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Full-scale maturation ponds working below a latitude of 43°S in a semiarid area: seasonal performance and removal mechanisms

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bacterial removal; full-scale sewage treatment; maturation ponds; nitrogen dynamics; phytoplankton development; semiarid region.

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Abstract

Stabilisation ponds are the most frequently used wastewater treatment technology in Argentina. This study focuses on the performance of two maturation ponds (MPs) that are part of the full-scale sewage treatment system of Puerto Madryn. Seventy-seven shots of surface water were analysed for organic matter, inorganic nitrogen, phytoplankton dynamics and bacterial removal. The system presented a clear evolution with respect to oxygenation and phytoplankton development. The treated wastewater reached values above 8 mg-O_2/L, an important organic matter removal, and this was accompanied by a strong increase in pH. NH_4^+ removal and oxidation, was active even during winter in the MPs, with average concentrations below 10 mg -NH_4^+ /L. Bacteriological removal resulted in a liquid that approached the WHO recommendations for unrestricted irrigation. These results show that is possible to generate treated wastewater in stabilisation ponds working in a semi-arid and temperate region, with bacterial content and conductivity suitable for irrigation.

Introduction

In recent years, many of the studies in stabilisation ponds have been directed towards their potential uses or the sub-products that can be obtained from their operation, for example, biogas or biofuels (Craggs *et al*. 2012; Konaté *et al*. 2013; Paredes *et al*. 2015; Fadeyi *et al*. 2016), the presence and removal of illicit and pharmaceutical drugs (Baker *et al*. 2014; Vuori *et al*. 2014), and the modelling of the processes that occur in these wastewater treatment systems (Pompeo *et al*. 2016; Ouedraogo *et al*. 2016). However, interest remains in understanding the operation and removal systems processes in municipal ponds in a full-scale system, especially for sites in temperate or cold climates.

The use of stabilisation ponds is common in coastal Patagonia, despite the presence of a temperate to cold climate (with average air temperatures below 7°C during the winter months). The ponds are present as far south as a latitude of 49.3°S (Luis Piedra Buena City). They are used in villages with as few as 600 inhabitants (e.g. Puerto Pirámides) to cities with over 100,000 inhabitants (e.g. Puerto Madryn, Trelew). However, their use is mainly motivated by economic benefits rather than to the efficient performance that has been observed in several of these systems (Esteves *et al*. 1996; Faleschini *et al*. 2012). For this reason, many sanitary engineers in Argentina have low confidence in these systems and prefer to use conventional systems where possible.

Of the various types of stabilisation ponds, maturation ponds (MPs) are mainly used to remove pathogens because their shallow depth increases the incidence of the solar radiation (Maynard *et al*. 1999; Craggs *et al*. 2004). Correctly design MPs can achieve bacteriological levels compatible with unrestricted irrigation, and these ponds have various benefits over energy and chemical consuming disinfection treatment methods (Davies-Colley *et al*. 1999; Von Sperling 2003). Additionally, they are remarkable efficient with respect to nutrient removal (Picot *et al*. 2009; Yi *et al*. 2009; Mayo 2013). The hydraulic retention time is the main design factor of these systems because it largely determines the quality of the generated treated water.

Many regions in Argentina, particularly in western Patagonia, face freshwater scarcity. It is estimated that 75% of the land surface in Argentina (2.07 million km^2) is arid, semiarid, or subwet surface (SAyDS 2006). However, final disposal of the treated wastewater is controversial; there are few examples of reuse of treated wastewater.

This study analysed the performance of a treatment system using stabilisation ponds in a site with a temperate climate that consists of two MPs in series after the passage

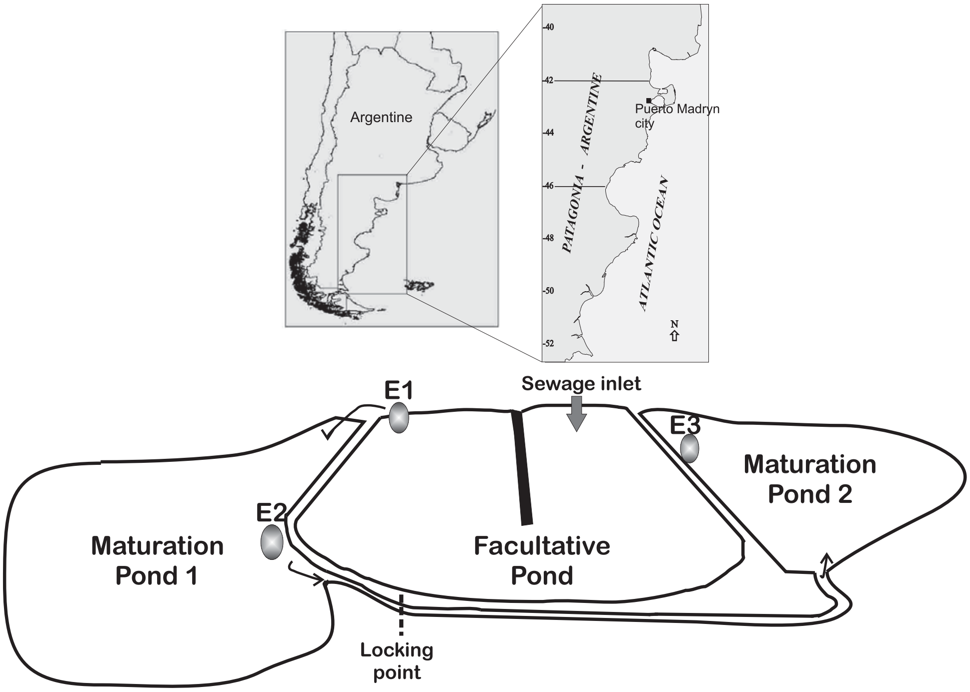

Fig. 1. Schematic diagram of the full-scale wastewater treatment plant at Puerto Madryn.

by a primary facultative pond. We particularly focused on the processes of organic matter transformation and removal of nutrients and bacteria.

Materials and methods

Study site

This study was conducted in the treatment system of domestic sewage in Puerto Madryn City (Patagonia, Argentina). The climate of the region is temperate and semiarid with marked variations in temperature and radiation between the cold and warm seasons. There are moderate to strong winds mainly from the west.

The treatment plant serves a population of approximately 80,000 inhabitants (which corresponds to 80% of the population, approximately). It consists of a primary facultative pond (FP) (25 hectares, 1.5 m deep, and U-shaped) and two MPs that work in series [maturation pond 1 (MP1) is 20 ha and maturation pond 2 (MP2) is 17 ha; both have an average depth of 1 m]. The raw sewage entered with an average temperature of 22.8°C (summer) and 14.3°C (winter). The raw wastewater is characterised by an important dilution (weak type according to Metcalf & Eddy, 1996), with the exception of ammonium, which is the strong type [which is the combined result of the biological hydrolysis of organic matter and the long residence time within the sewer system (i.e. 10 km from the city)]. The town is characterised by a strong water deficit, making agriculture unfeasible. The city does not have industries that drain metals into the sewer system. This was corroborated by Faleschini (2006), who registered cadmium, chromium, copper, lead and zinc in raw wastewater, in amounts between 10 and 760 times lower than recommended for irrigation by Ayers & Westcot (1985). Two major industries in the region (aluminum and fisheries) have their own wastewater treatment systems, not mixed with the domestic wastewater.

The flow that entered to the system increased from 11,000 m^3/day at the beginning of the study to 15,000 m^3/day at the end. Consequently, there was a decrease in hydraulic residence time from 18 days (MP1) and 15 days (MP2) to 13 days (MP1) and 11 days (MP2).

Three surface sampling points were selected: at the outlet of the facultative pond (E1), at a point in MP1 (E2) and at a point in MP2 (E3), to cover the liquid with more treatment in each of the ponds. During the summer and the late autumn months, the channel that connects MP1 with MP2 was shut, isolating MP2 from the system. During these periods, the liquid that left MP1 was derived through a canal, to enterprises that reuse the water, leaving MP2 to function as a storage reservoir (Fig. 1).

Sampling and analytical methods

Samples were collected during the morning (09:00-11:00), every other week for a period of 38 months (77 surveys were conducted in total). Temperature, pH, dissolved

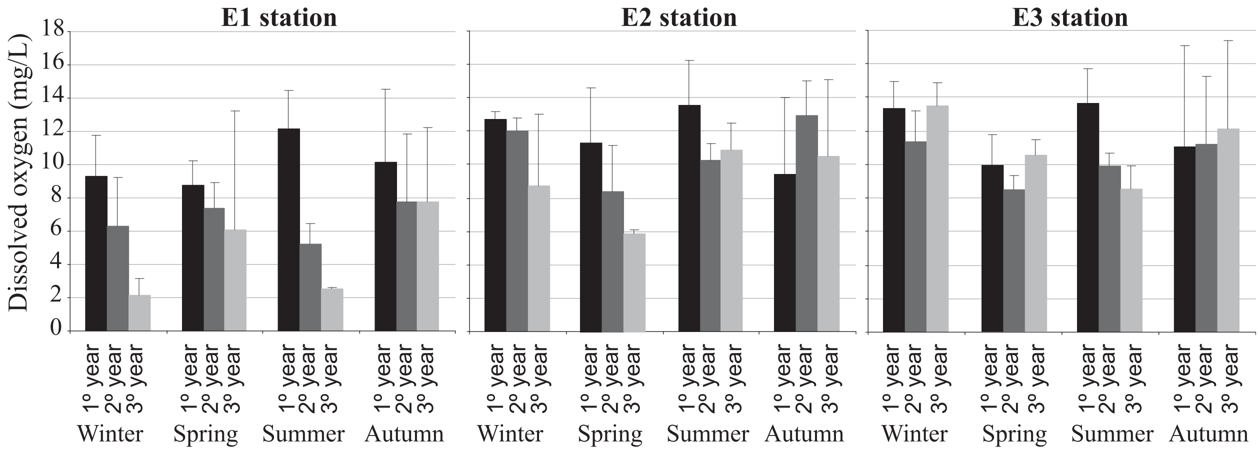

Fig. 2. Evolution of dissolved oxygen at the sampling stations (mean and standard deviation).

oxygen, and conductivity were measured *in situ* with a Horiba-U22 multiparameter probe.

Total and filtered (the last for E1 and E3) biochemical oxygen demand (method 507), ammonium (417C), nitrite plus nitrate (418C), chlorophyll-*a* and phaeophytin (1002G) and suspended solids (209D) were processed in laboratory, according APHA (1980). Total coliforms and *Escherichia coli* were analysed following the Quanti-Tray method (IDEXX Laboratory).

Both water sampling and *in situ* measurements were conducted in the surface water.

Results and discussion

In situ parameters

During the winter, there were periods when portions of the MPs had a surface layer of ice. This was mainly observed during the early morning; the ice extended approximately 5 m away from the shore, with a thickness of approximately from 3 to 5 cm, it began to disappear at noon.

The temperature ranged from 1.1°C during the winter to 20.4°C during the summer. In general, as the liquid passed by the treatment system, a decrease in temperature was registered.

At the E1 station, dissolved oxygen decreased throughout the course of the study. This decrease was most noticeable during the winter and summer months, which has been attributed to the flow and organic overloads in the facultative pond over the study period (Faleschini *et al*. 2012). In the final year, the minimum values were 1.27 mg-O_2/L or 17.3% (winter), 1.1 mg-O_2/L or 11.2% (spring), and 2.5 mg-O_2/L or 27.1% (summer). However, despite the low oxygen concentration events in the FP, the lowest average value registered in the MPs was 5.9 mg-O_2/L (at E2, during the spring). The maximum value recorded was 16.6 mg-O_2/L (at E2, during the summer), which corresponds to a saturation percentage of 179.0 (Fig. 2).

No significant variations in pH between seasons were observed in the FP ($P = 0.17$); the pH ranged from 7.04 to 8.05 (Fig. 3). MP1 had higher pH values compared to the FP in all cases. The largest increases were observed during the summer ($\Delta pH_{E2-E1} = 1.72$), and pH reached a maximum of 9.79. As expected, the highest absolute value was observed in MP2 during its closure, this coincided with the last cyanobacterial bloom, during which the pH reached a maximum value of 10.61. The pH in algal ponds increases with photosynthetic activity as algae consume carbon dioxide faster than it can be produced by bacterial respiration (Tadesse *et al*. 2004). Previous studies of MPs have not shown pH increases as large as those observed in Puerto Madryn (Yi *et al*. 2009; Mahapatra *et al*. 2013), although the hydraulic residence times in these cases were smaller than in our study.

Inside the FP, conductivity ranged from 1305 to 1625 μs/cm. In MP1, the conductivity ranged from 1418 to 2232 μs/cm and the maximum value was recorded during the summer. In MP2, the values were between 1613 and 3671 μs/cm; the maximum value was recorded during the final closure period.

Biochemical oxygen demand

For the E1 and E3 stations, we differentiate total BOD_5 into filtered BOD_5 (shown at the bottom of each bar) and particulate BOD_5 (shown at the top). The total height of each column represents the total BOD_5 concentration (Fig. 4).

At the outlet of the FP, the total BOD_5 increased during the spring and summer. The highest total BOD_5 values of the study were registered during the first year; these were 89.0 mg/L (spring) and 111.0 mg/L (summer). In the MPs, however, the total BOD_5 decreased, with mean values that generally did not exceed 40 mg/L. The exception was the

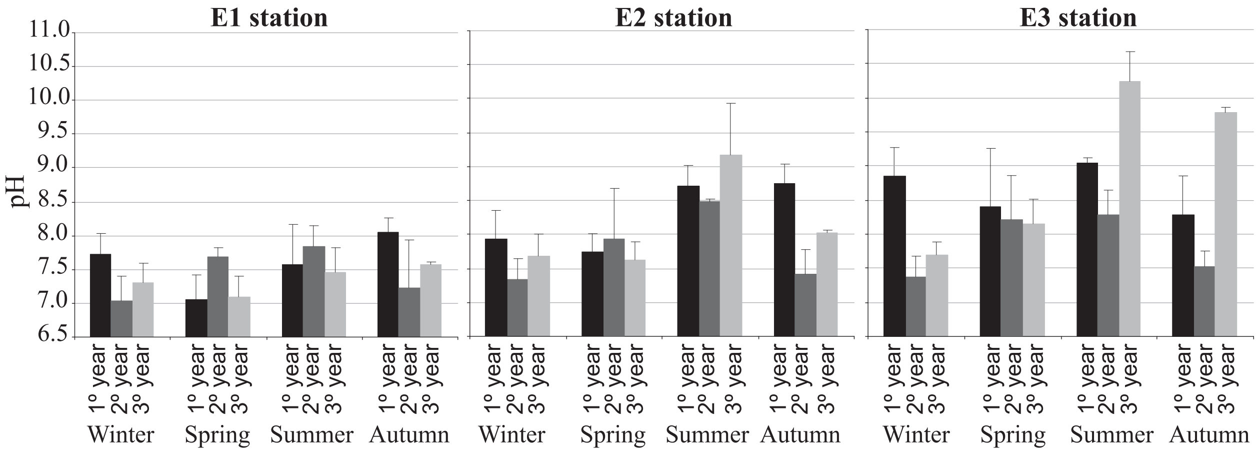

Fig. 3. Evolution of pH at the sampling stations (mean and standard deviation).

remarkable cyanobacterial bloom that occurred during the final summer, when a total BOD_5 of 64.5 mg/L was recorded.

The filtered BOD_5 at the E1 station increased during the winter and spring months over the course of the study; during the first winter, it was 7.7 ± 2.3 mg/L and increased to 28.4 ± 21.7 mg/L during the third winter, with a maximum recorded value of 47.5 mg/L. During the spring, the measured values were as follows: 5.4 ± 4.2 mg/L (1° spring) and 22.0 ± 15.4 mg/L (3° spring), with a maximum value of 38.7 mg/L. During the summer and autumn, there was no consistent trend; the filtered BOD_5 had an average value of 12.7 ± 6.1 mg/L. The filtered BOD_5 was more consistent at the E3 station, with an average value of 9.7 ± 3.2 mg/L.

Inorganic nitrogen

There was a clear seasonal pattern in NH_4^+ at the E1 station, with maxima concentration during the winter and minimum during the summer. The NH_4^+ concentration increased throughout the study, probably because of overloading of the FP (Faleschini *et al*. 2012). Despite the high NH_4^+ concentration that entered to the MPs from the FP during the autumn, winter, and spring; the MPs were able to efficiently remove NH_4^+ (Table 1). In MP1, NH_4^+ removal was not accompanied by pH values greater than 8.5; therefore, we could discard the ammonia volatilisation as a predominant removal process. This is consistent with the volatilisation field measured in a maturation pond in England by Camargo Valero & Mara (2007). During the summer, the NH_4^+ concentrations recorded at the E1 station were very low, leading to only minor concentrations in MP1 (<0.5 mg-NH_4^+/L). This was more obvious in MP2, because the closure prevented the continued input of NH_4^+ from MP1 (for MP2, concentrations were below 0.2 mg-NH_4^+/L) (Fig. 5). There was probably an internal recycling of nutrients from the sludge that maintained the phytoplankton population; this behaviour has been quantified in the facultative pond of Puerto Madryn (Faleschini & Esteves 2013).

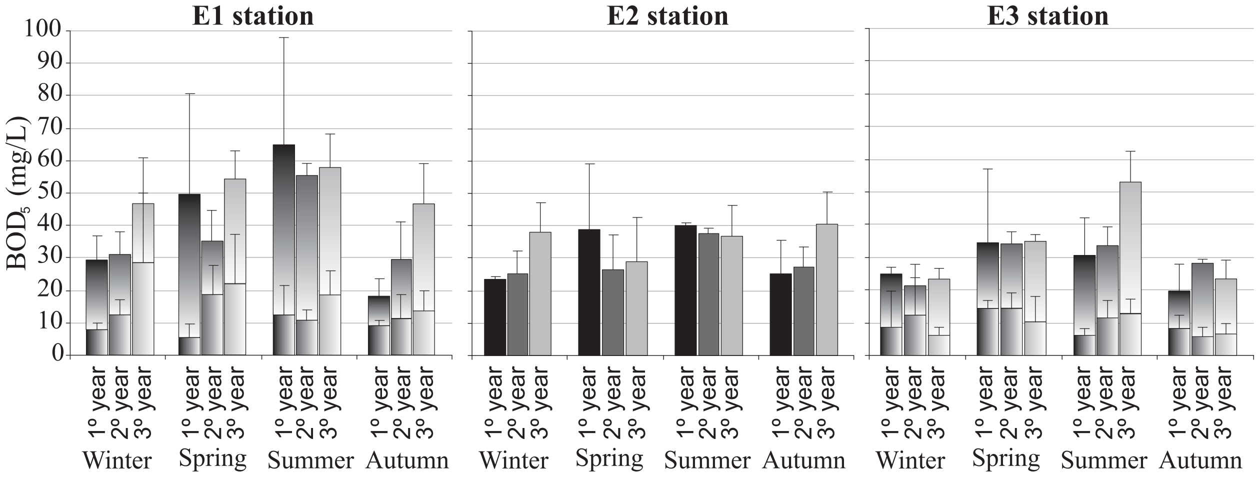

Fig. 4. Concentration of BOD_5 within the treatment system (mean and standard deviation).

Table 1 NH_4^- removal efficiency for each season

	NH_4^+ removal (%) between E1 and E2	NH_4^+ concentration (mg/L) at E2	NH_4^+ removal (%) between E1 and E3	NH_4^+ concentration (mg/L) at E3
Winter	40.88 ± 28.37	22.63 ± 12.81	80.62 ± 11.74	7.24 ± 5.89
Spring	50.26 ± 29.92	12.11 ± 17.47	70.15 ± 32.93	4.30 ± 6.05
Summer	81.04 ± 15.33	0.33 ± 0.58	89.90 ± 10.23	0.09 ± 0.11
Autumn	64.66 ± 23.95	6.59 ± 5.60	84.38 ± 14.68	2.10 ± 2.69

NH_4^+ concentrations in the FP were negatively correlated with temperature during the summer and winter ($r = -0.81$); this was also true in MP1 ($r = -0.79$). This correlation was not observed in MP2 ($r = -0.57$), mainly because NH_4^+ concentrations did not exceed 20 mg/L during the winter (despite temperatures below 5°C). This suggests the presence of active NH_4^+ removal/transformation processes.

Higher concentrations of $NO_2^- + NO_3^-$ were observed in the FP during the spring and summer (with a maximum value of 16.4 mg-$NO_2^- + NO_3^-$/L) and lower concentrations occurred during the winter. However, at both the E2 and E3 stations, there was NH_4^+ oxidation activity even during the winter. The concentrations ranged from 0.4 to 4.2 mg-$NO_2^- + NO_3^-$/L (for E2) and from 0.8 to 3.6 mg-$NO_2^- + NO_3^-$/L (for E3) (Fig. 5). Higher concentrations of oxidised forms of nitrogen (reaching 30 mg/L during warm periods) have been recorded in MPs of France (Picot *et al*. 2009). During the summer, the concentrations of oxidized forms of nitrogen were considerably lower in the MPs than in the FP. A possible explanation for this feature is that a fraction of the NO_2^- and NO_3^- entering MP1 from the FP, could have been removed from the system by ANAMMOX and denitrification processes. Camargo Valero *et al*. (2010) demonstrated the relevance of the denitrification process by tracer experiments with ^{15}N-labelled ammonium and nitrite in MPs. Additionally, Mayo (2013) suggested that this process was the main ammonium removal mechanism in a maturation pond in Tanzania. At the same time, NO_2^- and NO_3^- entering MP1 from the FP could be rapidly taken up by phytoplankton, in the case of a shortage of nitrogen in the form of NH_4^+. In addition, the low NH_4^+ concentrations in these ponds (<0.5 mg/L) would limit the production of new oxidized forms of nitrogen. This behaviour was more pronounced in MP2 during the closed periods, when there was a massive proliferation of cyanobacteria that coincided with inorganic nitrogen concentrations below 1 mg/L. Some genera of cyanobacteria are able to fix atmospheric nitrogen; this feature could have

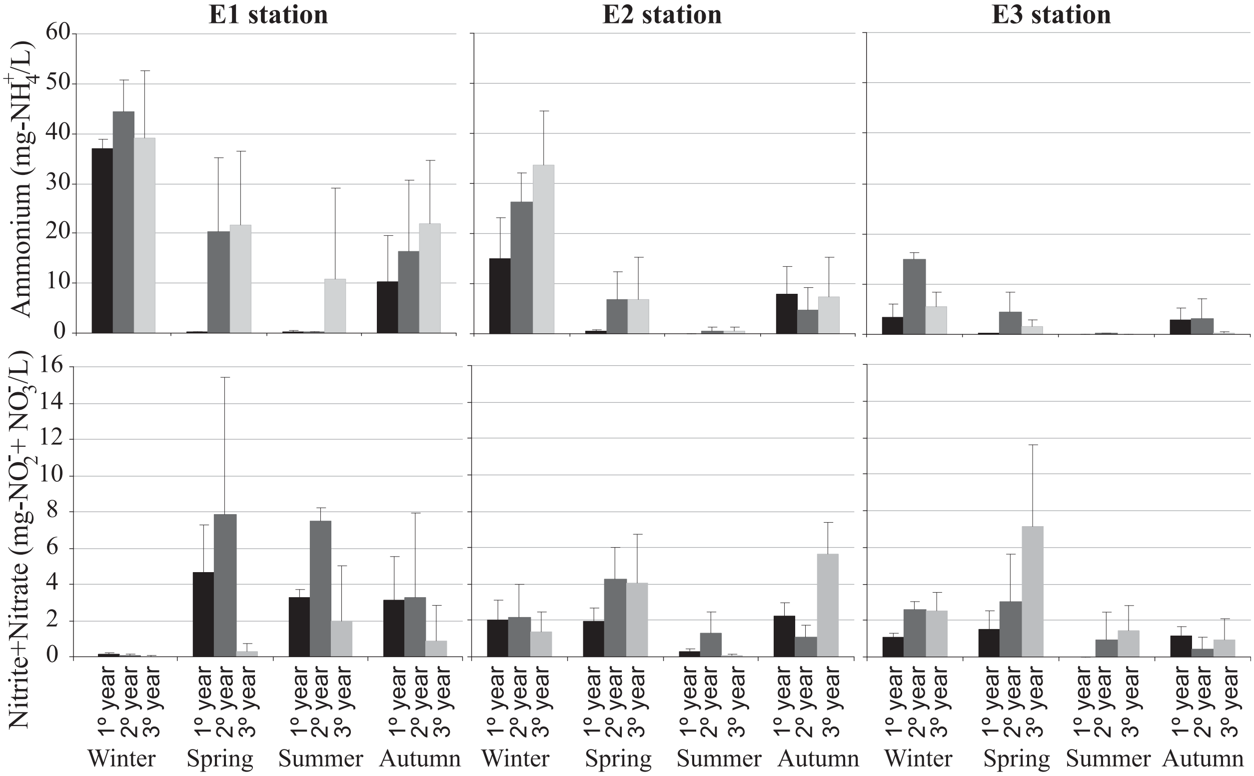

Fig. 5. Evolution of NH_4^+ (above) and $NO_2^- + NO_3^-$ (below) concentrations at the sampling stations (mean and standard deviation).

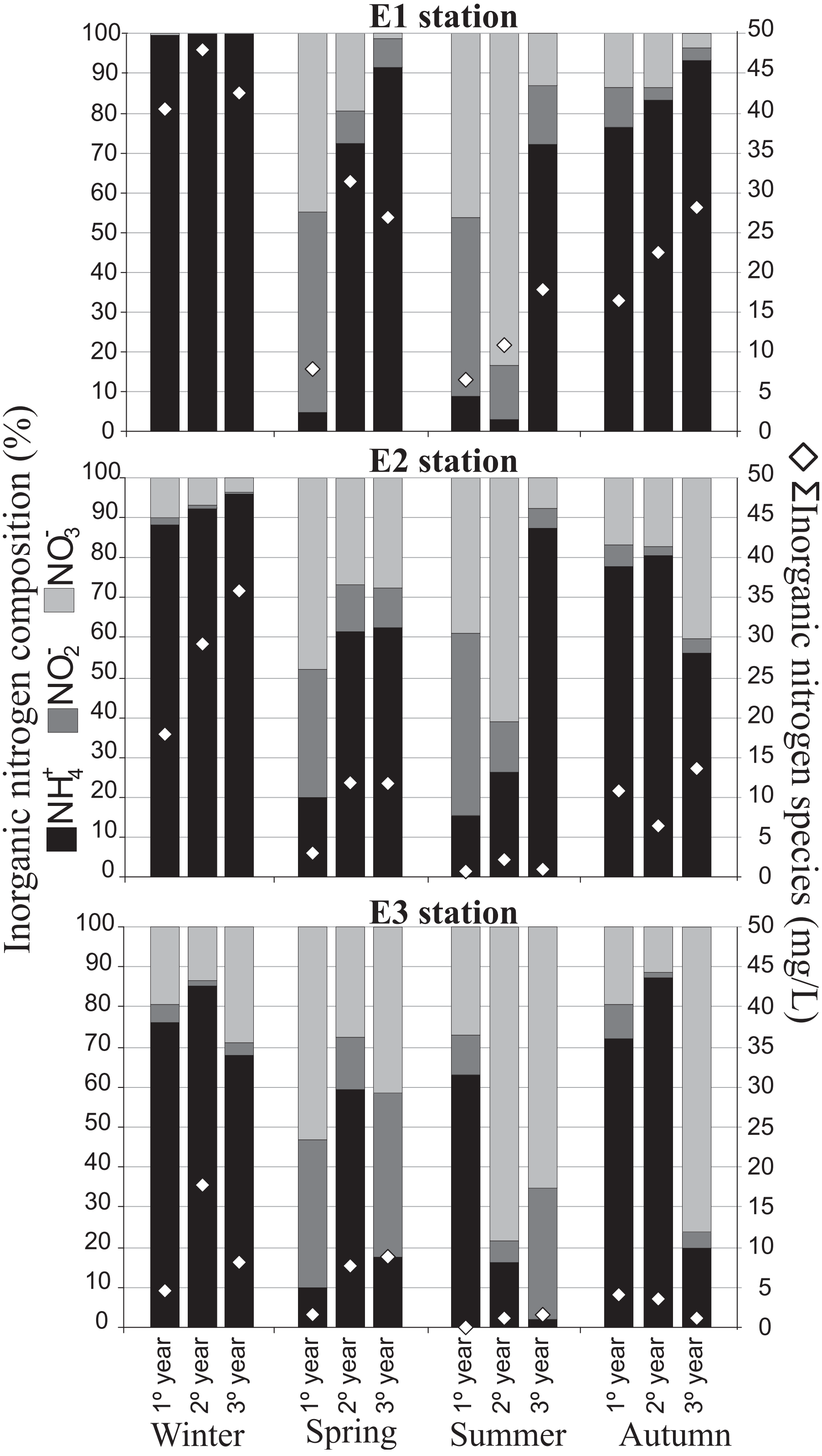

Fig. 6. Percentage distribution and total concentration of inorganic nitrogen forms.

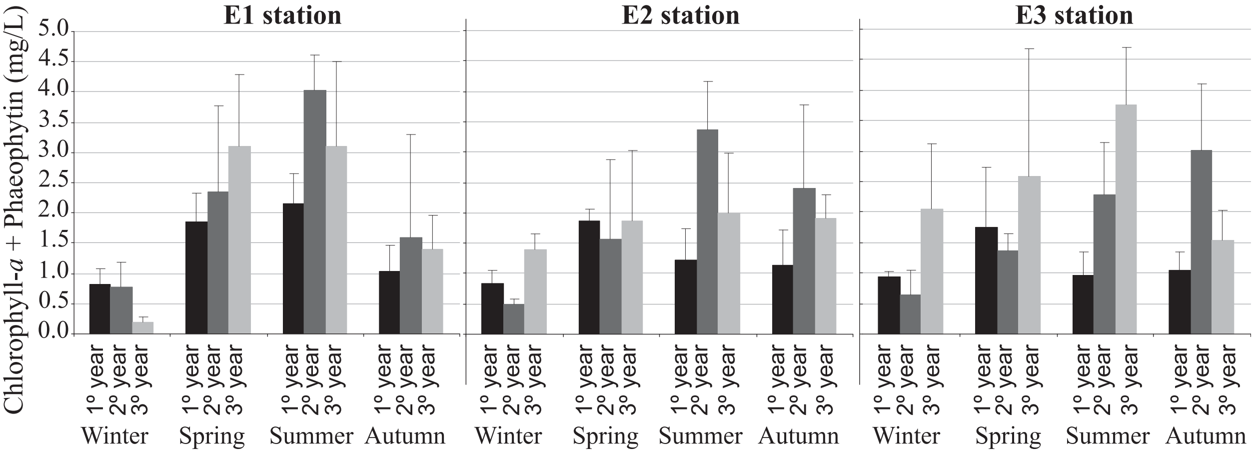

Fig. 7. Pigment concentrations (chlorophyll-*a* + phaeophytin) inside the treatment system (mean and standard deviation).

proven adaptive advantage, allowing these genera to proliferate over other groups that require the presence of dissolved nutrients (Chevalier *et al.* 2000). In our study, we identified organisms of *Anabaena* genus, which have this feature. Amengual-Morro *et al.* (2012) observed a cyanobacteria bloom at the same time as a decrease in hydraulic load.

The presence of oxidized forms of nitrogen in the MPs during the winter, supports the idea that the disruption of nitrification in the FP during the cold months was not unique nor directly related to the low temperature. Instead, conditions during the winter conditions affect other factors that control the nitrification process (e.g. lower oxygen content and lower concentration of phytoplankton). Another factor that could explain the disruption is the washout of nitrifying bacteria, a process that was described by Arauzo *et al.* (2000).

In the FP, NH_4^+ was dominant over the oxidized forms of nitrogen during the winter; NH_4^+ production was greater than removal, which was reflected by the higher NH_4^+ concentrations in E1 than in the raw wastewater [which had a concentration of 42.2 mg/L; Faleschini *et al.* (2012)]. This also occurred during the autumn and the final spring and summer; but a marked removal was observed). Despite this behaviour, significant NH_4^+ removal occurred in MP1 (even during the winter, when oxidized nitrogen concentrations were approximately 2 mg/L). However, there was a marked rise in the inorganic nitrogen concentration during the winter, which could be explained by the increase in NH_4^+ (from 17.1 mg/L during the first winter to 35.0 mg/L during the last winter). The MP2 was not negatively affected by the decline in performance in the FP and MP1; reflected that during the winter, NH_4^+ concentrations were below 15 mg/L and concentrations of the oxidized forms of nitrogen were between 1.0 and 2.6 mg/L (Fig. 6).

Phytoplankton development

There was a marked difference between the chlorophyll-*a* concentration during the winter in the FP (with average value below 0.33 mg/L and a minimum value of 0.04 mg/L) compared to the rest of the year (spring: 2.1 ± 1.2 mg/L; summer: 3.1 ± 1.1 mg/L and autumn: 1.3 ± 0.9 mg/L) (Fig. 7). For the majority of the winter, the facultative condition was absent (chlorophyll-*a* <0.3 mg/L), according to description of Pearson (1996).

There was no difference in chlorophyll-*a* in the MPs, with the exception of the winter, when the chlorophyll-*a* concentration was higher than 0.5 mg/L. MP2 had maximum values of chlorophyll-*a* (3.9 mg/L) when it was closed and there was a large cyanobacteria bloom. The chlorophyll-*a* values reached a in MP2 (0.05 mg/L) in short periods during the spring, when an important zooplankton density was observed. During these periods, phaeophytin dominated over the chlorophyll-*a*. A similar feature was observed in a high rate algae pond in France (Mesplé *et al.* 1995).

The chlorophyll-*a* values in our work have been higher than the maximum reported in other paper: 1.6 mg/L for a FP and 2.0 mg/L for a MP in Portugal (Pereira *et al.* 2001).

Bacteriological removal

Pathogen removal from wastewater is particularly important to improve public health in developing and transitional countries (Buchauer 2007).

In the Puerto Madryn treatment system, total coliform removal was 80.28 ± 7.75% (E1 vs. E2) and 96.97 ± 0.72% (E1 vs. E3). For *E. coli* the removal was 74.08 ± 8.76% (E1 vs. E2) and 96.79 ± 0.92% (E1 vs. E3).

Bacterial concentration reached a minimum when MP2 was closed. They exhibited a median value below 1,000 MPN/100 mL for *E. coli* during the last two summers. Even during the cyanobacteria bloom, when the pH was 10.61, there was a minimum *E. coli* value of 23 MPN/100 mL (Fig. 8).

In the FP, no significant difference in removal efficiency was observed between seasons. When MP2 was open (during the winter, spring and first and second autumns), the median

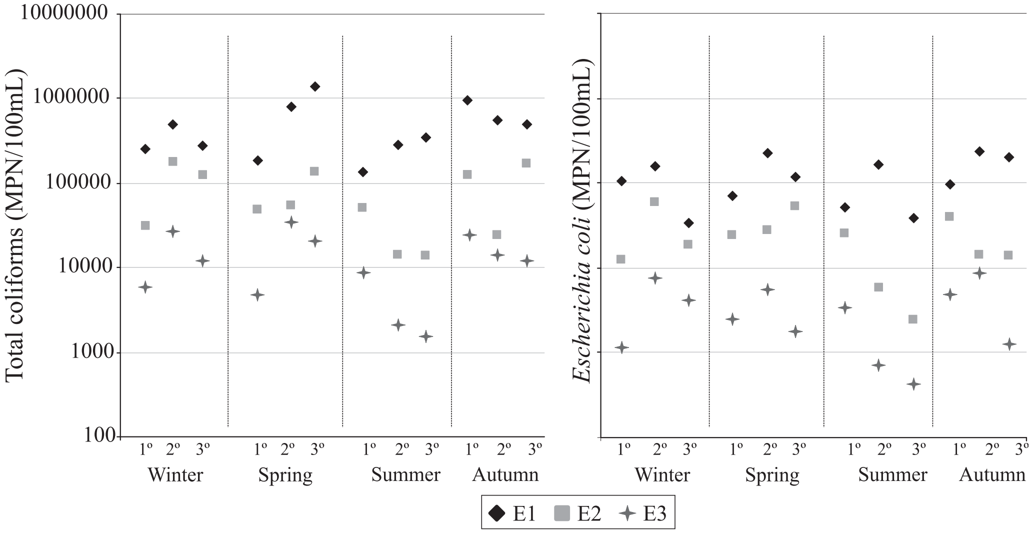

Fig. 8. Total coliforms and *Escherichia coli* concentrations at each sampling point in each season.

values for total coliforms and for *E. coli* were 1.4×10^4 MPN/100 mL and 4.3×10^3 MPN/100 mL respectively. These values are close to the value necessary for unrestricted irrigation (WHO 1989). The total theoretical residence time was approximately 50 days. The largest removals at the E3 station were observed during the summer. Bacterial mortality cannot be attributed to a single factor (Maynard *et al*. 1999; Davies-Colley *et al*. 2000). Different factors such as increased hydraulic retention time, high temperature, presence of cyanobacterial bloom, and likely algal toxins, along with rapid pH fluctuations (Amengual-Morro *et al*. 2012), could contribute to more efficient removal.

Although it is becoming increasingly important, the measurement of viruses in wastewater in our laboratories is still difficult. However, a study carried out in India recorded a removal efficiency of 88–98%, with a detention time between 2.7 and 17.2 days (Rao *et al*. 1981). Because the Puerto Madryn system had a detention time of 50 days, we feel confident that there would be efficient virus removal.

Conclusions

The results of this study illustrate the efficient performance of a full-scale wastewater treatment plant consisting of three stabilisation ponds operating in series [a primary facultative pond (FP) and two MPs (MP1 and MP2)]. The system treats wastewater from the city of Puerto Madryn (ca. 80,000 inhabitants) in a semiarid region with a temperate climate. Our main conclusions are as follows:

(1) The MPs facilitated a proper recovery during the periods in which the FP showed a loss of performance, mainly during the winter, when anaerobic conditions dominated. In those periods, water in the MPs was oxygenated, with low dissolved organic matter, high phytoplankton development and active NH_4^+ removal processes. Average NH_4^+ concentrations were below 25 mg/L (MP1) and 10 mg/L (MP2).

(2) NH_4^+ concentrations in the MPs during the summer, were always less than 1.5 mg/L, and NH_4^+ oxidation activity was registered during all seasons (during the winter, it was >2 mg-NO_{2+3}/L), although this was not the case in the FP during the winter.

(3) The disruption of nitrification during the cold months is not unique nor directly related to the effects of low temperature. Rather, winter conditions affect other parameters that limit nitrification process.

(4) Bacteriological levels in the wastewater that underwent the most treatment were close to the values necessary for unrestricted irrigation without restrictions. This water had a total hydraulic residence time of approximately 50 days.

(5) Although is not the objective of the final disposal in Puerto Madryn (where wastewater reuse is encouraged because of strong water deficits), is interesting to emphasize as a simple and inexpensive natural treatment system is capable of generate treated wastewater with suitable removal of organic matter, NH_4^+ and bacteria, and may be appropriate for cities that have as main alternative the disposal in a receiving body.

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