NUTRIENT LOSSES IN TWO LANDSCAPE PONDS USED FOR GOLF COURSE IRRIGATION

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ABSTRACT

Reclaimed municipal wastewater has been used for irrigation of the Mas Nou golf course, Girona, Spain, since 1989. Disinfected activated sludge effluent is stored in two landscape ponds connected in series. The morphological and operational characteristics of this pond system result in considerable differences in the hydraulic retention times of the ponds, and in the physical, chemical and biological processes taking place in them. Nutrient mass balances indicate a 28% total nitrogen loss (2 300 kg N) in the first pond and a 59% total nitrogen loss (930 kg N) in the second pond. The nitrogen species responsible for the losses are ammonia, when pH reaches up to 9,7, and nitrates, during denitrification episodes. Mass balances of soluble orthophosphate indicate a 7% loss (120 kg PO_4-P) in the first pond, and a 34% soluble orthophosphate loss (130 kg PO_4-P) in the second pond. Variations of soluble orthophosphate concentration show a close relationship with phytoplankton blooms. The quality polishing process taking place in this pond system points out the interest of a flexible design (piping and pumping systems), to allow water extraction from either of the ponds, and to achieve an effective nutrient control strategy. The use of reclaimed wastewater effluent for golf course irrigation offers an alternative water source and allows a partial recovery of the nutrients present in the effluent, with significant fertilizer savings.

KEYWORDS

Irrigation; golf course; nitrogen; nutrients; phosphorus; ponds; removal; reuse; wastewater.

INTRODUCTION

As water is becoming a scarce resource in many areas of the world, there is a need to develop alternative water sources where available supplies are not sufficient to meet increasing water demands. One alternative water source is reclaimed wastewater, which can be successfully used for many purposes, such as golf course irrigation (Mujeriego and Sala, 1991; Crook et al, 1992). To satisfy the irrigation schedules of golf courses, reclaimed water is usually stored in landscape ponds, where significant changes of its biological and chemical composition take place, particularly affecting the total amount and the chemical speciation of nutrients (nitrogen and phosphorus). Phytoplankton and bacterial populations fostered by the nutrients present in reclaimed wastewater effluents are responsible for a series of chemical and biological processes that cause important nutrients losses in the storage ponds. An understanding of the factors governing those processes should be very useful to optimize the beneficial use of nutrients by landscape irrigation and also to polish wastewater effluents with nutrient concentrations high enough to damage the plant species irrigated with them.

The main objectives of this paper are to determine the operational and water quality conditions favoring and/or governing the nutrient losses occurring in landscape ponds used for irrigation with reclaimed wastewater, and to establish operational criteria for a better nutrient management in similar irrigation systems. The specific objectives of this paper are: 1) to determine water quality variations and inputs, outputs and internal variations of nutrients in both ponds during 1992, 2) to estimate the annual mass balance of nitrogen and phosphorus, with special interest in nutrient losses, and 3) to identify the physical, chemical and biological processes responsible for those losses.

MATERIALS AND METHODS

The Mas Nou golf course is located at 300 m height in the resort town of Castell-Platja d'Aro, Girona, Spain, and uses reclaimed wastewater from the Castell-Platja d'Aro wastewater treatment plant for irrigation. Disinfected activated sludge effluent is stored in two landscape ponds connected in series (subsequently designated *pond 1* and *pond 2*, respectively). Pond 1 has 13 300 m^3 capacity and 4.5 m maximum depth, while pond 2 has 21 000 m^3 capacity and 5.5 m maximum depth. Reclaimed effluent flows through a surface weir into pond 1, whereas the flow from pond 1 to pond 2 takes place through a connecting pipe located at 2 m water depth. Pond 1 is used to irrigate 21 ha of golf course and the landscape areas of a nearby residential area, while pond 2 serves to irrigate the remaining 13 ha of golf course. Each pond has a pumping station and a wet well, with capacities of 180 m^3 (pond 1) and 150 m^3 (pond 2), connected to the bottom layers of the pond. Each pond has an ornamental water jet that takes water from the wet well and returns it to the pond surface. Additional information about the golf course irrigation system can be found in Mujeriego and Sala (1991).

Samples of reclaimed effluent and irrigation water from both ponds were analyzed weekly during 1992 for all parameters considered. Effluent samples were generally taken from 8 to 10 am. Surface water samples were taken at the nearest point to the pumping station of each pond; bottom water samples were taken from the pumping stations wet wells. Pond water samples were generally taken from 10 to 12 am.

To evaluate the physical, chemical and biological quality of the water, the following parameters were measured: pH, temperature, turbidity, suspended solids, electrical conductivity, alkalinity, calcium, magnesium, sodium, potassium, nitrogen (ammonia, nitrite, nitrate, organic), dissolved orthophosphate, dissolved oxygen, total iron, chlorophyll *a*, total aerobic bacteria, total and faecal coliforms, and faecal streptococci. All physical and chemical analysis were performed according to Standard Methods (APHA, 1989), except those listed below. Temperature and electrical conductivity were measured *in situ*, and compensations of conductivity variations caused by temperature were calculated according to Bührer and Ambühl (1975). Water pH was determined potentiometrically. Calcium and magnesium concentrations were analyzed by the EDTA titration method (Estrada, 1986). Total nitrogen was calculated as the sum of ammonia, nitrite, nitrate and organic nitrogen. Ammonia concentration in secondary effluent was determined using Aquaquant 14423 kits (Merck), while ammonia concentration in pond water samples was determined by Solorzano's method (1969). Organic nitrogen analyses were performed monthly according to Standard Methods (APHA, 1989). Chlorophyll *a* analysis was conducted according to Montesinos

(1982) and its concentration calculated following Richards and Thompson (1952) equations. Microbiological analyses were conducted by membrane filtration (Generalitat de Catalunya, 1986).

Considering that the organic nitrogen forms in the reclaimed effluent had little influence on the organic nitrogen concentration of pond 2, it was assumed that the organic nitrogen concentration in pond 2 was mainly associated with phytoplankton biomass. A good correlation was derived between organic nitrogen and chlorophyll *a* concentrations in water samples from pond 2, as shown by the following expression:

$$\text{Organic nitrogen (mg N/L)} = 5.478 \times \text{Chlor } a \text{ (mg/L)} + 1.433 \quad (r = 0.992 \; ; \; n = 16)$$

This expression was used to estimate the organic nitrogen concentration associated with the phytoplankton biomass of both ponds, based on the chlorophyll *a* concentrations actually measured. The organic nitrogen contribution of reclaimed effluent to pond 1 was estimated by its yearly average (1.8 mg N/L), due to the lack of weekly values for the organic nitrogen concentration in reclaimed effluent. Average nutrient concentrations in the ponds were calculated as the arithmetic average of the concentrations measured in surface and bottom water samples.

Mass balance calculations were performed weekly for both nitrogen and soluble orthophosphate according to the following expression:

$$I = O + N + L$$

where :
- I = mass input (from reclaimed secondary effluent)
- O = mass output (by irrigation water)
- N = net change in mass content of the pond (surface and bottom water)
- L = mass loss

Due to the irregular shape of both ponds, and based on the observations made since 1989, the mass content of each pond was estimated considering that one half of the water in the pond was surface water and the other half was bottom water (irrigation water).

RESULTS

Water Flows and Hydraulic Retention Times (HRT)

During 1992, the total water flows into pond 1 were 241 000 m^3 of reclaimed effluent (approximately 4% of the annual wastewater effluent) plus 7 300 m^3 of well water and 5 600 m^3 of rainfall. The maximum reclaimed wastewater inflow was observed in August (61 400 m^3) when the need for irrigation water was the highest. Total outflows from pond 1 were 179 000 m^3 of irrigation water (golf course and landscape areas) plus 67 100 m^3 of water pumped to pond 2 and 7 800 m^3 of evaporative losses. The maximum monthly average HRT (690 days) was observed in December, whereas the minimum HRT (7 days) occurred in August; the yearly average HRT for pond 1 was 19 days. Total water flows into pond 2 were 67 100 m^3 of water pumped from pond 1 plus 7 300 m^3 of rainfall; total outflows were 64 300 m^3 of irrigation water and 10 100 m^3 of evaporative losses. The maximum monthly average HRT (830 days) was observed in December, whereas the minimum HRT (39 days) occurred in August; the yearly average HRT for pond 2 was 100 days.

Nutrient Concentrations and Mass Balances

Nitrogen concentration in reclaimed effluent was always greater than 20 mg N/L; the highest values (up to 45 mg N/L) were observed during August and September. Dilution caused by storm water runoff was responsible for nitrogen concentrations lower than 20 mg N/L. Soluble orthophosphate concentration in the reclaimed effluent was highly variable, but generally greater than 4 mg PO_4-P/L. Total nitrogen and soluble phosphorus concentrations in both ponds varied markedly during 1992, the values for pond 1 being generally higher than those for pond 2.

Total nitrogen in pond 1 was higher than 20 mg N/L from May to mid June, and from August to December, whereas total nitrogen in pond 2 exceeded that value only in September, but remained higher than 10 mg N/L from May to July, and from September to October. Ammonia was the predominant nitrogen species in pond 1 from mid March until June and from August to October, reaching a concentration close to that of the reclaimed effluent (up to 38 NH_3-N/L) during the highest water demand period, when HRT decreased below 10 days. Ammonia was the predominant nitrogen species in pond 2 from May to mid July and at certain times during the summer period, reaching a peak value of 14 NH_3-N/L in late May.

Nitrite, an intermediate species of ammonia nitrification, reached its highest concentrations in pond 1 during June and October, with a maximum value of 14 NO_2-N/L. Nitrite concentration in pond 2 reached its highest value, 8 mg NO_2-N/L, in September. Nitrate, the final result of ammonia nitrification, reached its highest concentrations in pond 1 during mid June and early November, with a maximum value of 23 mg NO_3-N/L. Nitrate concentration in pond 2 reached its highest value, 11 mg NO_3-N/L, in mid September.

Soluble orthophosphate concentration in pond 1 ranged usually from 4 to 10 mg PO_4-P/L, except from February to March and during the second half of July, when it was lower than 4 mg PO_4-P/L. Soluble orthophosphate concentration in pond 2 ranged from 2 to 6 mg PO_4-P/L.

Total nitrogen and soluble orthophosphate mass balances were calculated for 1992 using weekly average values for water flows and nutrient concentrations. As cyanobacteria biomass did not reach a significant value during the study period, particularly in pond 1, it was assumed that nitrogen input via nitrogen fixation had been very low compared to inputs from reclaimed effluent.

Nitrogen Mass Balances for Pond 1

The irrigation schedule during 1992 resulted in 30 weeks (58% of the year) of reclaimed effluent inflows to pond 1 (See Figure 1). The most frequent weekly nitrogen input was below 300 kg N/week (36% of weekly contributions), although the input consistently exceeded that level from mid July to early September (22%). A maximum weekly nitrogen input (700 kg N/week) was observed from 3 to 8 August, due to the large inflow of reclaimed effluent to the pond and its high nitrogen concentration. The annual nitrogen input to pond 1 was estimated at 8 150 kg N/year. Nitrogen output from pond 1 showed a pattern similar to that of nitrogen input, and also reached its maximum values (480 kg N/week) two weeks after (17 to 23 August) the maximum input value was reached. The annual nitrogen output by irrigation water and water pumped to pond 2 was estimated at 5 780 kg N/year. The annual nitrogen variation was low compared to the input and output values indicated above, and it represented a gain of 75 kg N/year. This annual gain resulted from the difference in total nitrogen concentrations at the end of the year (11.2 mg N/L) and at the beginning of the year (7.4 mg N/L).

Weekly nitrogen balances indicate a dominance of weekly losses (77% of the weeks) as compared with weekly gains (23%). Weekly losses lower than 100 kg N/week were the most frequent (75% of weekly losses), followed by weekly losses from 100 to 200 kg N/week (18%); the maximum loss (340 kg N/week, or 15% of the annual loss) was observed from 20 to 26 July. Weekly gains were usually below 100 kg N/week (83% of weekly gains). The annual nitrogen loss was estimated at 2 300 kg N, corresponding to 28% of the total nitrogen input.

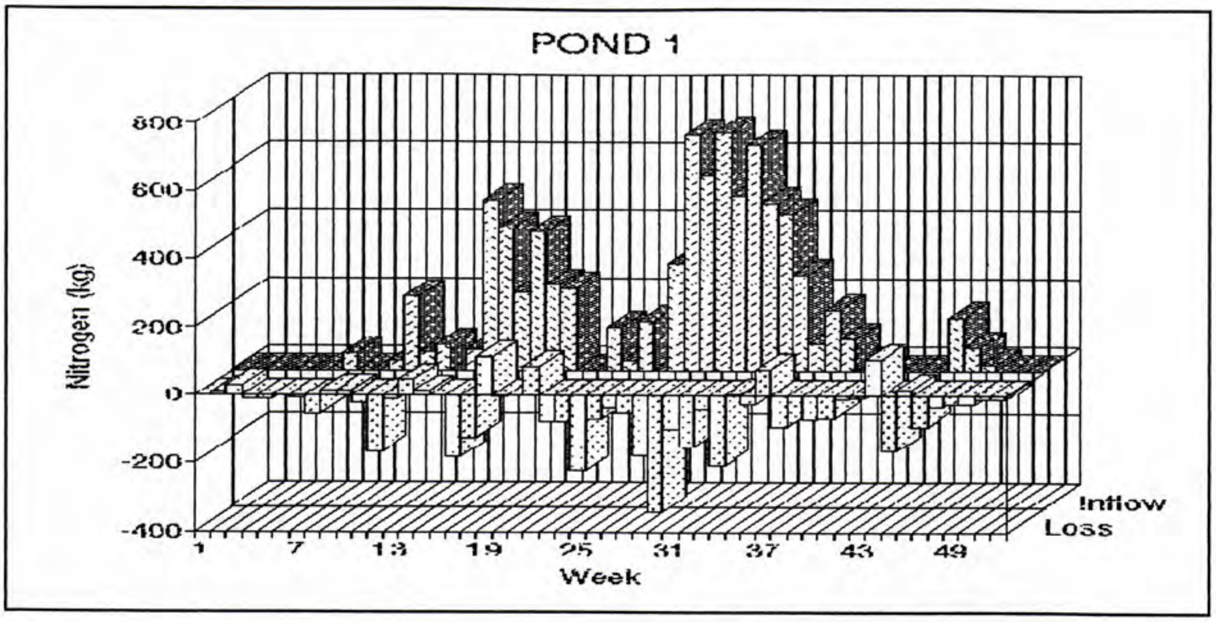

Fig. 1. Weekly nitrogen balances in pond 1 of Mas Nou golf course during 1992.

Nitrogen Mass Balances for Pond 2

The irrigation schedule during 1992 resulted in 33 weeks (63% of the year) of water flows from pond 1 into pond 2 (See Figure 2). Nitrogen inputs to pond 2 were much lower than those to pond 1, generally below 100 kg N/week (49% of weekly contributions). Nitrogen inputs greater than 100 kg N/week occurred during mid-spring and summer weeks, with values reaching up to 135 kg N/week from 17 to 23 August, accounting altogether for 15% of the weekly contributions. The annual nitrogen input to pond 2 was estimated at 1 600 kg N/year. Nitrogen output by irrigation water followed a pattern similar to that of nitrogen input and reached its maximum value (70 kg N/week) one week after (31 August to 6 September) the maximum input value was reached. The annual nitrogen output by irrigation water was estimated at 630 kg N/year. The annual nitrogen variation resulted in a gain of 20 kg N/year; however, great differences were observed between weekly values, specially during the summer period, due to the intense metabolism of the photosynthetic algae growing at that time.

Weekly nitrogen balances indicate, similarly to those for pond 1, a dominance of weekly nitrogen losses (69% of the weeks) as compared with weekly gains (31%). Weekly losses lower than 50 kg N/week were the most frequent (72% of the weekly losses), followed by weekly losses from 50 to 100 kg N/week (16%); the maximum weekly loss (240 kg N/week) was observed from 20 to 26 July. Weekly nitrogen gains were usually below 50 kg N/week (88% of weekly gains). The estimated annual nitrogen loss was 930 kg N/year, equivalent to 59% of the total nitrogen input.

Soluble Orthophosphate Mass Balances for Pond 1

Soluble orthophosphate inputs to pond 1 were much lower than those of nitrogen. The most frequent weekly input values were below 100 kg PO_4-P/week (48% of weekly contributions), although they showed greater values during mid-spring and summer weeks (10%), reaching a maximum value of 150 kg PO_4-P/week from 17 to 23 August. Similarly to the case of nitrogen, the irrigation schedule resulted in no soluble orthophosphate input during 22 weeks (42%). The annual soluble orthophosphate input was estimated at 1 930 kg PO_4-P/year. Soluble orthophosphate output followed a pattern similar to that of inputs from reclaimed effluent, and reached its maximum value (130 kg PO_4-P/week) in the same week. The annual soluble orthophosphate output by irrigation water and water pumped to pond 2 was estimated at

1 460 kg PO_4-P/year. The weekly variations of pond soluble orthophosphate showed considerable fluctuations during the year, accounting for an annual gain of 80 kg PO_4-P/year.

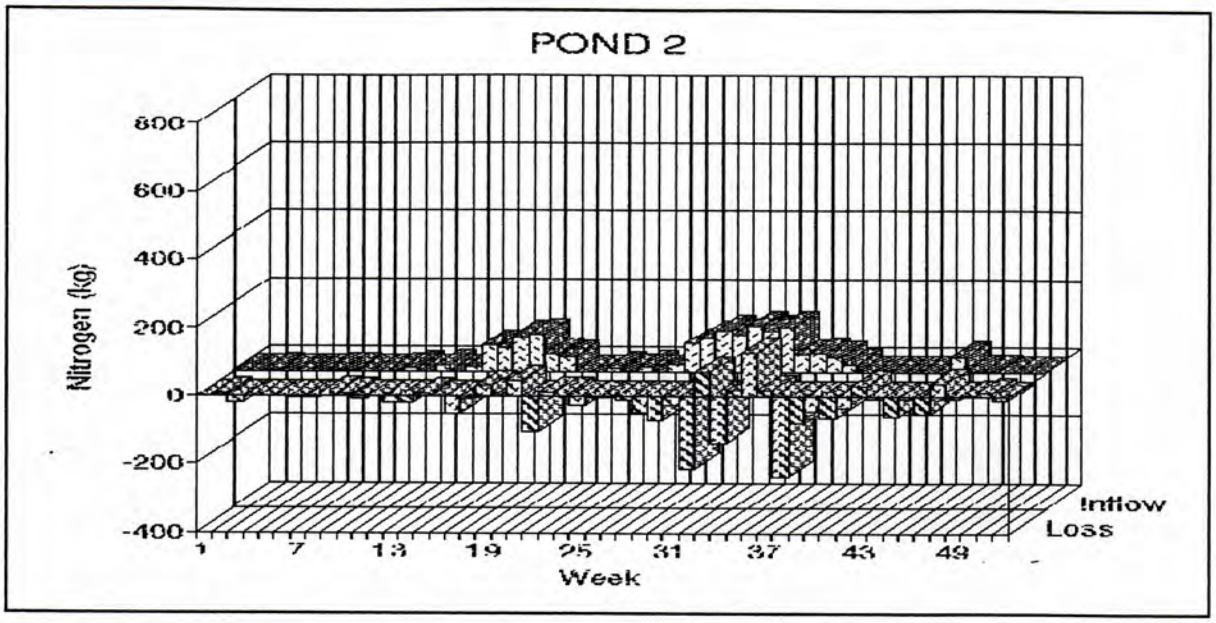

Fig. 2. Weekly nitrogen balances in pond 2 of Mas Nou golf course during 1992.

Weekly soluble orthophosphate balances indicate an equal distribution of weekly losses and gains during the year (50% each), although weekly losses were quantitatively greater than weekly gains. Weekly losses lower than 20 kg PO_4-P/week were the most frequent (69% of weekly losses), followed by weekly losses from 20 to 40 kg PO_4-P/week (19%); the maximum weekly loss (55 kg PO_4-P/week) was observed from 4 to 10 May, and from 20 to 26 July. Weekly gains of soluble orthophosphate were usually below 20 kg PO_4-P/week (96% of weekly gains). The annual soluble orthophosphate loss was estimated at 120 kg PO_4-P/year, corresponding to 7% of the total soluble orthophosphate input.

Soluble Orthophosphate Mass Balances for Pond 2

Soluble orthophosphate inputs to pond 2, similarly to nitrogen inputs, were much lower than those to pond 1. They were usually below 30 kg PO_4-P/week (51% of weekly contributions), but they showed greater values during mid-spring and summer weeks (13 %), reaching a maximum value of 37 kg PO_4-P/week from 17 to 23 August. Similarly to the nitrogen input pattern, the irrigation schedule resulted in no soluble orthophosphate input during 19 weeks (36%). The annual soluble orthophosphate input was estimated at 390 kg PO_4-P/year. Weekly soluble orthophosphate output by irrigation water reached its maximum value (22 kg PO_4-P/week) from 11 to 17 May and from 20 to 26 July, several weeks after receiving considerable weekly inputs. The annual soluble orthophosphate output by irrigation water was estimated at 260 kg PO_4-P/year. Weekly variations of soluble orthophosphate showed negative values during episodes of intense photosynthetic activity by algal populations, while positive values were observed when the algal biomass was low, accounting for a annual loss of 3 kg PO_4-P/year.

Weekly soluble orthophosphate balances indicate an almost equal distribution of weekly gains and losses during the year (48% and 52%, respectively), although total losses exceeded total gains. Weekly losses lower than 10 kg PO_4-P/week were the most frequent (60% of weekly losses), followed by weekly losses from 10 to 20 kg PO_4-P/week (20%); the maximum weekly loss (46 kg PO_4-P/week) was observed from 20 to 26 July. Weekly gains were usually below

10 kg PO_4-P/week (74% of weekly gains). The annual soluble orthophosphate loss was estimated at 130 kg PO_4-P, corresponding to 34% of the total soluble orthophosphate input.

DISCUSSION

The physical, chemical, and biological results obtained were used to interpret the nitrogen and phosphorus mass balances previously presented.

Nitrogen Losses in Pond 1

Nitrogen losses in pond 1 were observed almost all year round, due to a combination of different processes (ammonia volatilization, denitrification, and organic matter sedimentation). Summer losses were quantitatively important when algal blooms raised the pH well above 8.0, which was practically the minimum value measured in surface waters. At these pH values, specially during high summer water temperatures (up to 29°C), ammonia converts to gas and escapes to the atmosphere. This seems to be an important pathway for nitrogen losses in pond 1, due to the continuous inflow of ammonia-rich reclaimed effluent discharging in the pond's surface, where algal populations maintain a high pH value.

Remarkably high weekly losses were observed when the pH of surface water was 9.2 (340 kg N/week from 20 to 26 July), 8.7 (170 kg N/week from 16 to 22 March), 8.7 (180 kg N/week from 13 to 19 July) and 8.5 (220 kg N/week from 15 to 21 June). However, important weekly losses were also detected at pH values slightly lower, as when pH was 8.0 (130 kg N/week from 27 April to 3 May), 8.0 (210 kg N/week from 17 to 23 August) and 8.1 (150 kg N/week from 3 to 8 August). The last three weekly episodes occurred mainly when algal populations decreased to low values (less than 50 μg chlorophyll *a*/L) and ammonia concentrations increased because of the high inflow rate of reclaimed effluent to the pond; both processes must have acted together, causing a washout of algal populations and an inhibitory effect on photosynthetic activity due to the increasing ammonia concentration (Abeliovich and Azov, 1976). However, those losses were not apparently caused by volatilization, as pH was relatively low, suggesting as a plausible explanation a combined effect of an intensive denitrification process and an algae die-off and sedimentation process, as indicated by a decrease in chlorophyll *a*. According to this hypothesis, a nitrate buildup would not be detected in the pond during the summer, because of the high denitrification activity, whereas the lower denitrification activity during the autumn might have allowed a nitrate accumulation in the pond.

Partial weekly nitrogen gains must have their origin in ammonia contributions from the sediment, which is very rich in organic matter coming from algae deposition. Bacterial decomposition of this algal biomass, specially at water temperatures above 20°C, represents a significant source of nitrogen for the pond system. Avnimelech and Wodka (1988) established that ammonia accumulation in sediments is normally produced by organic matter decomposition under anaerobic conditions as those prevailing in a hypertrophic impoundment like pond 1.

From October to December, when dissolved ammonia is practically depleted and reclaimed effluent inflows are at a minimum, nitrogen losses occurred via nitrification/denitrification and organic matter sedimentation. The irrigation recess brought about by early autumn rains caused the HRT to increase, allowing important algal populations to develop which provided enough dissolved oxygen to support a fast nitrification of dissolved ammonia; relatively warm water temperature during october (from 14 to 20°C) helped to keep this processes at a high rate. Although nitrifying bacteria are considered obligate aerobes, they are apparently able to grow under anaerobic conditions (Abeliovich, 1987), which could explain the sudden nitrification episode that took place immediately after the irrigation season ended (late September). By the end of October, nitrification was almost fully completed and nitrate was the predominant nitrogen species. At that time, denitrification became obvious, but it was interrupted in mid December, when nitrate concentrations were below 6 mg NO_3-N/L, probably because the sudden drop in water temperature from 14°C in early December to 8°C in mid December. Nitrogen losses via denitrification were observed despite the aerobic conditions exhibited by the pond during this period. This observation agrees with the fact that denitrification does not need an absolute anoxia, but it can be carried out by some bacterial species in the presence of dissolved oxygen concentrations as high as 80% of air saturation (Robertson and Kuenen, 1992); denitrification is also favored by high pH values (Margalef, 1986), and it can be generally considered as the most important nitrogen removal process in lakes (Dudel and Kohl, 1992).

Nitrogen Losses in Pond 2

Nitrogen losses in pond 2 showed a pattern similar to those in pond 1. Nitrogen losses were partly caused by ammonia volatilization during summer months, when ammonia-rich water from pond 1 found active algal populations which kept water pH up to 9.7 from 3 to 8 August, bringing about an important nitrogen loss (210 kg N/week). Nitrogen losses were also caused by a variable rate nitrification/denitrification process, depending on water temperature and composition, and by organic matter sedimentation. There were some nitrogen gains in late August and early September, apparently due to ammonia release by organic matter mineralization in the sediments.

Ammonia depletion showed the significant nitrogen losses occurred via nitrification/denitrification during September. Losses up to 240 kg N/week (the highest in this pond) occurred from 14 to 20 September, and were followed until mid November by weekly losses of 80, 45, 65, 35 and 60 kg N/week. Those losses brought down the total nitrogen concentration in pond 2 from 23 mg N/L in mid September to values close to 5 mg N/L in mid November. This process occurred in pond 2 one month earlier than in pond 1, due to its higher HRT values.

Soluble Orthophosphate Losses in Pond 1

Soluble orthophosphate losses were significantly smaller than those of nitrogen, mainly due to the lack of a gaseous phase in the phosphorus cycle. In general, soluble orthophosphate losses observed can only be attributed to either chemical precipitation or conversion into organic phosphorus by biological assimilation. Decomposition of organic matter in the sediments, mainly made up of dead phyto- and zooplankton biomass developed on the nutrients of reclaimed effluent, may have caused a quick release of soluble orthophosphate, specially under low dissolved oxygen conditions such as those usually prevailing in bottom layers of pond 1 from May to October. However, the phosphorus trapped in the sediments cannot be considered a true loss from the system, as it can redissolve as soluble orthophosphate. The estimated soluble orthophosphate annual loss was only 120 kg PO_4-P (7% of total soluble orthophosphate inflow), due to the release of some of the phosphorus trapped in the sediments.

Soluble Orthophosphate Losses in Pond 2

Although the annual soluble orthophosphate loss in pond 2 was slightly greater than in pond 1 (130 kg PO_4-P), it accounted for 34% of the total soluble orthophosphate inflow. Assuming a similar phosphorus release from the sediment as in pond 1, soluble orthophosphate losses in pond 2 must have come via chemical precipitation, as suggested by the high pH values (up to 9.7, and greater than those of pond 1) recorded in its surface waters during most of the year.

Golf Course Irrigation

The physical and chemical quality of irrigation water was within the recommended safety limits for all parameters tested (Mujeriego, 1990), and both turfgrass and ornamental plants remained in healthy condition during the year. Nitrogen and phosphorus contributions to the area irrigated with pond 1 accounted for 190 kg N/ha.year and 120 kg P_2O_5/ha.year, greater than the contributions to the area irrigated with pond 2, which were 48 kg N/ha.year and 48 kg P_2O_5/ha.year. These nutrients contributions were equivalent to 31 000 kg of commercial fertilizer, with an estimated value of 26 000 US$.

CONCLUSIONS

Approximately 250,000 m^3/year of reclaimed effluent is used for irrigation of the Mas Nou golf course, which accounts for only 4% of the annual flow of activated sludge effluent from the Castell-Platja d'Aro wastewater treatment plant. To satisfy the irrigation schedule of this golf course, reclaimed effluent is stored in two landscape ponds connected in series. While most of the physico-chemical parameters of the secondary effluent are relatively stable during the year, the ponds effluents quality show significant variations, particularly concerning the total amount and the chemical speciation of nitrogen and phosphorus. The two ponds in series bring about a significant reduction of both nutrients; while the annual mean concentrations in the secondary effluent were 31.3 mg N/L and 7.2 mg P/L (irrigation season) those for pond 1 effluent were 20.4 mg N/L and 6.3 mg P/L, and those for pond 2 effluent were 8.2 mg N/L and 4.0 mg P/L.

Weekly mass balances have shown that from the 8 150 kg N and 1 930 kg PO_4^--P entering pond 1 with the reclaimed effluent, an estimated 28% nitrogen and 7% phosphorus were lost from pond 1, while the losses from pond 2 were 59% nitrogen and 34% phosphorus. The system of two ponds in series has resulted in a total loss of 72% nitrogen and 51% soluble orthophosphate. The main processes responsible for those changes are: 1) physical (ammonia volatilization and organic matter sedimentation), 2) chemical (orthophosphate precipitation), and 3) biological (nutrient assimilation and nitrification/denitrification) with indirect effects on both physical and chemical processes.

The stepwise water quality polishing process taking place in this pond system points out the considerable interest of a flexible design (piping and pumping systems): 1) to allow water extraction from either of the two ponds, depending on the water quality (nutrient contents) most adequate during each irrigation season, 2) to ensure a uniform nutrient contribution to all the golf course vegetation, and 3) to achieve an effective nutrient control strategy and bring nutrients concentrations within desired limits, by preventing pond stratification and thus partially limiting the denitrification process occurring in anoxic zones. Finally, the use of reclaimed wastewater effluent for golf course irrigation in a water-short region offers an alternative water source and provides the added benefit of recovering part of the nutrients present in the effluent, resulting in significant savings of commercial fertilizers.

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