SPATIO-TEMPORAL DYNAMICS OF PHYSICO-CHEMICAL AND CHEMICAL FACTORS IN THE WATER OF A HEAVILY TRANSFORMED MEDITERRANEAN COASTAL LAGOON, THE ETANG DE SALSES-LEUCATE (FRANCE)

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ABSTRACT. - The Mediterranean lagoon of Salses-Leucate was studied from October 1994 to November 1997. Approximately 160 surveys were made with over 8,000 measurements of physico-chemical parameters (temperature, pH, dissolved oxygen, oxygen saturation, salinity, conductivity, redox potential and tributaries water flow). Approximately 400 chemical analyses were performed of the main nutrients. The measured parameters were found to follow a well-defined seasonal rhythm in spite of large absolute variations and interannual differences. For several parameters a very good correlation with meteorological conditions was found. The lagoon was heavily transformed around 1970 by urbanization and the creation of three large channels allowing permanent exchange with the open sea. A comparison with observations recorded before these changes show that the salinity rose from 12-30 % up to 27-41 % today but that the seasonal dynamics remained unchanged. Special observations on the karstic springs are showing their great influence on the water balance. The open sea strongly influences the conditions inside the lagoon. Regions far from the entrance channels have generally higher water temperature and pH but lower oxygen concentration and redox potential. Anoxic crises and heavy oxygen oversaturation only appeared here, and the absolute variations of abiotic parameters are higher and the cycling dynamics less regular. Man has largely influenced negatively the topographical and hydraulic environment of the lagoon and special efforts are needed to manage the different uses and to stop the further degradation of the lagoon.

RÉSUMÉ. - La lagune de Salses-Leucate, sur la côte méditerranéenne française, a été étudiée d’octobre 1994 à novembre 1997. Plus de 8 000 mesures des paramètres physico-chimiques (température, pH, O₂ dissous, saturation en O₂, salinité, conductivité, potentiel Redox, débit des affluents) et 400 dosages des principaux nutrients ont été effectués à intervalles réguliers pendant ces trois années. Il est apparu que ces divers paramètres suivaient un rythme saisonnier bien marqué malgré d’importantes variations interannuelles. Pour certains de ces paramètres, de très bonnes correlations avec les conditions météorologiques ont été trouvées. De grands travaux d’aménagements touristiques ont considérablement transformé la lagune dans les années 70, notamment par la création de trois grands chenaux de communication avec la mer. Depuis cette époque, les échanges d’eau et d’organismes vivants sont devenus permanents avec le milieu marin. La comparaison des résultats de la présente étude avec les observations antérieures aux aménagements a montré que l’intervalle de variation de la salinité de la lagune est passé de 12-30 % à 27-41 %, mais que la dynamique saisonnière est restée inchangée. Une étude particulière des venues d’eau douce d’origine karstique a montré leur rôle important dans le bilan hydrique de la lagune. Les conditions à l’intérieur de la lagune sont fortement influencées par le milieu marin. Les points les plus éloignés des graus montrent les valeurs de température et de pH les plus élevées et les concentrations en oxygène et du potentiel Redox les plus basses. C’est en ces points particuliers uniquement, où les variations absolues des facteurs abiotiques sont les plus fortes et les moins régulières, qu’apparaissent des zones de forte sursaturation et des crises d’anoxie. Les grands travaux d’aménagement réalisés dans le passé, dont l’objectif n’était d’ailleurs pas le bon fonctionnement de l’étang, ont eu une incidence très négative sur la topographie de la lagune et sur l’environnement aquatique. Des efforts importants seraient nécessaires pour gérer correctement les divers usages du milieu et arrêter sa dégradation.
INTRODUCTION

Approximately 40,000 ha of the French Mediterranean littoral zone are covered by coastal lagoons, water bodies of varying size, separated from the sea by a sandy barrier, interrupted by one or more channels remaining open at least intermittently. These channels enable the exchange of water, sediment, flora and fauna with the sea. Mediterranean lagoons are not subject to tidal mixing but their salinity can vary from fresh water to hypersaline water, according to their hydrological balance. Because of the general shallowness of water bodies, the extreme weather conditions in the Mediterranean and the seasonal pattern of human activities (tourism), the physico-chemical, chemical and hydrobiological characteristics vary greatly. Under these conditions euryhaline and eurythermal flora and fauna have developed in the lagoons but many species need to migrate to the open sea for reproduction.

In the last 30 years, urbanization, particularly the development of tourism and construction of infrastructure have been the reason for a massive loss and degradation of wetlands in the Mediterranean. Natural processes in the wetlands have been greatly modified. Together with increasing environmental stress and nutrient load, these modifications cause frequently critical situations with eutrophication crises, phytoplankton blooms and anoxic conditions. Most lagoons are typical eutrophic ecosystems: highly productive areas with a relatively low species diversity.

The Salses-Leucate lagoon, one of the largest French Mediterranean lagoons (5,400 ha) can be considered as a "restricted lagoon" (Kjerfve 1986), consisting of a large, wide water body, shore-parallel orientated and possessing three entrances. In the late 1960s the sandy barrier between the lagoon and the open sea was highly urbanised for tourism by constructing roads, houses, hotels and two harbours. The former two channels to the open sea were extended and deepened and a third was dug. The biotic and abiotic conditions inside the lagoon changed completely following these developments. Today, the three channels are up to 100 m wide, several meters deep and up to 3 km long and provide permanent openings to the sea.

In the past, almost no fishery or conservation management existed for the Salses-Leucate lagoon. This absence of management did not result in any problems until the 1970s, when new activities began, producing competition between traditional and new uses for space and resources. Overexploitation of stocks, deterioration of water quality and the appearance of a great number of tourists with a wide range of activities created conflicts between traditional users and "new-comers". Today, efforts are made to manage the lagoon and the human activities without damaging the ecosystem. But while crises seem to appear more frequently (Jacques et al. 1975, Boutière et al. 1982, Anon 1995), a lack of sound knowledge of the functioning of the lagoon has been identified (Roux & Tesson 1992). However, a sustainable use of the lagoon requires prudent management of the resources, based on a reliable knowledge of natural and artificial processes affecting the lagoon.

Although several studies of abiotic parameters of the lagoon have been carried out in the past (Mars 1966, Arnaud 1967, Arnaud & Raimbault 1969, Cahet et al. 1974, Jacques et al. 1975, Hervé 1978), the abiotic conditions and cycles inside the lagoon are still not well known. No regular physico-chemical and chemical analyses of water have been made since the change in the hydrological conditions of the lagoon. The salinity has been the sole parameter studied more frequently, but not since 1978 and only limited to a one year cycle. (Hervé 1978). Today, only shellfish and phytoplankton is analysed regularly (Anon 1995, Le Bec et al. 1997a, b).

The present study aims to contribute to an increased knowledge of the abiotic dynamics inside the Salses-Leucate lagoon ecosystem, to describe the spatio-temporal variations of the physico-chemical and chemical parameters and to understand the influence of fresh water streams and karstic springs on the lagoon. Several authors thought that since the substantial hydraulic works in the late 1960s and early 1970s, the lagoon has been transformed into a marine bay (Clanzig 1987) and that the ecological equilibrium is not yet established (Boutière et al. 1982). This study aims to determine how the conditions changed inside the lagoon with the works (Arnaud 1967, Arnaud & Raimbault 1969). The main objective is to find out if 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 Salses-Leucate lagoon. The Salses-Leucate lagoon is situated approximately 40 km north of the French Spanish Mediterranean boarder. Its mean water depth is approximately 2 m, reaching a maximum of approximately 3.5 m. Its maximum length is 14 km and its maximum width 6.5 km. The lagoon is separated from the sea by a sandy barrier up to 1.5 km in width. The geological origin and sedimentary filling have been well studied (Martin 1978, Gadel et al. 1984).

Several aspects of benthic fauna (Mars 1966, Clanzig 1987, Licari 1998) and fish feeding and migration (Cris-
Fig. 1. - The lagoon of Salses-Leucate : geographical situation and position of sampling stations.

DYNAMIQUE DES CARACTERES ABIOTIQUES D'UNE LAGUNE MEDITERRANEENNE

In recent years, problems linked to water quality have appeared frequently: the sale of shellfish has been forbidden for several weeks almost every year because of faecal contamination and toxic phytoplankton (Ladagnous 1993, Le Bec et al. 1997a, Ladagnous & Le Bec 1998). Between 1991 and 1993 the presence of Salmonella was detected several times in shellfish with a maximum concentration of 20,000 cell/l (Anon 1995). In 1993 60% of the shellfish samples contained toxins (Anon 1995). The appearance of toxic Dinophysis also seems to have increased in the lagoon (Le Bec et al. 1997b). A heavy eutrophication crisis occurred in 1979-80 that destroyed a large part of the benthic fauna, shellfish and fish because of an extended anoxia after a bloom of Nannochloris (Boutiere et al. 1982).

2. The catchment area. The lagoon receives fresh water from a relatively small catchment area (160 km$^2$). Several small streams, mostly flowing intermittently, are situated on the north-western and western side of the lagoon. Only one, situated near the village of Salses, flows for the whole year. No study has been made in the past on water quality or water flow.

Several karstic springs are situated on the western shore of the lagoon. Geological, speleological and hydrological features of the two largest, Font Dame and Font Estramar, are well studied by Got 1965, Kiener & Petit 1968, Salvayre 1971, 1974 and Erre 1977. The two springs have subterranean contact with salt water that mixes with the fresh karstic water. The outflow is weakly brackish water. The water flow and the physico-chemical characteristics of the springs have not been analysed regularly.

Inside the lagoon, several small springs, in contact with the submerged karst, bring up more oligohaline water but their influence on the water balance of the lagoon has not yet been estimated (Arnaud 1967, Cazal et al. 1971).

The building of two seaside resorts (Port-Leucate, Port-Barcarès) on the sandy barrier between the lagoon and the sea began in the 1970s, considerably changing the landscape. Today more than 150,000 tourists populate the shoreline of the lagoon in summer while in winter less than 10,000 people live in the six small villages around the lagoon.

A large number of human activities take place on the lagoon and in the surrounding wetlands. More traditional activities such as fishing and shellfish farming (for oysters, mussels and carpet shells) in the lagoon, fish farming (for sea bass) in artificial ponds, shellfish hatcheries (for shrimps and oysters), agriculture and hunting for water fowl are now forced to share space and resources with activities linked to more recent tourism (such as windsurfing, pleasure boats, fishing for pleasure, beach activities, etc.). From October to March the three entrances are closed by steel fences to prevent migration of fish out of the lagoon, giving fishers the opportunity to catch adult fishes in winter. Water and fish larvae can still pass through the fences in both directions.

Rainfall is approximately 600 mm per year with October being generally the wettest month and July the driest. The maximum daily rainfall can reach more than 200 mm causing significant floods.

The north-westerly wind, often very dry and reaching up to 200 km/h, and the southerly sea wind, normally wet and accompanied by heavy rainfall dominate. Between 1950 and 1980 131 stormy days (windspeeds of more than 16 m/s) occurred per year. The years 1996 and 1997 were particularly stormy with
was carried out monthly with standard solutions ("Han-

using small portable electronic instruments. Calibration

potential, conductivity (référence température : 25 °C),

centres at Perpignan and Carcassonne that centralise

in situ,

salinity and dissolved oxygen were measured

data from several local meteorological stations.

logical data were obtained from the "Meteo-France"

whole water column (Schwoerbel 1994). The meteoro-

by a factor of 0.85 to obtain the mean speed of the

measured using a plastic floater : the mean time taken

with the mean water depth and width. Water speed is

culated by multiplication of the mean current speed

Analyses

5.

0.5 m.

side" of the lagoon, behind a small peninsula with little

than 2 m. The point L7 is situated on the "continental

regular current between them and a water depth of more

of the lagoon, between two entrances (Ll, L3), with a

water streams (Fl to F7) and 1 station at the most

important karstic spring (KS). Weekly sampling was

sampled in the lagoon (Ll to L8), 7 stations in fresh

Indications on figure 1. A total of 8 stations have been

sites of the sampling stations are

Physico-chemical analyses. Température, pH, redox

results by spectrophotometer ("HACH 2000") with a précision of ap-

ammonium, mg NH4/l

inorganic nitrogen, mg N/l

Phosphates, mg PO4/l

Iron, mg Fe/l

Silicon, mg Si/l

Copper, mg Cu/l

232 days when wind velocity exceeded 16 m/s and 43
days with more than 28 m/s (Ascensio 1984, Anon

4. Sampling. Samples were taken on foot approximately

10 m from the shore and at least 50 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 1. A total of 8 stations have been

sampled in the lagoon (Ll to L8), 7 stations in fresh

water streams (Fl to F7) and 1 station at the most

important karstic spring (KS). Weekly sampling was

carried out at the same time each day (11 a.m. to 1

p.m.) to avoid variation in the physico-chemical mea-

surements caused by diurnal variations (temperature

changes, insolation, photosynthesis etc.).

A comparison of physico-chemical and chemical pa-

rameters was made for two particular points inside the

lagoon. The point L2 is situated in the "marine side"

of the lagoon, between two entrances (L1, L3), with a

regular current between them and a water depth of more

than 2 m. The point L7 is situated on the "continental

side" of the lagoon, behind a small peninsula with little

water circulation and water depth of approximately

0.5 m.

5. Analyses

Physical analyses. The tributaries water flow is cal-

culated by multiplication of the mean current speed

with the mean water depth and width. Water speed is

measured using a plastic floater : the mean time taken

for this to travel 5 m on the water surface is multiplied

by a factor of 0.85 to obtain the mean speed of the

whole water column (Schwoerbel 1994). The meteorolo-

data were obtained from the "Meteo-France" centres at Perpignan and Carcassonne that centralise
data from several local meteorological stations.

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. Calibration

was carried out monthly with standard solutions ("Han-

na Instruments"). The oxymeter was calibrated in air

and controlled with a zero-oxygen solution. Oxygen

saturation has been 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 spec-

trophotometer ("HACH 2000") with a précision of ap-

proximately ± 1.5 %. The photometer was calibrated for

analyses in seawater (Aminot & Chaussepied 1983).
The analyses were carried out the same day in the

laboratory to prevent chemical changes in the samples

over time.

RESULTS

1. Temporal variations

Absolute variations

The mean values and the absolute minima and maxima of all parameters for the whole study period are given in table I. The total amplitude between absolute minimum and absolute maximum is for salinity 35.1 %o, for conductivity 49.4

mS/cm, for water temperature 27.9 °C, for pH 2.3

units, for redox potential 425 mV, for dissolved

oxygen 24 mg/l and for oxygen saturation 376 %.
The physico-chemical and chemical conditions vary less in the karstic spring than in the fresh

water rills.

Weekly variations

The weekly variations in rainfall are shown for

the whole period in figure 2a. Generally the

Table I. – Absolute variations of all studied parameters in the lagoon, the karstic spring and the fresh water streams during the whole studied period.

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Lagoon</th>
<th>Karstic spring</th>
<th>Fresh water streams</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>medium</td>
<td>max</td>
</tr>
<tr>
<td>Weekly rainfall, mm</td>
<td>0</td>
<td>12</td>
<td>128</td>
</tr>
<tr>
<td>Air temperature, °C</td>
<td>2.5</td>
<td>16.0</td>
<td>29.6</td>
</tr>
<tr>
<td>Water flow, m/s</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Salinity, %o</td>
<td>17.8</td>
<td>34.9</td>
<td>52.9</td>
</tr>
<tr>
<td>Conductivity, mS/cm</td>
<td>27.0</td>
<td>50.4</td>
<td>76.4</td>
</tr>
<tr>
<td>Water temperature, °C</td>
<td>2.1</td>
<td>16.2</td>
<td>30.0</td>
</tr>
<tr>
<td>pH</td>
<td>7.3</td>
<td>8.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Redox potential, mV</td>
<td>-210</td>
<td>95</td>
<td>215</td>
</tr>
<tr>
<td>Dissolved oxygen, mg/l</td>
<td>0.3</td>
<td>9.4</td>
<td>24.3</td>
</tr>
<tr>
<td>Oxygen saturation, %</td>
<td>4</td>
<td>116</td>
<td>380</td>
</tr>
<tr>
<td>Nitrates, mg NO3/l</td>
<td>0.09</td>
<td>1.45</td>
<td>4.40</td>
</tr>
<tr>
<td>Nitrites, mg NO2/l</td>
<td>0.003</td>
<td>0.026</td>
<td>0.100</td>
</tr>
<tr>
<td>Ammonium, mg NH4/l</td>
<td>0.02</td>
<td>0.77</td>
<td>3.84</td>
</tr>
<tr>
<td>Inorganic nitrogen, mg N/l</td>
<td>0.12</td>
<td>0.96</td>
<td>3.56</td>
</tr>
<tr>
<td>Phosphates, mg PO4/l</td>
<td>0.01</td>
<td>0.26</td>
<td>1.90</td>
</tr>
<tr>
<td>Iron, mg Fe/l</td>
<td>0.01</td>
<td>0.18</td>
<td>0.68</td>
</tr>
<tr>
<td>Silicon, mg Si/l</td>
<td>0.18</td>
<td>0.90</td>
<td>1.50</td>
</tr>
<tr>
<td>Copper, mg Cu/l</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
</tr>
</tbody>
</table>
greatest weekly rainfall can be observed between October and March, exceeding 100 mm several times. In summer, weekly rainfall remains generally below 50 mm. Between November 1994 and November 1995, the rainfall never exceeded 50 mm.

Air temperature is shown in Fig. 2b. Maximum mean temperatures are observed in summer (approximately 30 °C) and minimum mean temperatures in winter (0 to 5 °C).

In summer the water flow of the karstic spring (Fig. 3a) is stable and always under 5 m³/s, in winter it is less regular and often exceeds 10 m³/s. The water flow of all fresh water streams (Fig. 3b) is almost non-existent in summer and rarely exceeds 0.5 m³/s in winter. For both types of spring, the maximum flow was observed in December 1996.

The weekly variations of the physico-chemical parameters inside the lagoon are shown in the figures 4a to 4g. Salinity (Fig. 4a) and conductivity (Fig. 4b) generally increase gradually in early spring and decrease more sharply in autumn.

Water temperature (Fig. 4c) is generally at a maximum in July and at a minimum in January.

The pH values (Fig. 4d) vary around a pH of 8.2, with minima close to the mean values and maxima that can be more than one unit higher in summer.

The measurements of redox potential (Fig. 4e) were not available before December 1996. Generally the redox potential is higher in winter than in summer when largely negative values can be observed. The variation between the 8 sampling stations can reach more than 200 mV on the same day.

The concentration of dissolved oxygen (Fig. 4f) varies around 10 mg/l during the year with generally little difference between absolute minimum and maximum. This difference can be much higher in summer, with more variable conditions.
The values of oxygen saturation (Fig. 4g) follow the concentrations of dissolved oxygen with mean values generally around 110 %. The saturation can reach 400 % in summer.

**Monthly variations**

The monthly variations of mean rainfall for the whole period studied are shown in figure 5a. A dry season can be determined between February and August with a weekly minimum of 3.3 mm rainfall in July. The rainy season lasts from September to January with a weekly maximum of 25.4 mm in December.

The mean air temperature (Fig. 5b) displays a maximum in August (23.4 °C) and a minimum in January (9.7 °C).

The mean water flow of the karstic spring (Fig. 6a) is below 3 m³/s in summer and can reach 6.5 m³/s in winter. The maximum values are more variable than the minimum values and can reach 35 m³/s in December.

The total mean water flow of all fresh water streams (Fig. 6b) is below 0.2 m³/s between March and November (minimum in summer: 0.05 m³/s) and reaches a maximum of 0.37 m³/s in December. In winter the maximum values are very variable and can reach 2 m³/s in December.

The figures 7a-f indicate the mean monthly conditions of physico-chemical parameters in the water of the karstic spring.

The mean salinity (Fig. 7a) is relatively stable during the year (2.9 to 4.6 %). The difference between minimum and maximum is less in summer (1-2 %) than in winter (up to 5 %).

The mean water temperature values (Fig. 7b) display a maximum between June and September and a minimum in December. The difference between maximum and minimum values is less in summer than in winter, when it can reach 3.1 °C. The mean pH values (Fig. 7c) are very stable (7.3 to 7.4) with a possible difference between minimum and maximum of 0.6 units. The redox potential (Fig. 7d) is relatively variable during the whole year and does not seem to follow a monthly cycle. The mean values of dissolved oxygen (Fig. 7e) decrease from December to April and remain relatively unchanged between April and October before they rise again. The minimum and maximum concentrations follow this cycle, with a greater amplitude in winter than in summer. The evolution of oxygen saturation (Fig. 7f) is similar to the variations in the concentrations of dissolved oxygen.

The mean monthly values of the physico-chemical parameters in the lagoon are shown in Fig. 8a-f.

The salinity (Fig. 8a) increases from February to September and decreases after this. The amplitude between mean maxima and minima is around 6.5 % throughout the year. The water temperature (Fig. 8b) increases between January and August and decreases during the rest of the year. The temperature changes are very regular and the difference between mean minimum and maximum does not exceed 4 °C. The pH (Fig. 8c) rises between November and June. The difference between mean minimum and maximum can reach 0.7 pH units. The redox potential (Fig. 8d) increases between June (when negative values can be reached) and December, and decreases afterwards. The maximum values vary less than the minimum
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.
values. The concentrations of dissolved oxygen (Fig. 8e) decrease between March and July and rise between October and March. The minimum values were measured between July and October. The mean values of oxygen saturation between March and September are approximately 20% higher than the rest of the year. The maximum values are more variable than the minimum values.

A comparison of mean monthly values of the water temperature of the lagoon and the open sea (Picco 1990) with the temperature of the air indicates that the air temperature is closer to the water temperature of the lagoon than the sea temperature. In winter, the water temperature in the lagoon is lower and in summer higher than in the open sea. The minimum water temperature of the open sea was measured later (February and March) than in the lagoon (January). The maximum has been found for both temperatures in August.

Seasonal variations

The seasonal variations of physico-chemical and chemical parameters are shown in Tabl. II for the lagoon and the karstic spring (Winter period: October to March, Summer period: April to September). In winter, the mean weekly rainfall doubles and maximum values are nearly three times higher than in summer. The mean air temperature doubles in summer with little difference in mean maximum values but large differences between minimum values in both seasons. In the lagoon, the mean salinity is approximately 4.5% higher, the mean water temperature is 8°C higher in summer. The pH values are higher in summer than in winter. The mean redox potential is lower in summer. The maximum values differ little, but the minimum values can reach highly negative values in summer (−210 mV) whereas they are always positive in winter. The concentrations of dissolved oxygen reach more extreme values in summer with an amplitude of 24 mg/l. In both seasons heavy oversaturation can be observed, but the difference between minimum and maximum saturation is less in winter than in summer. The mean concentrations of nitrates, ammonium and phosphates are higher in summer, while those of nitrates and inorganic nitrogen are higher in winter. The variability of nearly every nutrient is higher in summer, only nitrates show a greater difference between minimum and maximum concentrations in winter.
The physico-chemical parameters in the karstic spring water are relatively stable during the two seasons except for the mean water flow that doubles in winter with maximum flows approximately 6 times higher than in summer.

Correlation

Table III shows the correlation factor ($r^2$) of air temperature, rainfall and all measured weekly physico-chemical parameters in the lagoon.

There is a strong positive correlation between mean weekly air temperature and water temperature ($r^2 = 0.86$). The best correlation ($r^2 = 0.89$) between these two parameters was found for the mean air temperature of a five day period preceding the sampling day (Fig. 9a). A fifteen day period before sampling still gives a correlation ($r^2$) of 0.83. The minimum and mean values of water temperature are generally better correlated with the air temperature than the maximum values.

Weekly rainfall shows weak correlations with physico-chemical factors inside the lagoon. The correlation with conductivity and salinity improves for the rainfall of 7 days ($r^2 = 0.17$) and 14 days ($r^2 = 0.15$) preceding the sampling. Higher air and water temperatures are generally accompanied by higher salinity, conductivity and pH and by lower redox potential and oxygen concentration. A strong positive correlation ($r^2 = 0.59$) has been found between maximum pH values and maximum oxygen concentration and saturation (Fig. 9b). Concerning the chemical parameters, a
Fig. 8. – Monthly variations of physico-chemical parameters in the lagoon (average values between October 94 and November 97); a: Salinity; b: Water temperature; c: pH; d: Redox potential; e: Dissolved oxygen; f: Oxygen saturation.

strong positive correlation was found between pH and iron ($r^2 = 0.64$) and nitrates and iron ($r^2 = 0.56$). Table IV shows the correlation factor ($r^2$) of all measured weekly physico-chemical parameters in the karstic spring. A higher water temperature in the karstic spring is accompanied by a higher salinity and conductivity and a lower oxygen concentration and saturation. A higher water flow is correlated with a lower water temperature, salinity and conductivity and a higher oxygen concentration and saturation.

The evolution of correlation factors between the water flow of the karstic spring and the rainfall of different periods preceding the sampling day is shown in Tabl. V. The best correlation ($r^2 = 0.74$) was found for the period of six days before sampling.

2. Spatial variations

The mean, minimum and maximum spatial differences between sampling stations are shown for the two seasons in Table VI. The difference in spatial variation between winter and summer is low for salinity, conductivity, water temperature and pH, and higher for redox potential, dissolved oxygen and oxygen saturation. In summer, the difference between sampling stations can reach 255 mV redox potential, 16 mg/l dissolved oxygen and 271 % saturation.

The comparison of two special sampling stations (L2 on the “marine side” and L7 on the “continental side”) shows no difference in chemical characteristics. The differences in physico-che-
Table III. - Correlation coefficients ($r^2$) of all physico-chemical parameters in the lagoon.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Weekly rainfall</th>
<th>Air temperature (min)</th>
<th>Air temperature (max)</th>
<th>Salinity (min)</th>
<th>Salinity (max)</th>
<th>Conductivity (min)</th>
<th>Conductivity (max)</th>
<th>Water temperature (min)</th>
<th>Water temperature (max)</th>
<th>Redox potential (min)</th>
<th>Redox potential (max)</th>
<th>Dissolved oxygen (min)</th>
<th>Dissolved oxygen (max)</th>
<th>Oxygen saturation (min)</th>
<th>Oxygen saturation (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekly rainfall</td>
<td>-0.03</td>
<td>-0.04</td>
<td>-0.05</td>
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<td>0.28</td>
<td>0.35</td>
<td>0.27</td>
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<td>0.88</td>
<td>0.83</td>
<td>0.10</td>
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<td>-0.20</td>
<td>-0.14</td>
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<td>0.35</td>
<td>0.36</td>
<td>0.29</td>
<td>0.33</td>
<td>0.28</td>
<td>0.88</td>
<td>0.88</td>
<td>0.83</td>
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<td>0.12</td>
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<td>-0.26</td>
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<tr>
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<td>0.27</td>
<td>0.86</td>
<td>0.87</td>
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<td>0.98</td>
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<td>0.26</td>
<td>0.22</td>
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<td>-0.19</td>
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<td>-0.18</td>
<td>-0.22</td>
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<tr>
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<td>0.88</td>
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<td>0.28</td>
<td>0.22</td>
<td>0.00</td>
<td>0.00</td>
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<td>-0.24</td>
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<td>Water temperature (mean)</td>
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<td>0.94</td>
<td>0.14</td>
<td>0.14</td>
<td>0.10</td>
<td>0.14</td>
<td>-0.16</td>
<td>-0.14</td>
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<td>0.14</td>
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<tr>
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<td>-0.16</td>
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<td>0.01</td>
<td>0.17</td>
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<td>Redox potential (min)</td>
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<tr>
<td>Redox potential (max)</td>
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<td>0.01</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Dissolved oxygen (min)</td>
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<td>0.58</td>
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<td>0.04</td>
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<td>Dissolved oxygen (mean)</td>
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<td>0.81</td>
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<tr>
<td>Oxygen saturation (min)</td>
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<td>0.18</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Oxygen saturation (mean)</td>
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<td></td>
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</tbody>
</table>

Table IV & V. - IV, Correlation coefficients ($r^2$) of all physico-chemical parameters in the karstic spring (KS). V, Correlation coefficients ($r^2$) between different rainfall periods and salinity of the karstic spring.

**DISCUSSION**

Several authors assumed extremely variable conditions in abiotic parameters for the Salses-Leucate lagoon (Mars 1966, Bruslé 1980, Boutière et al. 1982, Clanzig 1987, Le Bec et al. 1997a). This hypothesis is not however proven by the data from regular and systematic environmental monitoring. Only the salinity of the lagoon has been studied several times in the past, showing very variable conditions (Arnaud 1967, Arnaud & Rainbault 1969). The last regular study was carried out in 1978 with monthly samplings for a year (Hervé 1978).

On the basis of three years' weekly monitoring at 16 sampling stations inside the lagoon and the catchment area and more than 8,000 data sets, we can confirm the extreme spatio-temporal variability of salinity and of all other physico-chemical and chemical factors. The high values of oxygen saturation measured several times in the past (Cahet et al. 1974, Ladagnous & Le Bec 1998) are correlated than the pH, redox potential, dissolved oxygen and oxygen saturation with the mean results of the lagoon. Dissolved oxygen and oxygen saturation show a weaker correlation between L2 and L7.
Table VI, VII & VIII. — VI, Spatial variations of physico-chemical parameters in the lagoon the same sampling day. VII, Variation of physico-chemical parameters between the "marine" sampling station (L2) and the "continental" sampling station (L7). VIII, Correlation coefficients ($r^2$) of physico-chemical parameters at special sampling stations (L2 : "marine" side; L7 : "continental" side; lagoon : L1, L3, L4, L5, L6, L8).

**VI**

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Winter mean value (min - max)</th>
<th>Summer mean value (min - max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity, %</td>
<td>6.6 (0.5 - 17.5)</td>
<td>6.4 (1.5 - 17.0)</td>
</tr>
<tr>
<td>Conductivity, mS/cm</td>
<td>8.7 (0.5 - 19.6)</td>
<td>8.0 (1.5 - 18.2)</td>
</tr>
<tr>
<td>Water temperature, °C</td>
<td>2.3 (0.5 - 6.3)</td>
<td>2.9 (1.0 - 8.4)</td>
</tr>
<tr>
<td>pH</td>
<td>0.5 (0.1 - 1.1)</td>
<td>0.5 (0.2 - 1.3)</td>
</tr>
<tr>
<td>Redox potential, mV</td>
<td>20 (0 - 180)</td>
<td>60 (0 - 255)</td>
</tr>
<tr>
<td>Dissolved oxygen, mg/l</td>
<td>3.3 (0.2 - 11.9)</td>
<td>4.6 (0.7 - 16.0)</td>
</tr>
<tr>
<td>Oxygen saturation, %</td>
<td>48 (2 - 162)</td>
<td>76 (21 - 271)</td>
</tr>
</tbody>
</table>

**VII**

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Sampling station L2 mean value (min - max)</th>
<th>Sampling station L7 mean value (min - max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity, %</td>
<td>34.6 (21.1 - 42.6)</td>
<td>35.1 (18.3 - 51.3)</td>
</tr>
<tr>
<td>Conductivity, mS/cm</td>
<td>50.0 (31.0 - 64.1)</td>
<td>51.1 (27.8 - 72.8)</td>
</tr>
<tr>
<td>Water temperature, °C</td>
<td>16.0 (3.8 - 27.5)</td>
<td>17.1 (3.0 - 29.4)</td>
</tr>
<tr>
<td>pH</td>
<td>8.2 (7.8 - 8.5)</td>
<td>8.4 (7.4 - 9.6)</td>
</tr>
<tr>
<td>Redox potential, mV</td>
<td>+100 (-10 - +200)</td>
<td>+70 (-210 - +200)</td>
</tr>
<tr>
<td>Dissolved oxygen, mg/l</td>
<td>8.7 (5.3 - 12.0)</td>
<td>11.3 (0.3 - 24.3)</td>
</tr>
<tr>
<td>Oxygen saturation, %</td>
<td>105 (85 - 130)</td>
<td>140 (4 - 380)</td>
</tr>
</tbody>
</table>

**VIII**

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Correlation L2 - Lagoon</th>
<th>Correlation L7 - Lagoon</th>
<th>Correlation L2 - L7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity, %</td>
<td>0.92</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td>Conductivity, mS/cm</td>
<td>0.94</td>
<td>0.94</td>
<td>0.90</td>
</tr>
<tr>
<td>Water temperature, °C</td>
<td>0.98</td>
<td>0.96</td>
<td>0.94</td>
</tr>
<tr>
<td>pH</td>
<td>0.72</td>
<td>0.88</td>
<td>0.74</td>
</tr>
<tr>
<td>Redox potential, mV</td>
<td>0.92</td>
<td>0.85</td>
<td>0.66</td>
</tr>
<tr>
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<td>0.61</td>
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<tr>
<td>Oxygen saturation, %</td>
<td>0.59</td>
<td>0.56</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Fig. 9. — Regression line; a: Mean air temperature during the five days before sampling and water temperature; b: pH maximum and oxygen saturation maximum.
have also been confirmed (mean value: 116%). This oversaturation can be explained by the high photosynthetic activity at the chosen sampling time (Bougis 1974).

It has been shown that the influence of fresh water streams on the lagoon is negligible, compared to the karstic springs. The studied karstic spring has a mean water flow approximately 25 times higher than the water flow of all the fresh water streams together. It seems that this spring contributes approximately 60% to the total water flow of all karstic springs (Petit 1953, Kienner & Petit 1968, Got 1965, Erre 1977). In this way a total of more than 220*10^6 m^3 water enters the lagoon annually, representing 2.5 times its volume (Arnaud & Raimbault 1969).

The near absence of fresh surface water is coupled with a low sediment transport to the lagoon. The Salses-Leucate lagoon is one of the rare Mediterranean lagoons where the accumulation of sediment does not cause problems. The “life time” of this lagoon has been estimated to be approximately 3,000 years, while other lagoons such as the Etang de Canet could be completely filled in 30 years (SMNLR 1992).

The concentration of nutrients in the Salses-Leucate lagoon are higher today than in the past (Jacques et al. 1975, Ladagnous & Le Bec 1998). These concentrations are also higher than in the Thau lagoon (Hénard 1978) but lower than those measured in the Canet lagoon (Wilke 1998), in the Campignol lagoon (Dusserre 1998) or in the Palavas lagoons (Raoul 1990). The concentrations are comparable to those measured in the Bages-Sigean lagoon (Dusserre 1998). The nitrogen concentrations are higher in summer than in winter, reflecting the influence of heavy tourist activities in summer and problems with waste water treatment. In other lagoons such as the Canet lagoon, the waste water treatment plants for the seaside resorts do not discharge their water into the lagoon and the higher consumption of nutrients in summer (Bougis 1974) even causes lower concentrations in this season (Wilke 1998).

In spite of the extreme variability of physico-chemical and chemical characteristics of the lagoon of Salses-Leucate and the great variation in the meteorological situation between different years, the abiotic factors inside the lagoon 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 lagoon, the fresh water streams and the karstic spring. Generally the extreme summer values are observed between July and September, the extreme winter values in December and January. In the past, this cyclical nature of abiotic parameters has been shown only for salinity (Arnaud 1967, Arnaud & Raimbault 1969, Hervé 1978) and for water temperature (Arnaud & Raimbault 1969).

The abiotic situation inside the lagoon is closely related to meteorological conditions: weather changes entail rapid changes in the water column. Several water parameters are closely correlated to air temperature and rainfall. The mean water temperature shows a strong correlation to the mean air temperature of the prior six days. The correlation is better between the air temperature and the water temperature of the lagoon than between the lagoon and the open sea, where the temperature is higher in winter and lower in summer.

A comparison of a sampling point close to the entrances (L2) with a sampling point at the opposite side of the lagoon (L7) has shown great differences in the physico-chemical characteristics. The mean values of chemical parameters did not differ between these two points but the variations of physico-chemical parameters were much larger at the station further from the marine influence. Generally the water temperature and the pH were higher and the oxygen concentration and the redox potential lower at this side of the lagoon. Anoxic crises and heavy oversaturation only appeared here, the absolute variations in abiotic parameters are higher and the cycling dynamics are less regular. Similar characteristics have been found in the Canet lagoon, which has a low water depth, is normally closed to the sea and has a very large catchment area (Wilke 1998).

It seems that the influence of the open sea buffers the internal biochemical activity of the lagoon: the variations in abiotic factors are smaller and the dynamic cycles are more regular.

In the 1980s several authors found that the hydrobiological and physico-chemical equilibrium of the lagoon had not yet been re-established after the great hydraulic changes (Boutière et al. 1982) or even that the lagoon had been transformed into a marine bay, with open sea dynamics (Clanzig 1987).

Before the hydraulic works the salinity varied between 12 and 30% (Le Calvez & Le Calvez 1951, Feldmann 1953, Arnaud 1967, Arnaud & Raimbault 1969). After the changes the salinity rose up to the 27 to 41% found today (1994-97), but there was no change in the cyclical nature of the variations (Arnaud & Raimbault 1969). The Salses-Leucate lagoon has remained a real lagoon with "normal" dynamics. The data indicate that equilibrium of the abiotic factors has been established. More research is needed to determine whether the hydrobiological equilibrium has also been established.
CONCLUSION

Coastal lagoons are still less extensively studied than estuaries, fjords or tidal rivers (Kjerfve 1994). It seems however that a large amount of information concerning coastal lagoon processes has been inferred from investigations on estuaries (Smith 1994). The validity of this process is already arguable for tidal mixed lagoons (Smith 1994) but even more so for Mediterranean lagoons where tidal variations have no influence. Mediterranean lagoons are unique coastal ecosystems that require separate attention. The generalisation of observations and models obtained from the study of other ecosystems (estuaries, Atlantic lagoons etc..) cannot give valid results. The knowledge of Mediterranean lagoons should be reviewed to distinguish between information obtained from these ecosystems and those resulting from non-Mediterranean ecosystems. There is a need for more research on basic processes such as the water, salt and heat balances of Mediterranean lagoons, interactions with the open sea and the catchment area, sediment transport processes and exchange of flora and fauna with the surrounding ecosystems. Modelling of biotic and abiotic dynamics of Mediterranean coastal lagoons requires more comprehensive and long-term data sets, obtained by the use of a standardised methodology.

A better knowledge of the ecosystem would allow a better management and preservation of the ecosystem, help to prevent crises, harmonise different uses of the lagoons and increase biodiversity. Only careful protection and well-planned management can preserve the natural resources and avoid overexploitation and destruction.

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