ratio equal or larger than 1.

Performance of membrane

At the beginning of the winter season 2005/06 only two membrane modules (left and right module, see Figure 7) were operated, the same ones that were used during the previous ski season. Attempts to increase the low permeability of about 60 l m^{-2} h^{-1} bar^{-1} by chemical and mechanical cleanings were unsuccessfully. Due to low permeability and high water consumption (multiple toilet flushing), a third revised module (left module) was installed at the end of February. Also here all cleaning strategies failed to stabilize the initial permeability of about 450 l $m^{-2}h^{-1}bar^{-1}$. In order to treat the increasing daily amount of toilet wastewater and to have enough flushing water for the toilets, a minimal filtration capacity of at least about 5 l min^{-1} was kept by exchanging the right module with a revised one. As seen in Figure 7 this module also lost its permeability continuously. For future seasons the plant will be equipped with three new or revised membrane modules; to avoid rapid permeability decrease all modules should be exchanged simultaneously.

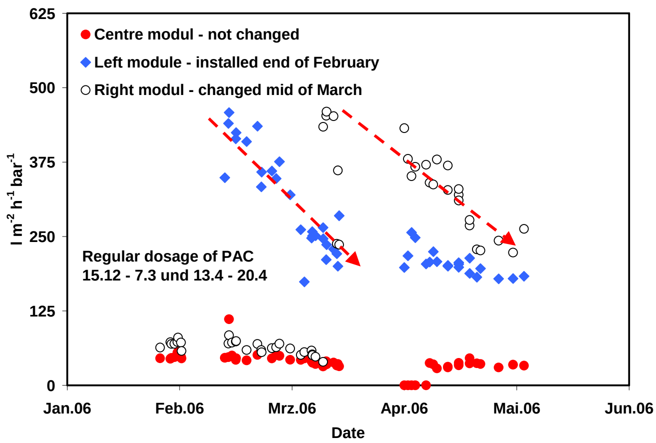

Figure 7. Membrane performance during winter season 2005/06

As shown by simulation runs, permeability and filtration capacity both have a strong impact on the nutrient removal efficiency of the MBR. With high filtration capacity (for example, with 3 new modules) the aerobic contact time of wastewater decreases which is correlated with insufficient nitrification. In the case of the WWTP Hohtälli the filtration capacity should not exceed 10 l $m^{-2}h^{-1}$.

Sludge handling and long term maintenance

According to the load of the plant and in order to keep sludge concentration at a maximum of 15 kgCOD m^{-3}, excess sludge was removed from the MBR. For convenient handling and to reduce the amount of sludge for disposal, the sludge (volatile suspended solids 50 to 55%) was dewatered by gravity and air drying in filter bags to a dry solid content of about 10 to 15%. The sludge was disposed of with domestic waste.

To avoid a complex start up phase with non adapted sludge and artificial substrates additions at the beginning of next season a specific sludge treatment strategy during summer time was applied. At the end of the winter ski season all activated sludge was transferred to the MBR and aerated for 60 seconds every 4h. This prevented anaerobic conditions and allowed the ammonium released from sludge decay to be nitrified. A batch test conducted at the end of November showed a nitrification capacity of about 50% of the maximum winter capacity (Figure 5).

Economic-efficiency and energy consumption

The driving factors of the project were to reduce the cost of the dry toilet, increase customer comfort and to build a biological WWTP in line with environmental requirements.

Until 2004, the dry toilets at the cable car station needed to be replenished with tubular bags daily. The tubular bags (filled with urine, faeces and toilet paper) were disposed in containers. This daily process had to be done manually and was linked with unpleasant odor. The operation and maintenance of the system, including cleaning and transportation of the filled waste containers from the top of the mountain down to the nearest local waste deposit in the valley, corresponded to about 30% of a full time job – ca. 70 working days per year, plus the significant cost for the tubular bags.

With the new MBR, facility maintenance, cleaning and quality control could be reduced to 15 days a year. Considering an annual average salary of EUR 48.000.- the annual savings (for only operational staff) could amount to over EUR 11.000.-.

After reducing the water requirement for a single toilet flush from 6 l to 4 l the energy consumption was determined to be 11.5 kWh per m^3 treated toilet wastewater Compared to conventional full scale MBRs, the observed energy consumption is about 11 times higher (about 1 kWh m^{-3} treated wastewater, MUNL, 2003, Wedi, 2005). This great difference is due in part to the smaller scale, a UV disinfection unit, and also because the toilet wastewater is 10 to 15 times less diluted than municipal wastewater. However, there is potential for energy optimization (e.g. better permeability would result in significant reduction in operation time of the membrane, at the Hohtälli facility.

Disinfection of permeate by UV irradiation was operated at Hohtälli during the winter season 2005/06. The energy consumption for the disinfection unit (incl. recirculation pump) was about 3.4 kWh per treated toilet wastewater. In an Eawag project (Aquamin, Abegglen and Siegrist, 2006) where also a small-scale membrane bioreactor for domestic wastewater treatment without disinfection is operated, microbial counts comply with the European requirements for bathing water (EU, Directive 2006/7/EC, 2006). Harms and Englert (2006) found no pathogens in permeate in their decentralized wastewater treatment plant with submerged ultra filtration membranes. In light of these data and the fact that in coming winters the sinks at Hohtälli will be operated with fresh water (salinity) no disinfection will be conducted anymore. Therefore, energy consumption below 8.1 kWh per m^3 treated toilet wastewater can be expected (especially if membrane operation at higher permeability is achieved). Hence, a daily total maximum energy consumption of about 16.5 kWh d^{-1} can be assumed. In this context, an internal energy supply by 20 m^2 solar panels should be feasible (solar radiation 0.95 kW m^{-2}, daylight 8h, solar system efficiency 10%). The operation of the system without batteries would be significantly more cost effective though it may require some additional space for more liquid storage, i.e. the plant would only be operational during daylight hours.

Conclusions

A MBR for toilet wastewater treatment and with water re-use for toilet flushing was continuously operated in the 2005/06 ski season. Complete elimination of nitrogen and of about 65% phosphorus was achieved. This high nutrient elimination was achieved by optimizing the sludge recycle ratio and intermittent aeration. Sludge recycle ratios between 1 and 2 generated efficient hydrolysis of particulate COD and the accumulation of phosphorus accumulating organisms (PAOs).

Furthermore, strategies for sludge removal and long term sludge activity conservation during the summer season with low ammonia and COD loads were tested. In addition, decolouration of permeate by adequate PAC dosages was achieved. The gathered experience and treating strategies for the specific wastewater proved that nearly complete water re-use with MBR treatment is a practically option. The results were documented in an operating manual, which will support the operators in next winter ski seasons. The plant demonstrates an innovative solution for wastewater treatment and re-use and sludge management for sensitive regions with water scarcity.

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