Twenty years' monitoring of Mèze stabilisation ponds: part I – removal of organic matter and nutrients

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Abstract The Mèze stabilisation pond system has been monitored over more than 20 years. Despite the enlargement of the plant, the organic load doubled between the early 1980s and recent years, the removal of organic matter and nutrients has been maintained at the same level for COD and increased for BOD_5, N and P. Combining anaerobic, step-fed aerated and maturation ponds and multiplying the number of cells resulted in a significant improvement in the performances of the plant. Respectively 34, 24 and 23% of the applied COD was eliminated in the anaerobic, the step-fed and the first three maturation ponds, while the figures for BOD_5 were 47, 26, and 19% respectively. 38% of the applied nitrogen was eliminated in the first three maturation ponds. Nitrification and denitrification seem to be a major process of nitrogen removal in warm periods. Most of the phosphorus removal was observed to take place in the two polishing ponds.
Keywords Nitrogen; phosphorus; removal; step-fed facultative pond®; upgrading; waste stabilisation pond

Introduction

Waste stabilisation ponds (WSPs) systems have been widely developed during the last 30 years in France. They account for over 20% of the wastewater treatment plants. They are chosen both for small communities because of their low operation and maintenance costs, low risk of failure and low production of sludge and for bigger coastal towns because of their ability to treat variable loads in tourist zones and to achieve good removal of pathogens when the discharge is located in bathing waters or shellfish breeding areas.

Very few waste stabilisation ponds have been monitored for SS, organic matter, nutrients and microbiological faecal indicators over more than 20 years. The Mèze WSP system which aims to protect the Thau lagoon where more than 10% of the French production of oysters takes place, is an outstanding exception. This paper presents the performance of the plant from the beginning of the 1980s up to 2004. The impacts of pollution load, the ageing of the plant and its enlargement and retrofitting on the removal of organic matter and nutrients are discussed. The specific performance of each stage of treatment is quantified and methods of pollution removal specified.

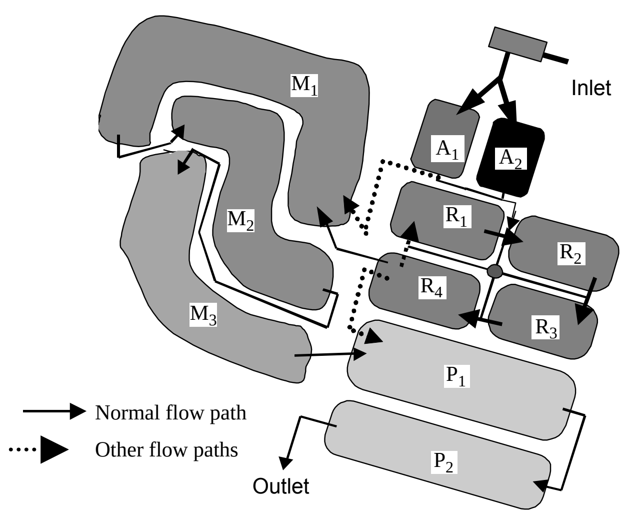
Material and methods

Site description

The Mèze WSP plant located on the Mediterranean coast (03°35′06″E, 43°25′10″N) was a typical example of the French state-of-the-art when it was constructed in 1980. Made up of three ponds with a total surface of 8 ha, the plant was designed with a treatment capacity of 8,000 p.e. and a design organic load of 50 kg BOD $ha^{-1}\,d^{-1}$. It received an initial average organic load of only 33 kg BOD $ha^{-1}\,d^{-1}$ augmented with winery wastewater, particularly in autumn. It discharged into the Thau lagoon. As the population connected to the plant increased, as sludge accumulated and the criteria applying to the treated water quality became more exacting, maintenance and enlargement works had to be undertaken. In October 1994, a 1.5 ha area of the 4 ha primary pond was dredged and 800 tonnes of dried matter were extracted. In 1996 the 3 initial ponds (M_1, M_2, M_3) were supplemented with 2 polishing cells in series (P_1 and P_2), in order to improve the microbiological quality of effluents. Two anaerobic ponds in parallel (A_1 and A_2) were added in 1998 and 4 step-fed facultative ponds (SFP) in series (R_1 to R_4) with recirculation and aeration® in 1999 (Entech patent). Each pond has a surface area of 0.65 ha, is 1.6–1.8 deep and equipped with an 11 kW stirring aerator. Step feeding distribution (50% R_1, 30% R_2, 20% R_3), and recirculation from R4 to R1 were based on a previous study (Sambuco *et al.*, 2002). The total area of the ponds nowadays is 14.4 ha; the load to be treated amounts to up to 1120 kg BOD_5 per day, being equivalent to 19,000 p.e. The present installation can be operated combining new and old ponds either in series or in parallel, the 2 polishing cells serving in both cases (Figure 1). Actually the SFP received a constant flow of about 2500 m^3d^{-1}, excess of flow at the outlet of A_{1-2} entered directly in M_1.

Sampling and analysis methods

From 1980 to 1992 the WSP was monitored at the inlet and outlet of the 3 initial facultative ponds M_1, M_2 and M_3 fortnightly at first and then every 3 months. Since 2000 the inlet and the outlet have been monitored fortnightly and the inflow and outflow recorded



Ponds	Type	Area (ha)	Depth (m)	Start up
A_1, A_2	Anaerobic ponds then surface aerated anerobic ponds	2 × 0.23	3.1	1998 2001
R_1, R_2, R_3, R_4	Step-fed facultative ponds with recirculation (SFP)®	4 × 0.67	1.8	1999
M_1, M_2, M_2	Facultative then maturation ponds	4 + 2 + 2	1.4 – 1.7	1980 1999
P_1, P_2	Polishing ponds	1.9 + 1.2	0.8 – 1.3	1996

Figure 1 Lay-out of the current Mèze waste stabilisation pond system

with an electromagnetic flow meter. During the year 2003–2004 analysing the water quality fortnightly at the inlet and outlet of: (i) the anaerobic ponds in parallel, (ii) the step-fed ponds, (iii) the 3 first maturation ponds, and (iv) the 2 last polishing ponds allowed specification of the role of each type of pond in the overall performance. Composite 24 h samples were taken and analysed daily. The following parameters were measured according to *Standard Methods*: suspended solids (SS), total chemical oxygen demand (COD), filtered COD (Whatman GF/*C* filters), Kjeldahl nitrogen (TKN), ammonia (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), total phosphorus (TP) and orthophosphate (PO_4-P). Biological oxygen demand (BOD) and filtered BOD were measured with a respirometer (Oxytop WTW). *E. coli* and faecal enterococci were analysed using microplate methods. Removal efficiency was calculated in % concentration (inlet concentration – outlet concentration reported to inlet concentration) or in % mass flow (inlet mass flow – outlet mass flow reported to inlet mass flow).

Results and discussion

Comparison of performance at the starting up and prior and after upgrading

During the first 2 years of operation the average overall organic load on the system was 33 kg BOD ha^{-1} d^{-1} and performances were high, 73% COD and 55% N-NH_4 removal, 2.9 log unit faecal coliform and 2.6 log unit enterococci reductions (Table 1).

After 9 years of operation the organic load had increased (65 kg BOD ha^{-1} d^{-1}) due to population growth. Meanwhile removal, mainly nitrogen removal, (19%), COD (60%) and faecal coliform (2.3 log unit removal efficiency) had decreased due to both increase in loading rates and accumulation of sludge in the first cell which reduced the hydraulic residence time.

After the enlargement and retrofitting at the end of the 1990s the area of the plant was 8.3 m^2/P.E. The overall improvements to effluent quality from the upgraded WSP have been substantial, particularly for faecal coliform and enterococci indicators (average removal during the last 4 years of 4.1 and 3.4log. units respectively). Brissaud *et al.*, (2005) investigated this improvement in the microbiological effluent quality. Despite the enlargement of the plant, the surface organic loading still doubled between the early 1980s and the present time but the same level of COD has been maintained and even BOD_5 and nutrient removals increased. While influent ammonia concentrations increased with time, effluent ammonia concentrations decreased. Influent phosphorus concentrations decreased with time due to less use of phosphorus in washing products, P removal was the same but effluent concentrations were lower.

It is interesting to investigate the performance of the first two stages of treatment: a surface aerated anaerobic pond (AP) and step-fed facultative pond (SFP). With an area of 1.7 m^2/p.e removal efficiencies were high for SS, COD and BOD_5 (68, 67 and 82% respectively). These first two stages (or one of them) could be used when retrofitting to increase the capacity of overloaded WSPs.

Evolution of performances of the upgraded Mèze WSP

Mean daily inflow increased between 2000 and 2003 from 1875 m^3 d^{-1} to 3127 $m^3 d^{-1}$. In summer the outflow is halved by evaporation (Figure 2). During periods of heavy rain, the plant can have an inflow greater than 10,000 $m^3 d^{-1}$ and the maturation ponds $M_{1\text{-}2\text{-}3}$ and polishing ponds $P_{1\text{-}2}$ have a reserve height of 30 cm and 60 cm respectively to cope with sudden increases in hydraulic charge.

During the same time population increased between by 14000–18800 p.e. Significant seasonal variations of organic matter and nutrients contents and removal were observed, due to tourist population, winery effluents and climate conditions.

Table 1 Comparison of Mèze WSP performance during the first 2 years of operation, after 9 years of operation and after upgrading works for overall plant. Mean, [standard deviation], % removal and log unit reduction for faecal indicators

Years	**1981–1982**			**1988–1990**			**2000–2003**		
Type	**3 cells in series**			**3 cells in series**			**4 stages-10 cells in series**		
Surface area	**8 ha**			**8 ha**			**14.4 ha**		
Population (p.e.)	**4400**			**8700**			**17300**		
Area (m^2/p.e.)	**18**			**9.3**			**8.3**		
Surface loading	**33 kg DBO/ha.d**			**65 kg DBO/ha.d**			**72 kg DBO/ha.d**		
	In	**Out**	**%**	**In**	**Out**	**%**	**In**	**Out**	**%**
TSS (mg/L)	171			251(109)	136 (69)	46	266 (133)	109(63)	59
COD(mg/L)	430	116 (27)	73	541(409)	216 (91)	60	645 (225)	179(72)	72
fCOD(mg/L)				337 (407)	76 (26)	77 (86*)	262(120)	80 (29)	69 (88*)
BOD(mg/L)	172 (13)	58 (14)	66				405 (136)	50 (23)	88
fBOD (mg/L)							163(72)	9 (6)	94 (98*)
NTK (mg/L)				42 (6)	34 (5)	19	46 (13)	15 (8)	67
NH4-N (mg/L)	24 (3)	11 (4)	55	27 (7)	21 (9)	22	36 (11)	8 (9)	77
TP (mg/L)				14.7 (3.3)	11.3 (3.2)	23	7.9 (2.8)	5.0 (1.7)	37
PO4-P (mg/L)	15 (2/4)	10 (2.7)	35	9.1 (3.2)	5.0 (3.6)	45	4.5 (1.7)	2.8 (1.8)	38
FC (log_{10}/100 ml)	6.2 (0.5)	3.4 (1.2)	2.9	7.0 (0.5)	4.7 (1.0)	2.3	6.8 (0.5)	2.7 (0.7)	4.1
Entero. (log_{10}/100 ml)	5.2 (0.6)	2.6 (0.7)	2.6	6.0 (0.3)	3.6 (0.3)	2.4	6.0 (0.5)	2.6 (0.7)	3.4

% removal was calculated with concentration (in-out/in); fCOD* removal was calculated COD_{in}-f COD_{out}/ COD_{in}; FC and enterococci removals were expressed in mean(log. unit) reduction

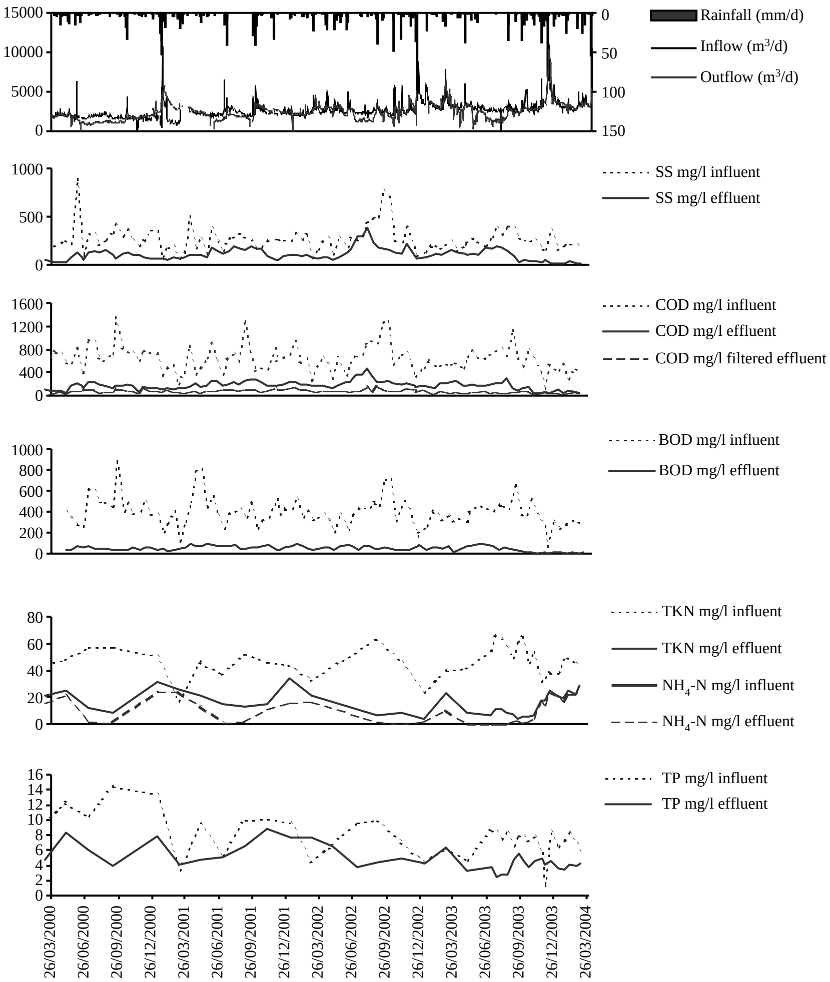


Figure 2 Times series (2000–2004) of influent wastewater and effluent from Mèze WSP for flow, SS, COD, BOD, Kjeldahl nitrogen (TKN), ammonia (NH_4-N) and total-P

Table 2 Annual mean concentrations (standard deviation $n = 23$) and % removal calculated with concentrations or with mass flow in each stage of Mèze WSP from July 2003 until June 2004

	Influent	Anaerobic ponds	SFP	Maturation ponds	Effluent	Overall removal	
						% concentration	% mass flow
SS (mg/L)	256 (85)	158 (99)	81 (47)	54 (39)	70 (62)	73	79
COD (mg/L)	557 (208)	369 (169)	183 (72)	107 (46)	117 (66)	79	81
fCOD (mg/L)	237 (94)	161 (70)	86 (35)	51 (17)	55 (20)	77	77
BOD (mg/L)	347 (133)	187 (82)	63 (22)	32 (26)	26 (24)	92	94
TKN (mg/L)	51 (16)	43 (10)	39 (7)	20 (10)	16 (9)	69	68
NH_4-N (mg/L)	36 (9)	37 (7)	31 (5)	15 (13)	13 (11)	68	73
TP (mg/L)	7.1 (1.7)	6.2 (1.5)	5.6 (1.2)	5.3 (0.7)	4.3 (1.2)	40	45
PO4-P (mg/L)	4.3 (1.4)	3.5 (1.0)	3.0 (1.8)	4.0 (1.5)	3.0 (1.5	33	36

Peaks in COD and BOD_5 influent in autumn were due to the input of winery wastewaters loaded with high soluble COD. The overall hydraulic residence time (HRT) of effluent was long enough, about 95 days, and filtered COD and BOD_5 effluent were not season dependent. In summer SS, particulate BOD and COD concentrations increased due to algae growth while ammonia and phosphate decreased. Figure 2 illustrates the cyclic tendency of TKN and NH_4-N seasonal removal.

Role and performances of each treatment stage

Annual mean concentrations in the influent and effluent of each stage of treatment and overall removal from July 2003 until June 2004 are shown in Table 2.

The annual mean temperature in the last pond was 17 °C (minimum 5 °C, maximum 28 °C). Figure 3 shows the role of each stage in the overall removal and the part staying in the effluent. The first two stages of the plant were efficient in removal of SS, COD and BOD_5, the maturation and polishing ponds were efficient for nutrients. Step-fed facultative and maturation ponds were efficient for faecal coliforms and enterococci.

First stage: anaerobic ponds later transformed into surface aerated anaerobic ponds

The first stage of treatment is two deep cells (3.1 m) in parallel. From 1998 to 2000 these ponds were anaerobic with a mean volumetric loading of 86 g BOD_5/m^3d and a mean HRT of 4.6 days. SS removal was 55% and BOD_5 removal only 30% (Picot *et al.*, 2003). However odour nuisance due to the emission of hydrogen sulphide (H_2S) led to the addition of an aeration power of 4.4 W/m^3 to each cell (Paing *et al.*, 2003). These aerators have been in operation since 2001 and have resolved odour nuisances. Volumetric loading is now 105 g BOD_5/m^3 d and mean residence time is 3.5 days. Aeration decreases SS performance particularly in summer (39% average removal, 17% in summer) but increases BOD removal (47%) with a power consumption of less than 0.5 kWhr per kg of BOD_5 eliminated. This primary step of treatment has low efficiencies for removal of nutrients (16% N and 12% P) and faecal indicators (E. *coli*: 0.42 log unit, Enterococci: 0.45 log unit). It is possible to use surface aerated anaerobic ponds successfully at the beginning of the plant to upgrade an overloaded WSP plant with a low energetic cost. (Copin *et al.*, 2004).

Second stage: step-fed facultative ponds with recirculation and aeration® (SFP)

The mean residence time in the 4 step-fed facultative ponds with recirculation and aeration (SFP) is about 25 days. The organic loading applied to the 4 ponds is around

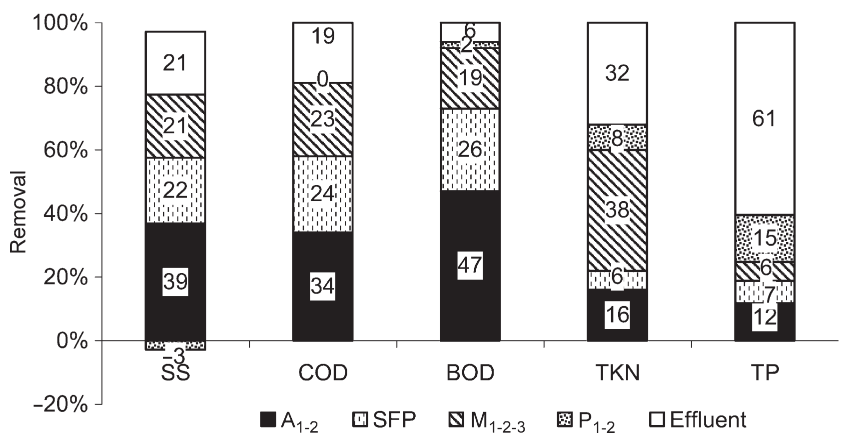


Figure 3 Contribution of each stage of treatment in the overall removal

166 kg BOD $ha^{-1}\,d^{-1}$ overall. A recirculation of once the inflow was applied after doing tests with ratios of 0.5, 1 and 2 (Sambuco *et al.*, 2002). Four aerators can work if necessary, preferably by night (0.5 kWhr/kgBOD eliminated). This step had very high removal performance SS (50%), COD (50%), dissolved (77%) and total (66%) BOD. It was also efficient to remove microbiological indicators (*E. coli*: 1.62 log unit in summer, 1.19 log unit in winter). This stage had a minimal contribution to the elimination of N (6%) and P (7%). The SFP effluent after these two stages of treatment is below the limit set by the EU Directive 1991 for COD and BOD. Recirculation of effluent from the 4 ponds also has the primary advantage of seeding active algal biomass into the first pond and maintaining aerobic conditions thus increasing pond efficiency. It is therefore possible to more than double the organic load on the first pond in comparison to the usual configuration of stabilisation ponds in series (Shelef and Kanarek, 1995).

During one year (2001) the first stage of treatment was stopped but the SFP still showed good efficiency even though the influent was not pre-treated in the anaerobic pond. However in this case sludge increased in the pond R_1. After 4 years of operation (including one of raw wastewater), sludge heights were still low, 0.30, 0.21, 0.18 and 0.14 m in R1, R_2, R_3 and R_4 respectively, leading to a reduction of volume of 16% R_1, 11% R_2, 10% R_3 and 7% R_4. The SFP is a stage which can replace the facultative pond in the waste stabilisation pond process and produces high effluent quality with decreased land requirements and low operating costs (Copin *et al.*, 2004).

Third stage: maturation ponds

The actual average organic load on the 3 maturation ponds M_{123} is 38 kg BOD $ha^{-1}\,d^{-1}$ and the hydraulic residence time is about 47 days. This stage of treatment removes the majority of total N (38%) and contributes to faecal indicators removal. The water level is kept low in the 3 ponds during summer to allow them to stock heavy autumn rain and limit its impact on the Thau lagoon.

Fourth stage: polishing ponds

The two last cells P_1 and P_2 are polishing ponds. They were commissioned to stock heavy autumn rain and limit its impact on the Thau lagoon. Loading rate was 26 kg BOD $ha^{-1}\,d^{-1}$ and the hydraulic residence time was 20 days. Removal was very low in these ponds for all parameters except phosphorus (15%). Increases in SS and particulate COD concentration were even observed due to algae in summer.

Decrease of organic pollution

Respectively 34, 24 and 23% of the applied COD was eliminated in the anaerobic, the step fed and the first 3 maturation ponds, while the figures for BOD_5 were 47, 26, and 19% respectively. The K coefficients for degradation, calculated according to the first-order kinetic equation of Marais (complete mixing) were high for the first 2 stages: $K_{COD(AP)} = 0.1\,d^{-1}$ in summer, $0.16\,d^{-1}$ in winter and $K_{BOD(AP)}$ $0.20\,d^{-1}$ in summer, $0.28\,d^{-1}$ in winter for deep aerated pond and $K_{COD(SFP)} = 0.04$ the same in summer and winter and $K_{BOD(SFP)} = 0.08$ in summer, 0.06 in winter for STPs.

Behaviour of nitrogen and phosphorus

After enlargement and retrofitting, the Mèze WSP system provided high nitrogen removal. Mean influent nitrogen concentration was 51 mg/L, 71% as ammonia. The overall mean removal of total nitrogen was 65% (removal was higher in summer (89%) than in winter (38%). Twenty six percent of influent total nitrogen was discharged into the Thau lagoon in the form of ammonia, 6% as organic-N and 3% as nitrite or nitrate.

The proportion of organic-N in the effluent was higher in summer and the beginning of autumn, than in winter or spring when N-NH_4 effluent concentrations were less than 1 mg/L. The first 2 stages of treatment (AP and SFP) removed very little nitrogen. Maturation ponds provided the bulk of the total nitrogen removal.

Mechanisms involved in N removal are: stripping of NH_3, nitrification/denitrification and sedimentation (of bacteria, algae and zooplankton) after biological nitrogen uptake. However scientists disagreed over predominant mechanisms. Pano and Middlebrooks (1982) argued that ammonia volatilisation largely explains total nitrogen removal from ponds. On the other hand Zimmo *et al.*, (2003) found that ammonia volatilisation in waste stabilisation ponds accounts for only a small fraction (1.5%) of total N-removal from domestic sewage and suggested that other nitrogen removal mechanisms such as nitrification/denitrification or sedimentation may be more important in overall nitrogen removal. On the basis of the low prevailing nitrate concentrations in pond systems, several studies concluded that nitrification does not take place and consequently denitrification does not play a major role in nitrogen removal (Reed, 1985).

In the Mèze WSP, although average concentrations of the oxidised forms of nitrogen in the effluent were low (annual mean 1.6 mgL^{-1}), nitrate concentration reached 5 mgN L^{-1} in the M_3 effluent for more than 15 days in October 2003 and 8 mgL^{-1} in June 2004 even though it was not present in the SFP effluent. Nitrification followed by denitrification could explain the low N-NH_4 concentration observed in summer in pond M_3 effluent. In October, when temperature was decreasing, denitrification was limited and N-NO_3 concentration increased; in November, the water temperature was less than 13 °C and nitrate decreased and ammonia increased. Nitrate was <0.5 mgL^{-1} in winter and spring and increased again in June when temperatures reached 24 °C. For the same pond M_3 prior to upgrading, Gomez *et al.*, (1995) demonstrated correlations that were negative between temperature and ammonium and positive between loss of ammonia and the oxidised forms of nitrogen and suggested the existence of a nitrification/denitrification processes.

The annual total phosphorus removal was 39%, higher in summer (63%) when phosphate concentration in effluent was <1 mgL^{-1} and lower in spring (12%). Most of the phosphorus removal was observed to take place in the two polishing ponds, except in summer where it also took place in maturation ponds

Conclusions

The Mèze facility is a successful example of enlargement and retrofitting of an overloaded WSP; though more sophisticated than the initial system and requiring more energy consumption, it remains reliable, easy to operate and maintain, with only a moderate increase in operation costs and improved performances.

The surface aerated anaerobic pond was very efficient in removing SS and organic matter so it could be used to upgrade an overloaded WSP plant with low land requirement and energetic cost. The step-fed facultative pond with recirculation and aeration is an innovative design pond efficient in removing BOD and faecal indicators; its surface organic loading is twice higher than what is usually applied in primary facultative ponds. Maturation and polishing ponds efficiently removed nutrients. They may have a significant part to play in the mitigation of storm events.

The quality of effluent discharged is in accordance with European Directives and could be improved in warmest periods when replacing polishing ponds with rock filters or constructed wetlands that would be more effective for removing SS and particulate pollution.

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