HYDROBIOLOGICAL, PHYSICAL AND CHEMICAL CHARACTERISTICS AND SPATIO-TEMPORAL DYNAMICS OF AN OLIGOTROPHIC MEDITERRANEAN LAGOON: THE ETANG DE LA PALME (FRANCE)

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MEDITERRANEAN LAGOON
OLIGOTROPHY
EUTROPHICATION
SALINITY
OXYGEN
REDOX POTENTIAL
PH
SPATIO-TEMPORAL DYNAMICS
SEASONALITY

ABSTRACT. – The Mediterranean lagoon of La Palme was studied from October 1994 to December 1998. Approximately 230 surveys were made with over 15,000 measurements of physico-chemical parameters (temperature, pH, dissolved oxygen, oxygen saturation, salinity, conductivity, redox potential and tributaries water flow). Approximately 400 chemical analyses of the main nutrients as well as more than 1,000 observations on flora, fauna and sediment were made. The La Palme lagoon was found to be one of the rare oligotrophic Mediterranean lagoons with very good water quality. The measured parameters were found to follow a well-defined seasonal rhythm in spite of large absolute variations and inter-annual differences. In spite of heavy transformations in the last century, the catchment area as well as the entrance channel to the open sea remain relatively natural. Special observations on the karstic springs show that they have great influence on the water balance. Via the catchment area meteorological conditions directly and indirectly influence strongly the conditions inside the lagoon. The exchange with the open sea buffers the extreme amplitude of abiotic parameters inside the lagoon but the lagoon "character" seems to be determined by sediment and nutrient input from the catchment area. The Etang de La Palme could serve as an excellent example of spatio-temporal dynamics inside undisturbed oligotrophic coastal lagoons.

LAGUNE MÉDITERRANÉENNE
OLIGOTROPHIE, EUTROPHISATION
SALINITÉ
OXYGÈNE
POTENTIEL REDOX
PH
DYNAMIQUE SPATIO-TEMPORELLE
RYTHMES SAISONNIERS

RÉSUMÉ. – La lagune méditerranéenne de La Palme a été étudiée entre octobre 1994 et décembre 1998. Pendant ce laps de temps, environ 230 sorties ont permis de réaliser plus de 15.000 mesures physico-chimiques (température, pH, oxygène dissout, taux de saturation en oxygène, conductivité, salinité, potentiel redox, débit des arrivées d'eau douce). Environ 400 dosages des principaux nutrients et plus de 1.000 observations des sédiments, de la flore et de la faune ont été exécutés. Ces mesures et ces observations montrent que l'étang de La Palme est l'une des rares lagunes oligotrophes méditerranéennes dont l'eau soit de bonne qualité. Les variables mesurées ont révélé l'existence d'un rythme saisonnier bien établi, en dépit des grandes variations de ces facteurs, tant en valeurs absolues qu'en fluctuations interannuelles. Malgré d'importants changements depuis le 19e siècle, le bassin versant et le chenal de communication avec la mer sont demeurés relativement naturels. Un suivi précis des sources karstiques a montré l'importance de leurs apports dans le bilan hydrique de l'étang. Par le bassin versant, les phénomènes météorologiques influencent fortement, directement et indirectement, les conditions de milieu à l'intérieur de la lagune. Les échanges avec la mer amortissent l'amplitude des variations des paramètres abiotiques internes à la lagune, cependant les caractéristiques du milieu semblent être déterminées principalement par les apports sédimentaires et en nutriments qui proviennent du bassin versant. L'étang de La Palme constitue un excellent exemple de dynamique spatio-temporelle d'un milieu lagunaire oligotrophe méditerranéen peu perturbé.

INTRODUCTION

The French Mediterranean coastal zone is covered by a great number of lagoons with a total surface of about 40,000 ha. These water bodies are separated from the sea by a sandy barrier, interrupted by one or more channels remaining open at least intermittently. The channels enable the exchange of water, sediment, flora and fauna with the sea. Because of the general shallowness of the water bodies, the extreme weather conditions in the Mediterranean and the seasonal pattern of human activities like tourism, the physical, chemical and hydrobiological characteristics of the lagoons vary greatly. Under these conditions, euryhaline and eurythermal flora and fauna were found with a large number of species needing migration to the open sea for reproduction.

Considered during centuries as insanitary, source of malaria, cholera and other water borne diseases as well as places of high risks of severe floodings, Mediterranean lagoons were dried out and surrounding wetlands were drained and diked. During the last 30 years, this massive loss and degradation have been accelerated by urbanisation, particularly for the development of tourism and the construction of necessary infrastructure. Natural processes in the wetlands have been greatly modified. Together with increasing environmental stress and nutrient load, these modifications frequently cause critical situations with eutrophication crises, excessive phytoplankton blooms and anoxic conditions. Today every Mediterranean lagoon has been modified by humans and most of them have become typical eutrophic ecosystems with unstable conditions for aquatic life.

The history of research on Mediterranean lagoons began in 1897 with the important study undertaken by Gourret on lagoon fisheries. During the first half of the 20th century, researchers visited these ecosystems especially to find new species of invertebrates. Only in the 1950s the ecology of Mediterranean lagoons was studied for the first time (Petit & Schachter 1951, Petit 1953, 1962, etc.). In the 1960s and 70s research turned to migration and reproduction of fauna in particular of fish (Cambrony 1977, Hervé 1978, etc.). Today, questions concerning public health, contamination of shellfish by faecal bacteria and toxic algae as well as the quality of bathing waters are in the centre of interest (Anonyme 1995, Le Bec *et al.* 1997).

However, the spatio-temporal dynamics, the water, salt and heat balance as well as the exchange processes between lagoons and open sea are still poorly understood. A research program of the Centre of Hydrobiological Studies (Perpignan, France) started in 1994 on several French Mediterranean lagoons. It was soon apparent that the lagoon of La Palme had not been well studied in the past (Wilke & Boutière 1998) in spite of the existence of several interesting particularities: the water quality is excellent, eutrophication crises are nearly totally absent, the catchment area is only slightly disturbed by humans and, most importantly, the lagoon possesses an unmodified connection with the open sea, evolving freely on the sandy beach, opening, deplacing and closing as a function of the meteorological conditions.

The present study is the third part of a research program aiming to contribute to an increased knowledge of the spatio-temporal dynamics inside Mediterranean lagoon ecosystems. In particular three lagoons have been studied: the Etang de Canet, artificially closed (Wilke 1998), the Etang de Salses-Leucate, artificially opened (Wilke 1999) and the Etang de La Palme with an unmodified opening to the sea. The spatio-temporal variations of the hydrobiological, physical and chemical parameters of the lagoon waters and the influence of fresh water and karstic springs on the water body in consideration of the oligotrophic character of the La Palme lagoon will be described. The main objective is to find out whether the measured parameters follow well-defined cycles in spite of their extreme variability and how these cycles are eventually influenced by meteorological conditions.

MATERIAL AND METHODS

1. *The La Palme lagoon*: The La Palme lagoon is situated approximately 60 km north of the French Spanish Mediterranean border. As this lagoon has never been fully studied in the past, even topographical characteristics like water depth, water volume, surface, etc. had not been established before the present study. The maximum length of the principal part of the lagoon is 4.5 km and its maximum width 2 km. The water depth has been estimated between 0.3 and 1.5 m, the surface with about 600 ha and the volume between 1.5 and 6 Million m^3. The lagoon is separated from the sea by a sandy barrier up to 1.5 km in width.

Several aspects of benthic fauna (Ax 1956, Mars 1966, Cantrelle, 1979, Lecomte-Finiger 1983) and fish feeding and migration (Gourret 1897, Cantrelle 1979, Quignard & Zaouali 1980, Lecomte-Finiger 1983, Cambrony 1983, 1984, Bourquard 1985) have been studied in the past. However before 1994, no general study has been undertaken focussing on the lagoon of La Palme and its ecology. The interactions between the biotic and abiotic environment remained unknown.

The construction of a railway track in 1870 with a three meter high dam closed three of the four entrance channels between the lagoon and the open sea. The installation of a salt evaporation facility in the 1920s separated a surface of about 430 ha from the lagoon. The construction of several dams and roads in the last century considerably changed the landscape. Humans significantly changed the topography and dynamics of the lagoon, but the catchment area was little changed. For example, the lagoon receives still a relatively small quantity of waste water. In contrast to most other French Mediterranean lagoons, the La Palme lagoon has no seaside resorts or industries nearby.

Several authors analysed abiotic parameters of the lagoon in the past (Gourret 1897, Petit & Schachter 1951, Ax 1956, CERIC 1975, Cantrelle 1979, Bourquard 1985), but no regular physico-chemical or chemical analyses of water were made and the abiotic conditions and cycles inside the lagoon have not been described. Our bibliographic study on the lagoon of La Palme has shown that during about 100 years (1896-1994) less than 30 analyses of salinity and only 2 measurements of pH, dissolved oxygen and water temperature have been made (Wilke & Boutière 1998).

2. The catchment area: The lagoon receives fresh water from a relatively small catchment area (about 65 km^2). Several small streams, all flowing intermittently, are situated on the north-western side of the lagoon. Several karstic springs, situated on the western shore of the lagoon flow during the whole year. The geological, biological and hydrological features of the largest were studied by Kiener & Petit (1968) and Erre (1977). The outflow of these springs is weakly brackish (about 5 g/l) because of subterranean contact with salt water that mixes with the fresh karstic water. Two small channels border the salt fields to prevent fresh water intrusion and to empty the salt basins. Their flow is intermittent. No study has been undertaken in the past on water flow and physico-chemical characteristics of the fresh water input.

3. The climatic conditions: The lagoon of La Palme is situated in the north Mediterranean climatic zone with mild winters, hot summers with intense dryness and relatively little annual rainfall. A great irregularity of climatic conditions between different years can be observed. The mean temperature of the last ten years is 15.4 °C with an absolute minimum of –4.5 °C and an absolute maximum of 41.0 °C. There are approximately 2,600 h of sunshine per year with a maximum of 10.2 h per day in July and a minimum of 4.5 h in December. Rainfall is approximately 600 mm per year with October being generally the wettest month and July the driest. The maximum daily rainfall can reach about 200 mm causing significant floods. The north-westerly wind, often very dry and reaching up to 60 m/s, and the south-easterly sea wind, normally wet and accompanied by heavy rainfall dominate. Between 1950 and 1980 131 stormy days (wind speeds of more than 16 m/s) occurred per year. The years 1996 and 1997 were particularly stormy with 232 days of wind velocity exceeding 16 m/s and 43 days with more than 28 m/s (Ascensio 1984, Anon 1998).

4. Sampling: Water samples were taken on foot approximately 10 m from the shore and at least 30 cm water depth, using an adjustable-length hand sampler including a 1-L HDPE beaker. The sites of the sampling stations are indicated on figure 1a. A total of 4 stations were sampled in the lagoon (L1 to L4), 1 station in the entrance channel (EC), 4 stations in fresh water streams (F1 to F4), 2 stations in the salt fields bordering channels (S1, S2) and 4 stations at the most important karstic springs (K1 to K4). Weekly sampling was carried out at the same time each day (10 a.m. to 1 p.m.) to avoid variation in the physico-chemical measurements caused by diurnal variations (temperature changes, insolation, photosynthesis, etc.). About 100 physico-chemical data series were taken by boat over the whole lagoon during two days (04/06/98 and 05/06/98) to determine the spatial variation as well as the short time changes of water parameters between morning (9 a.m. to 11.30 a.m.) and afternoon (2 p.m. to 4.30 p.m.). Vegetal biomass samples have been taken by placing a metallic frame of 0,25 m^2 on the ground and extracting all plants. Samples of sediment were collected with the help of a simple PVC-Corer (diameter 6 cm, area 28 cm^2, length 50 cm).

5. Analyses

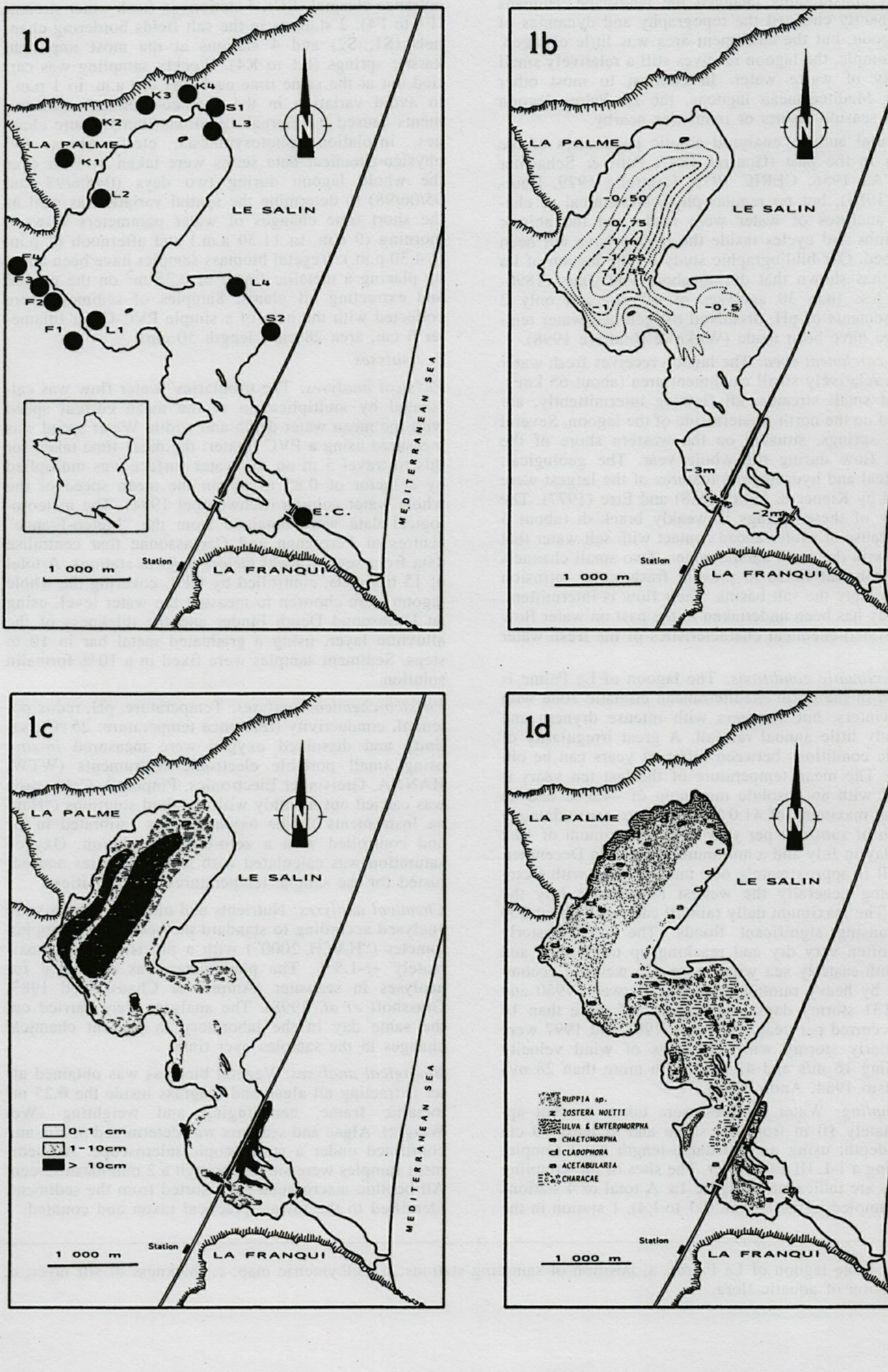
Physical analyses: The tributaries' water flow was calculated by multiplication of the mean current speed with the mean water depth and width. Water speed was measured using a PVC floater: the mean time taken for this to travel 5 m on the water surface was multiplied by a factor of 0.85 to obtain the mean speed of the whole water column (Schwoerbel 1994). The meteorological data were obtained from the "Meteo-France" centres at Perpignan and Carcassonne that centralise data from several local meteorological stations. A total of 15 transects, controlled by GPS, covering the whole lagoon were choosen to measure the water level, using an Ultrasound Depth Finder and the thickness of the alluvium layer, using a graduated metal bar in 10 m steps. Sediment samples were fixed in a 10 % formalin solution.

Physico-chemical analyses: Temperature, pH, redox potential, conductivity (reference temperature: 25 °C), salinity and dissolved oxygen were measured *in-situ*, using small portable electronic instruments (WTW, HANNA, Greisinger Electronics, Pinpoint). Calibration was carried out monthly with standard solutions ("Hanna Instruments"). The oxymeter was calibrated in air and controlled with a zero-oxygen solution. Oxygen saturation was calculated with standard tables and adjusted for the sample temperatures and salinities.

Chemical analyses: Nutrients and other chemicals were analysed according to standard methods by spectrophotometer ("HACH 2000") with a precision of approximately +/-1.5 %. The photometer was calibrated for analyses in seawater (Aminot & Chaussepied 1983, Grasshoff *et al.* 1998). The analyses were carried out the same day in the laboratory to prevent chemical changes in the samples over time.

Biological analyses: Vegetal biomass was obtained after extracting all algae and seagrass inside the 0,25 m^2 metallic frame, centrifuging and weighting (Wet Weight). Algae and seagrass was determined *in situ* and confirmed under a stereoscopic microscope. All sediment samples were sieved through a 2 mm mesh screen. All benthic macrofauna were sorted from the sediment, identified to the lowest practical taxon and counted.

Fig. 1. – The lagoon of La Palme. a, position of sampling stations; b, bathymetric map; c, thickness of silt layer; d, distribution of aquatic flora.


1a
K3
K4
S1
K2
L3
LA PALME
K1
L2
LE SALIN
F4
F3
F2
L4
F1
L1
S2
E.C.
MEDITERRANEAN SEA
1 000 m
Station
LA FRANQUI
1b
LA PALME
-0,50
LE SALIN
-0,75
-1,25
-1
-0,5
-3m
-2m
MEDITERRANEAN SEA
1 000 m
Station
LA FRANQUI
1c
LA PALME
LE SALIN
0-1 cm
1-10cm
> 10cm
MEDITERRANEAN SEA
1 000 m
Station
LA FRANQUI
1d
LA PALME
LE SALIN
RUPPIA sp.
ZOSTERA NOLTII
ULVA & ENTEROMORPHA
CHAETOMORPHA
CLADOPHORA
ACETABULARIA
CHARACAE
MEDITERRANEAN SEA
1 000 m
Station
LA FRANQUI

RESULTS

1. General characteristics

The field study determined the surface of the lagoon to be a total of 500 ha, with half taken by the north-western basin (265 ha) and about 170 ha by the central basin. The two basins south of the railway track are about 60 ha.

Bathymetry: The north-western basin is the deepest with a mean depth of 0.70 m under sea level and a maximum depth of 1.70 m. The central basin is less deep with a mean value of about 0.30 m and a maximum rarely deeper than 1 m. The sector south of the railway track has a mean depth of only 15 centimetres (Fig 1b).

The water level of the lagoon can vary between –0.30 m and +0.85 m during the year with minimum values in summer (absolute minimum generally in August) and maximum values in winter (absolute maximum generally in December). During one week, the water level could change 30 cm. During periods of maximum water level, the depth of the water column can reach about 2.50 m.

The lagoons' water volume can change considerably as a function of its water level. For a water level of 0.00 m (lagoon level = sea level) the lagoon's water volume is about 3.3 Million m^3 with about 70 % for the north-western basin and 25 % for the central basin.

Figure 1c shows the ground structure and the thickness of the silt layer. The ground of the lagoon is mostly sandy, only the region close to the small rivers in the western part of the north-western basin is mostly silty. The silty part of the sediment decreases and the sandy part increases when approaching the entrance channel to the Mediterranean. Parts of the lagoon are covered by marine mussel shells.

2. Hydrobiology of the lagoon

Aquatic flora

Figure 1d shows the distribution of seagrass and algae in the lagoon. The lagoon is mainly covered by the seagrass species *Ruppia* and *Zostera noltii*. Two species of *Ruppia* were found: *R. maritima* covering mainly the north-western basin and *R. rostellata* covering the less deep regions of the southerly basins. In the zones close to the mouths of the karstic springs *Potamogeton pectinatus, Myriphyllum, Ceratophyllum* and *Zanichellia* have been found. About 36 % of the north-western basin is covered by seegrass nearly exclusively *Ruppia*. Vegetal biomass analyses show an increasing gradient from 224 g wet weight per m^2 in the North of the basin up to 2,932 g wet weight per m^2 in the South of the zone covered. The mean value is approximately 1,660 g/m^2 which corresponds to about 1,200 tonnes of wet seagrass weight for the whole lagoon.

No phytoplankton bloom was observed between October 1994 and December 1998. Several species of macrophytic algae were found in the lagoon of La Palme but never causing blooms. *Ulva lactuca* and *Enteromorpha intestinalis* have been found mainly nearby the mouths of the karstic springs in the western part of the north-western basin. *Chaetomorpha*, covering the border of the *Ulva* and *Enteromorpha* area, produced high biomasses with mean values of about 2,300 g wet weight per m^2. *Acetabularia mediterranea* was found in abundance in the central basin on sandy grounds with a low water depth. Large areas of the central basin are covered by Characeae (*Lamprothamnium papulosum, Chara canescens, C. gallioides*) with wet weights of 552 g/m^2 reached by the dominant species *L. papulosum*. Several species of *Cladophora* were found in the lagoon as well as red algae *Gracilaria* sp. but no brown algae and no xenobiotic algae such as *Sargassum* or *Undaria* were present.

Aquatic fauna

Several species of mollusca were collected in the lagoon of La Palme, the most common being *Abra alba, Loripe lacteus, Ceratodesmus glaucum* and *Mytilus galloprovincialis*. Densities of *Abra* and *Loripe* are comparable with no predominance (700 *Abra*/m^2, 670 *Loripe*/m^2) but high variations between basins.

Ceratodesmus has been determined with about 20 individuals per m^2 in the central basin. A mean weight of 1 g flesh and 2.2 g shell per mussel gives a total biomass of about 100 tonnes chair and 220 tonnes calcareous shell material for the whole lagoon. *Mytilus* densities are very variable with a mean density of about 0.85 mussels per m^2. The maximum density has been found with 7 ind./m^2 for an average length of 6.4 cm.

For the other species of mollusca determined (*Donax* sp., *Tapes decussatus*, *Hydrobia* sp., *Neritula neritea, Retusa truncata, Pirenella conica, Potamopyrgus jenkinsis* and *Turitella* sp.) no biomass and density measurements were made because of their low densities.

Three species of decapodes were identified: *Carcinus mediterraneus, Crangon crangon,* and *Leander serratus*.

Quantification of isopods gave mean values for *Idothea baltica* of 1,044 ind./m^2 and 248 ind./m^2 for *Idothea granulosa* and for amphipodes *Gam-*

marus griseus 856 ind./m² and *Gammarus pinksii* 148 ind./m².

The following fish species were found frequently: *Anguilla anguilla, Atherina boyeri, Belone belone, Blennius pavo, Gobius niger, Liza aurata, Mugil cephalus, Potamoschistus microps, Potamoschistus minutus, Sparus aurata* and *Syngnathus* sp.

3. Physical and chemical dynamics

Absolute variations

The mean values and the absolute minima and maxima of all parameters measured inside the lagoon waters during the whole study period are given in table I. The total amplitude between absolute minimum and absolute maximum is for salinity 71.6 ‰, for conductivity 91.0 mS/cm, for water temperature 32.3 °C, for pH 1.7 units, for redox potential 360 mV, for dissolved oxygen 14.1 mg/l and for oxygen saturation 247 %.

Variations between morning and afternoon

The measurement of 100 data series in the morning and the afternoon during two days show for those sampling points situated between 40 and 160 cm water depth (no difference of mean depths between morning and afternoon) the following results: no difference between morning and afternoon values was found for salinity and conductivity. The water temperature rose the first day 0.9 °C (3.6 %) and the second day 2.2 °C (9.1 %) between morning and afternoon. pH values were unchanged the first day and raised 2.4 % the second day, redox potential changings were variable with raising values (+19.6 %) the first day and falling values (-17.8 %) the second day. The concentrations of dissolved oxygen and the oxygen saturation were the most influenced by sampling time: The first day the oxygen values rose 21.6 % and the second day 20.0 % the afternoon, the oxygen saturation rose 21.3 % the first day and 23.4 % the second day.

Weekly variations

The weekly variations in rainfall are shown for the whole period in figure 2a. Generally the greatest weekly rainfall was observed between October and March, exceeding 80 mm several times. In summer, weekly rainfall remained generally below 40 mm. Air temperature is shown in Figure 2b. Maximum temperatures were generally observed in July (approximately 30 °C) and minimum temperatures in January (0 to 5 °C). Difference between average weekly minimum and maximum was about 5°C.

Table I. – Variations of all studied parameters in the lagoon (values during the whole studied period, in winter and in summer).

Table II. – Spatial variations of physico-chemical parameters inside the lagoon (L1 to L4) and between lagoon and entrance channel (EC) the same sampling day.

I.

Measured parameter	Winter values			Whole study period values			Summer values		
	min	medium	max	min	medium	max	min	medium	Max
Salinity, ‰	3.6	27.1	59.9	3.6	29.8	75.5	7.9	32.6	75.5
Conductivity, mS/cm	6.1	39.7	77.3	6.1	43.5	97.1	11.5	47.3	97.1
Water temperature, °C	2.0	11.9	22.0	2.0	16.4	34.3	8.6	21.1	34.3
pH	7.5	8.2	9.1	7.5	8.3	9.2	7.6	8.4	9.2
Redox potential, mV	-65	110	200	-160	100	200	-160	90	195
Dissolved oxygen, mg/l	3.9	10.0	16.0	2.1	9.5	16.2	2.1	9.0	16.2
Oxygen saturation, %	51	109	198	28	115	275	28	122	275
Nitrates, mg N-NO_3/l	< d.l.	0.02	0.04	< d.l.	0.05	0.45	< d.l.	0.08	0.45
Nitrites, mg N-NO_2/l	< d.l.	0.001	0.002	< d.l.	0.001	0.002	< d.l.	0.001	0.002
Ammonium, mg N-NH_4/l	< d.l.	0.06	0.12	< d.l.	0.08	0.60	< d.l.	0.09	0.60
Inorganic nitrogen, mg N/l	0.02	0.03	0.12	0.01	0.06	0.21	0.02	0.08	0.21
Phosphates, mg PO_4/l	0.02	0.17	0.80	0.02	0.11	0.80	0.02	0.06	0.16
Silicates, mg SiO_2/l	0.04	0.18	0.43	0.04	0.41	2.20	0.13	0.64	2.20

II.

Measured parameter	Absolute variations				Spatial variations			
	Lagoon		Entrance channel		4 lagoon stations		Mean lagoon values Entrance channel	
	Medium	(min - max)	Medium	(min - max)	Medium	(max)	Medium	(max)
Salinity, ‰	28.4	(9.6 – 47.6)	37.9	(18.2 – 53.3)	4.5	(17.2)	12.0	(28.9)
Conductivity, mS/cm	43.7	(15.8 – 69.8)	56.9	(27.5 – 77.1)	6.5	(22.6)	16.1	(41.8)
Water temperature, °C	15.3	(2.3 – 28.6)	15.3	(4.1 – 27.5)	1.3	(3.2)	0.7	(2.3)
pH	8.2	(7.6 – 9.3)	8.2	(8.0 – 8.5)	0.2	(0.8)	0.1	(0.5)
Redox potential, mV	95	(-160 - +176)	100	(+43 - +175)	35	(240)	25	(250)
Dissolved oxygen, mg/l	10.5	(2.1 – 16.0)	9.6	(6.4 – 14.0)	2.8	(10.7)	2.0	(7.4)
Oxygen saturation, %	125	(28 – 215)	118	(92 – 170)	37	(152)	30	(96)

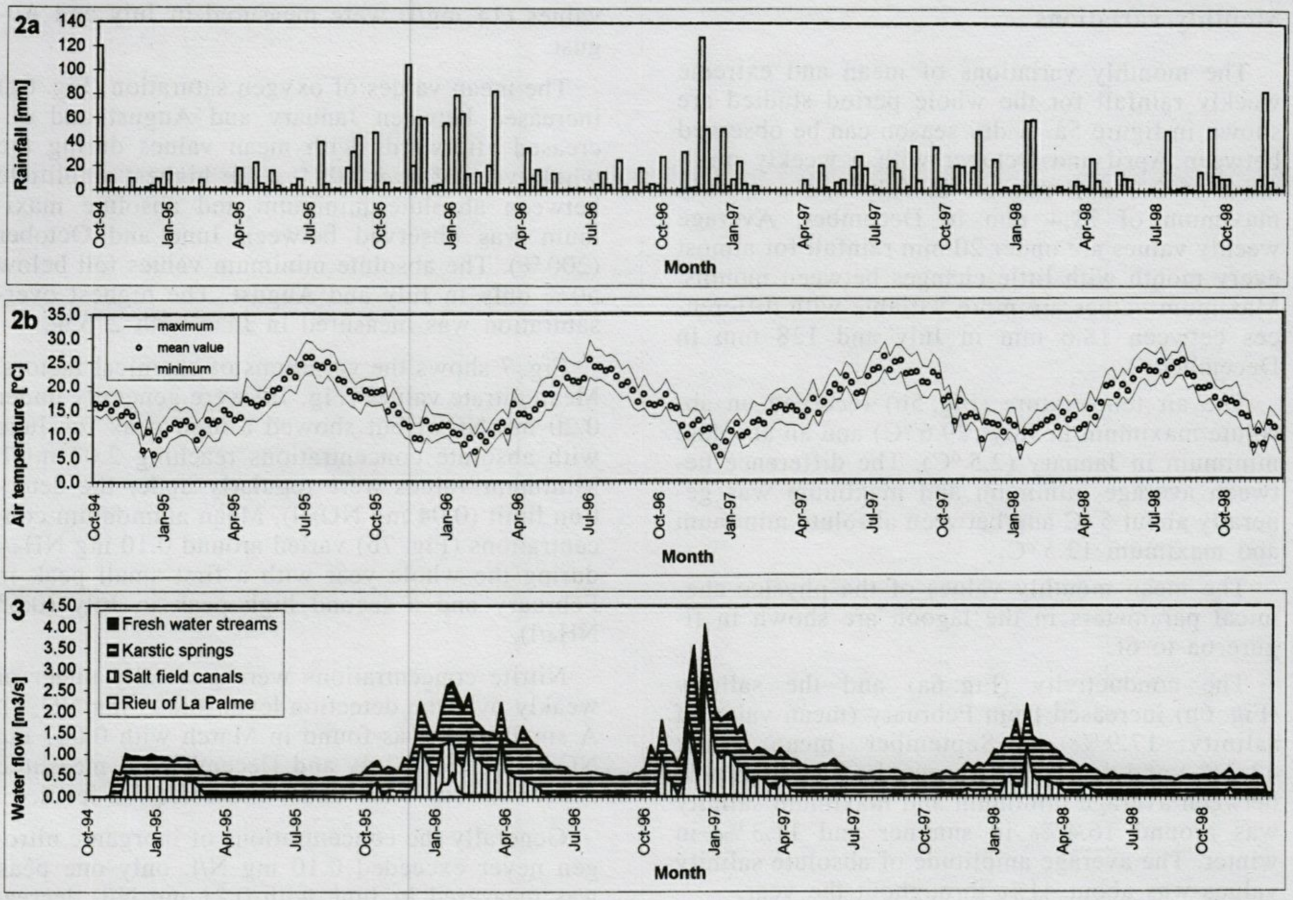


Fig. 2,3. – 2 : Weekly variations of weather conditions. a, Total weekly rainfall; b, Air temperature (mean values, average minimum and maximum). 3 : Total weekly water flow of tributaries.

The average weekly water flow (Fig. 3) of all karstic springs was relatively stable over the whole year (about $1 m^3/s$). All other sources of fresh or brackish water were almost non-existent in summer but could reach up to $3 m^3/s$ in winter with a maximum flow generally observed around January. The northern of the two channels bordering the salt fields (S1) was, with about 80 % of their total flow, the most important. The Rieu of La Palme was observed flowing twice during the study period (January 1996 and December 1996), the rest of the time the riverbed was dry. The four fresh water streams on the western side of the lagoon did not contribute in a significant way to the water input from the catchment area.

The weekly variations of the physico-chemical parameters inside the lagoon are shown in the figures 4a to 4g. Conductivity (Fig. 4a) and salinity (Fig. 4b) generally increased gradually in early spring and decreased more sharply in autumn. Results of the study showed different levels of salinity and conductivity with highest values in 1995 and the lowest values in 1996. At the end of the study period the values rested on a high level and no decrease has been observed. Water temperature (Fig 4c) was generally at a maximum in July and at a minimum in January. The pH values (Fig. 4d) varied around a pH of 8.4, with generally a difference between the extreme weekly values of about 0.5 units.

The measurements of redox potential (Fig. 4e) were not available before December 1996. Generally the redox potential was higher in winter than in summer when negative values could be observed. Apart from the four times when negative values were reached, only small differences between weekly maxima and minima were measured.

The concentration of dissolved oxygen (Fig. 4f) varied around 10 mg/l during the whole study period. Generally the conditions were more variable in summer with a higher amplitude between minima and maxima.

The values of oxygen saturation (Fig. 4g) follow the concentrations of dissolved oxygen with mean values generally around 110 %. The maximal saturation is generally reached around July with values of more than 200 %.

Monthly variations

The monthly variations of mean and extreme weekly rainfall for the whole period studied are shown in figure 5a. A dry season can be observed between April and October with a weekly minimum of 2.6 mm rainfall in July and a weekly maximum of 21.4 mm in December. Average weekly values are under 20 mm rainfall for almost every month with little changes between months. Maximum values are more variable with differences between 18.6 mm in July and 128 mm in December.

The air temperature (Fig. 5b) recorded an absolute maximum in July (29.6 °C) and an absolute minimum in January (2.5 °C). The difference between average minimum and maximum was generally about 5 °C and between absolute minimum and maximum 12.5 °C.

The mean monthly values of the physico-chemical parameters in the lagoon are shown in figure 6a to 6f.

The conductivity (Fig. 6a) and the salinity (Fig. 6b) increased from February (mean value of salinity: 17.9 ‰) to September (mean value: 43.2 ‰) and decreased afterwards. The amplitude between average minimum and maximum salinity was around 16.4 ‰ in summer and 11.3 ‰ in winter. The average amplitude of absolute salinity values was about 41‰ throughout the year.

The water temperature (Fig. 6c) increased between January and August and decreased during the rest of the year. The temperature changes were very regular and the difference between average minimum and average maximum was about 2 °C.

The pH (Fig. 6d) rose between January and July. The difference between average monthly minimum and maximum was generally about 0.3 units but was 0.5 pH units in summer. The highest variations between absolute values occurred in March and between July and September.

The redox potential (Fig. 6e) decreased between January and September and increased afterwards. Negative values could be reached between July and October. Between November and March the absolute variations were smaller (average difference: 120 mV) than in summer (average difference: 195 mV). The highest amplitude between extreme values was reached in August with 310 mV, the lowest in November with 90 mV.

The average concentrations of dissolved oxygen (Fig. 6f) decreased between January and October and rose afterwards. The lowest values (2 mg/l) as well as the highest amplitude between extreme values (14 mg/l) were measured in July and August.

The mean values of oxygen saturation (Fig. 6g) increased between January and August and decreased afterwards with mean values during the whole year of over 100 %. The highest amplitude between absolute minimum and absolute maximum was observed between June and October (200 %). The absolute minimum values fell below 50 % only in July and August. The highest oversaturation was measured in June with 275 %.

Fig. 7 shows the variations of chemical factors. Mean nitrate values (Fig. 7a) were generally under 0.20 mg NO_3/l but showed a high peak for June with absolute concentrations reaching 2.00 mg/l. Minimum values were regularly under the detection limit (0.04 mg NO_3/l). Mean ammonium concentrations (Fig. 7b) varied around 0.10 mg NH_4/l during the whole year with a first small peak in February and a second high peak in July (0.65 NH_4/l).

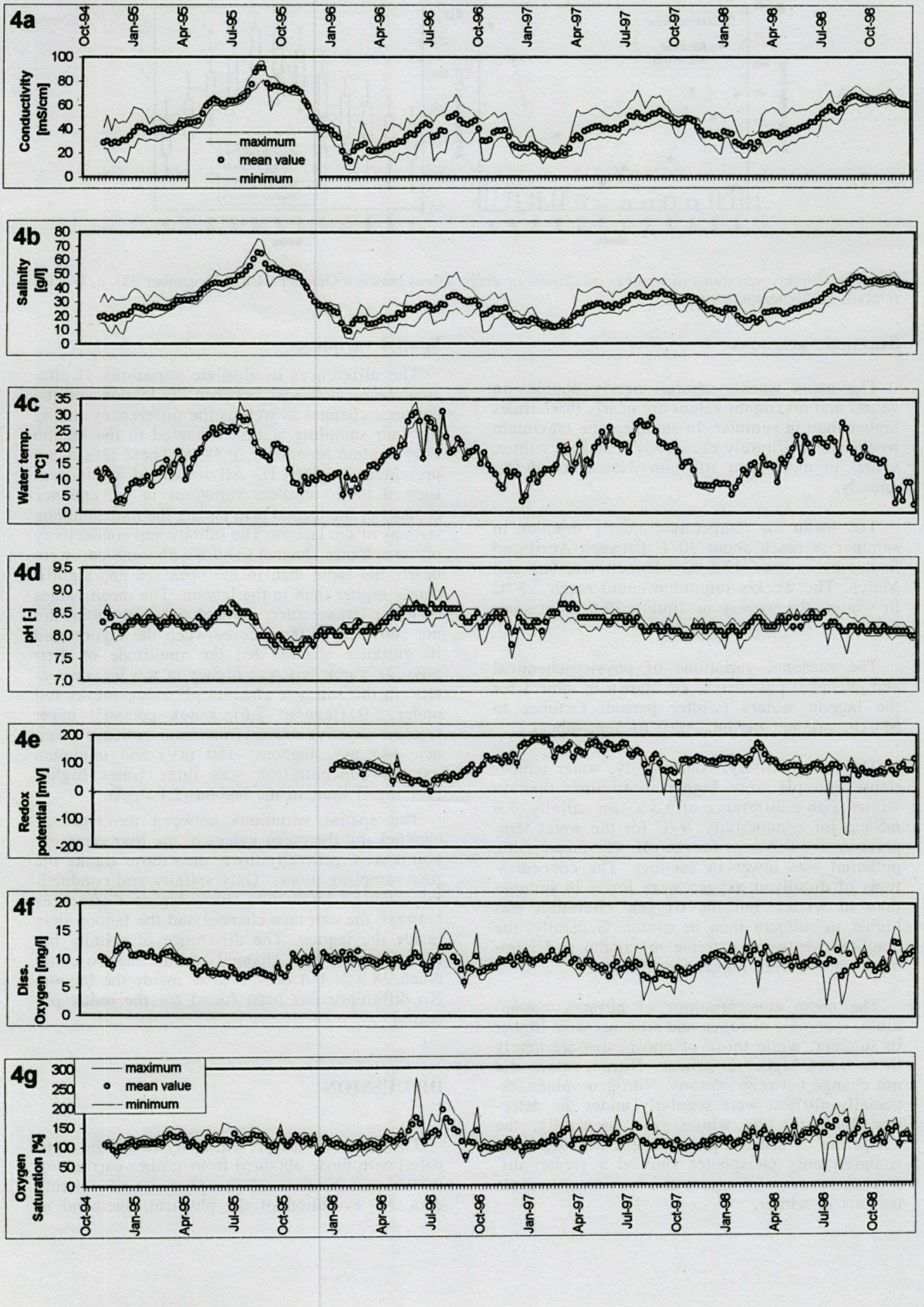
Nitrite concentrations were generally under or weakly over the detection level (0.003 mg NO_2/l). A small peak was found in March with 0.007 mg NO_2/l. Between July and December all measured concentrations were under the detection level.

Generally the concentrations of inorganic nitrogen never exceeded 0.10 mg N/l, only one peak was measured in June with 0.21 mg N/l, decreasing afterwards to reach 0.10 mg N/l again in August. The relation between nitrate nitrogen and ammonium nitrogen presented variations between 25 to 55 % of nitrate from the total inorganic from January to April. In May, the inorganic nitrogen formed for 100 % by nitrates, decreasing in June to 80 % and to 10 % in August before a raising in August and September (30 %) and a new 100 % value in October. In November and December the nitrates were absent and the ammonium nitrogen formed 100 % of the total inorganic nitrogen. The part of nitrite was insignificantly small in the total inorganic nitrogen.

The concentrations of phosphates (Fig. 7c) showed a peak in March with a maximum of 0.80 mg PO_4/l. The rest of the year the concentrations were relatively stable with values around 0.06 mg PO_4/l.

The concentrations of silicates (Fig. 7d) increased from April to reach an absolute maximum of 2.20 mg SiO_2/l in August. Between May and August the mean concentrations were up to 10 times higher than during the rest of the year, when mean values varied around 0.15 mg SiO_2/l.

Fig. 4. – Weekly variations of physico-chemical parameters inside the lagoon. a, Salinity; b, Conductivity; c, Water temperature; d, pH; e, Redox potential; f, Dissolved oxygen; g, Oxygen saturation.


4a
Conductivity [mS/cm]
maximum
mean value
minimum
4b
Salinity [g/l]
4c
Water temp. [°C]
4d
pH [-]
4e
Redox potential [mV]
4f
Diss. Oxygen [mg/l]
4g
Oxygen Saturation [%]
maximum
mean value
minimum
Oct-94
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
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Oct-97
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Apr-98
Jul-98
Oct-98

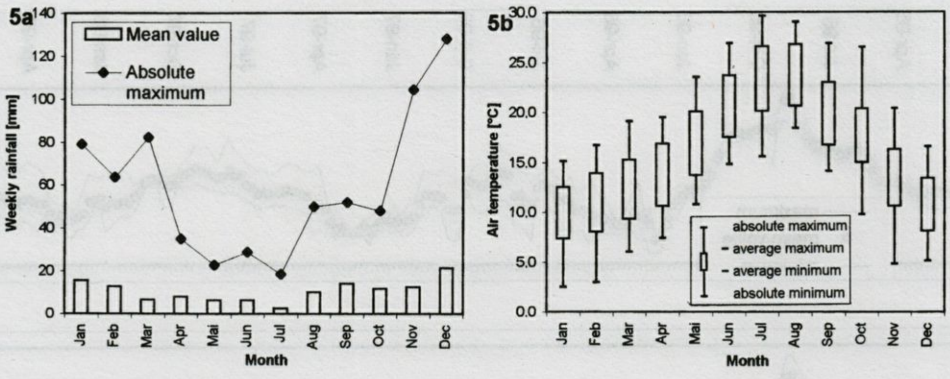

Fig. 5. – Monthly variations of weather conditions (average values between October 94 and December 98). a, Weekly rainfall; b, Air temperature.

Seasonal variations

The mean weekly rainfall nearly doubles in winter and maximum values are nearly three times higher than in summer. In summer, the maximum weekly rainfall rarely exceeded 30 mm. In winter, values of more than 100 mm were reached frequently.

The mean air temperature nearly doubles in summer to reach about 20 °C between April and September versus 12.5 °C between October and March. The weekly minimum could reach 2.5 °C in winter, the weekly maximum 29.6 °C in summer.

The seasonal variations of physico-chemical and chemical parameters are shown in table I for the lagoon waters (winter period: October to March, summer period: April to September).

The mean salinity, conductivity, water temperature and pH were higher in summer than in winter with a difference of 5.5 ‰ for salinity, 7.6 mS/cm for conductivity, 9 °C for the water temperature and 0.2 units for the pH. The mean redox potential was lower in summer. The concentrations of dissolved oxygen were lower in summer than in winter, but the oxygen saturation was higher in summer than in winter. Generally, the amplitude between extreme maximum and minimum values were higher in summer.

The mean concentrations of nitrates, ammonium, inorganic nitrogen and silicates were higher in summer, while those of phosphates are nearly three times higher in winter. Nitrite values did not change between seasons. Nitrogen values, especially nitrites, were regularly under the detection limit for the whole year. Generally, the variability of nearly every nutrient was higher in summer, only phosphates showed a greater difference between minimum and maximum concentrations in winter.

Spatial variations

The differences in absolute variations of physico-chemical factors between the lagoon and the entrance channel as well as the differences among the four sampling stations situated in the lagoon were studied separately in 1998. These results are presented in table II. All measured parameters showed lower absolute variations in the entrance channel of the lagoon than among the four sampling stations of the lagoon. The salinity and conductivity of the entrance channel (37.9 ‰; 56.9 mS/cm) were nearly the same than in the open sea and significantly higher than in the lagoon. The mean values of water temperature, pH and redox potential did not show any difference between the lagoon and its entrance channel but the amplitude of their possible variations was higher in the lagoon waters. In the entrance channel pH values never fell under 8.0 (lagoon: 7.6), redox potential never reached negative values (minimum entrance channel: +43 mV, lagoon: –160 mV) and minimum oxygen concentration was three times higher (6.4 mg/l) than in the lagoon (2.1 mg/l).

The spatial variations between the entrance channel and the mean values of the four sampling points were generally lower than those among the four sampling points. Only salinity and conductivity showed about two times higher differences between the entrance channel and the lagoon than inside the lagoon. The difference of salinity between the entrance channel and the lagoon could reach 28.9 ‰ but only 17.2 ‰ inside the lagoon. No difference has been found for the redox potential.

DISCUSSION

The results of the present study cannot be compared with those obtained from studies carried out in the past because of the poor set of existing data. No evolution of the physical, chemical or

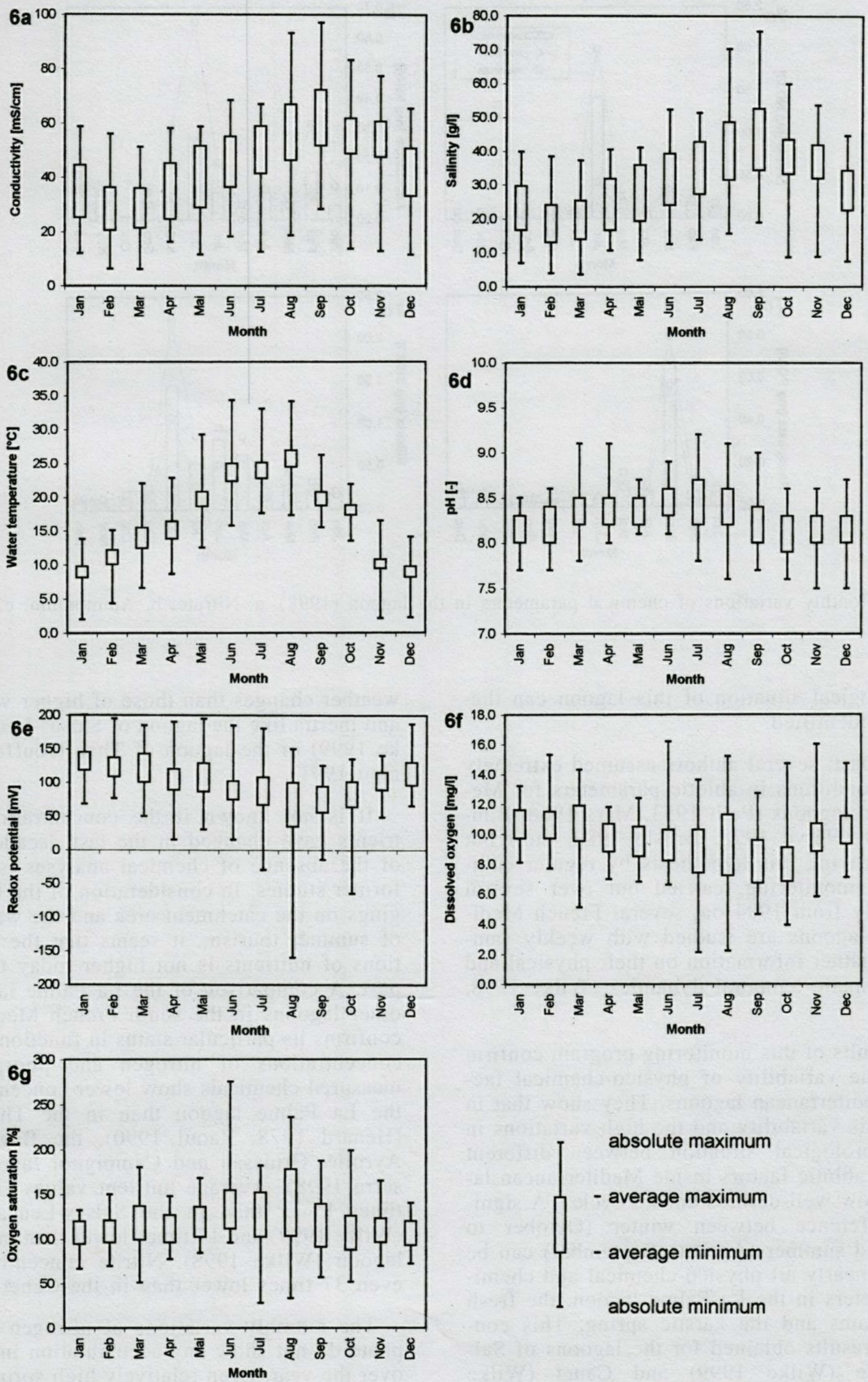

Fig. 6. – Monthly variations of physico-chemical parameters in the lagoon (average values between October 94 and December 98). a, Conductivity; b, Salinity; c, Water temperature; d, pH; e, Redox potential; f, Dissolved oxygen; g, Oxygen saturation.

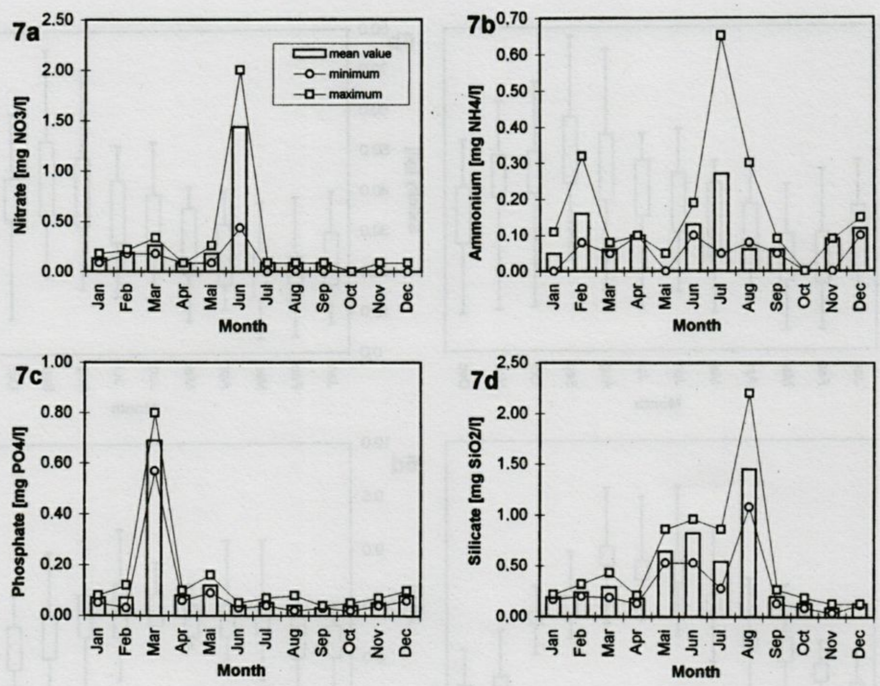

Fig. 7. – Monthly variations of chemical parameters in the lagoon (1998). a, Nitrate; b, Ammonium; c, Phosphate; d, Silicate.

hydrobiological situation of this lagoon can therefore be identified.

In the past, several authors assumed extremely variable conditions in abiotic parameters for Mediterranean lagoons (Petit 1953, Mars 1966, Boutière 1974, Hervé 1978, Bruslé 1980, etc.) but without proving this hypothesis by regular environmental monitoring, carried out over several years. Only from 1994 on, several French Mediterranean lagoons are studied with weekly samplings to gather information on their physical and chemical spatio-temporal dynamics (Wilke 1998, 1999).

The results of this monitoring program confirm the extreme variability of physico-chemical factors in Mediterranean lagoons. They show that in spite of this variability and the high variations in the meteorological situation between different years, the abiotic factors inside Mediterranean lagoons follow well-defined annual cycles. A significant difference between winter (October to March) and summer (April to September) can be found for nearly all physico-chemical and chemical parameters in the La Palme lagoon, the fresh water streams and the karstic spring. This confirms the results obtained for the lagoons of Salses-Leucate (Wilke 1999) and Canet (Wilke 1998). This dynamic cycling of physico-chemical parameters inside the lagoon is closely related to meteorological conditions. Lagoons with a low water depth and inertia, like the lagoon of La Palme react more rapidly and more extremely on weather changes than those of higher water depth and inertia like the lagoon of Salses-Leucate (Wilke 1999) or the lagoon of Thau (Jouffre & Amanieu 1991).

It is not known if the concentrations of nutrients have changed in the last decades because of the absence of chemical analyses issued from former studies. In consideration of the little changings on the catchment area and the weak impact of summer tourism, it seems that the concentrations of nutrients is not higher today than in the past. A comparison of the La Palme lagoon with other lagoons in the south French Mediterranean confirms its particular status in function of its low concentrations of nitrogen and phosphate. All measured chemicals show lower concentrations in the La Palme lagoon than in the Thau lagoon (Hénard 1978, Raoul 1990), the Bages-Sigean, Ayrolle, Gruissan and Campignol lagoons (Dusserre 1998). Average nutrient values are about 8 times lower than in the Salses-Leucate lagoon (Wilke 1999) and 17 times lower than in the Canet lagoon (Wilke 1998). Nitrite concentrations are even 37 times lower than in the Canet lagoon.

The monthly variations of nitrogen and phosphate do not show any accumulation in the water over the year. Even relatively high spring or summer peaks of unknown origin are immediately followed by low concentrations, proving the direct utilisation of the nutrients by phytoplancton and macrophytic algae (Bougis 1974). The absence of algae blooms in over four years of study indicates that the lagoon accommodates still with the amount of treated waste water input without showing unacceptable effects: the measured concentrations of nutrients seem to keep under the environmental capacity of the lagoon (GESAMP 1986).

The results of our study show a strong link between the characteristics of the catchment area and the sedimentological, physical, chemical and hydrobiological patterns of the lagoon. The rarity and intermittence of fresh surface water coupled with a clay poor soil and a low density of population entail a nutrient poor surface water inflow and a low sediment transport to the lagoon. The nutrient poor lagoon water and the large part of sandy bottoms has produced a special flora based in particular on *Zostera* and *Ruppia*, generally present on silty sediment and *Acetabularia* and *Characeae*, generally present on sandy sediment. Green algae are less frequent than in other Mediterranean lagoons and brown and red algae are nearly absent. These particularities entail a special macrobenthic fauna based on mollusca relatively low densities of crustaceans and annelids. This type of zoobenthos attracts especially fish species, feeding on mollusca like *Sparus aurata*. Fish species feeding on crustacean like *Dicentrarchus labrax*, are nearly absent. The whole food web seems to depend in this way on the amount of alluvium and the quality of water entering the lagoon (Boutière 1974).

The entrance channel of the lagoon shows different hydro-chemical dynamics compared to the rest of the lagoon: the amplitude of physico-chemical variations is smaller and the mean values are over the whole year closer to the marine values. Near the open sea, extreme pH values, negative redox potentials, high oversaturation of oxygen as well as oxygen deficits are absent. Similar characteristics have been found in the Salses-Leucate lagoon (Wilke 1999) confirming the hypothesis that the influence of the open sea buffers the internal bio-chemical activity of the lagoon. The influence of the catchment area and the consequences of the extreme Mediterranean weather conditions produce extreme physical, chemical and hydrobiological conditions in the lagoon. The amplitude between minimum and maximum values is as higher as the contact with the open sea is smaller. Lagoons with intermittent opening to the sea and weak exchange rates like the La Palme lagoon, the Canet lagoon (Wilke 1998) or the Campignol lagoon (Dusserre 1998) show higher variations in abiotic factors than those with a permanent opening to the sea and high exchange rates like the Salses-Leucate lagoon (Wilke 1999) or the Thau lagoon (Jouffre & Amanieu 1991).

CONCLUSION

The French Mediterranean coast line is marked by a multitude of different types of wetlands with different geological origin and different physical, chemical and biological characteristics. These wetlands have suffered in the past from human impacts, considerably modifying their topographic and hydraulic environment and thus natural dynamics. In recent decades there has been a massive loss and degradation of wetlands all over the world. Increasing environmental stress and nutrient input has transformed most lagoons into highly eutrophic ecosystems with regular algal blooms, fish mortality and fecal contamination of shellfish. The study of an oligotrophic wetland like the La Palme lagoon can contribute to a better knowledge of the biotic and abiotic dynamics of lagoons which have been minimally impacted by humans.

Our studies show that the natural dynamics of Mediterranean lagoons, which are not subject of tidal mixing, seem to depend largely on the human activity in their catchment area. The whole food web is based on the input and distribution of clay and nutrients coming from upstream. This influence is still not well understood because previous researchers generally focussed only on the marine influence on the lagoon because of the great part of lagoon flora and fauna coming from the sea. The exchange with the open sea seems to compensate the heavy variations caused by the extreme weather conditions in the Mediterranean and equalise their effects on the lagoon life, but the "character" of a Mediterranean lagoon is given by the amount of sediment and nutrients entering the lagoon and the activities of man in the catchment area (tourism, industries, agriculture, constructions, etc.).

Today, no valid model of the dynamics of non tidal mixed coastal lagoons exists because these ecosystems are still less extensively studied than estuaries, fjords or marine coastal zones (Kjerfve 1994). No real water quality model based on saprobial pollution index or threshold values for chemical substances has been developed for Mediterranean lagoons as it has for inland lakes and running waters. The generalisation of observations and models obtained from the study of other ecosystems (estuaries, Atlantic lagoons, etc...) cannot give valid results. The first hydrodynamic models of Mediterranean lagoons developed for the Thau lagoon (Lazure & Salomon 1991, Jouffre & Amanieu 1991) should be generalised for other, more shallow lagoons and the development of water quality models like those of Kitsiou & Karydis (1998) used for marine coastal zones should be adapted for lagoons.

There is still a need for more comprehensive and long-term data sets, obtained by the use of a standardised methodology before even basic processes such as the water, salt and heat balances, interactions with the open sea and the catchment area, sediment transport processes and exchange of flora and fauna with the surrounding ecosystems will be really understood and models could be developed. The co-operation of researchers working on different aspects of coastal lagoons is necessary to get a better knowledge of these ecosystems and only a sound knowledge of their dynamics will allow better management and preservation of these ecosystems and avoid their overexploitation and destruction.

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