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9.3 THE ECOLOGY OF THE MAR MENOR COASTAL LAGOON: A FAST CHANGING ECOSYSTEM UNDER HUMAN PRESSURE

Ángel Pérez-Ruzafa, Concepción Marcos, and Javier Gilabert

9.3.1 Functional Typology

9.3.1.1 Location, Origin, Climate, and Hydrography

The Mar Menor is a hypersaline coastal lagoon, with a surface area of 135 km^2 and a perimeter of 59.51 km. It is located on the southwestern Mediterranean coastline (37°42′00″ N, 00°47′00″ W) with a mean depth of 3.6 m and a maximum depth of 6 m. "La Manga," a sandy bar 22 km long and 100–900 m wide, acts as a barrier between the lagoon and the Mediterranean Sea. It is crossed by five more or less functional inlets called *golas*. Four are shallow (less than 1 m deep) and one of them, El Estacio, was widened and dug to a 5-m depth to make it a navigational channel. Altogether a total width of lagoon entrances is about 645 m, giving Mar Menor a restriction ratio of 0.015. Mar Menor is therefore a restricted lagoon according to the classification proposed by Kjerfve[1] (see Chapter 6). There are two main islands and three other smaller islands, one of which is artificially connected to La Manga. Figure 9.3.1 and Figure 9.3.2 show the location of the Mar Menor Lagoon and its main physiographic characteristics.

The origin and evolution of the Mar Menor Lagoon have been greatly influenced by the changing levels of the sea since the Tortonian, the volcanic activity that occurred during the Pliocene and formed the small hills and islands in the Mar Menor basin, and the Quaternary compressive system that helped shift the sandy barrier that encloses the Mar Menor.[2,3]

At present, the main geomorphological elements that determine the lagoon dynamics are (1) the sandy barrier enclosing the Mar Menor; (2) the inlets or *golas* that determine the entrances from the Mediterranean Sea and its hydrography and confinement; (3) the islands and volcanic outcrops that constitute the only natural rocky substrates and generate environmental diversity for biological assemblages; (4) the gullies or *ramblas* that contribute waters and materials from agricultural run-off and mining mountains; and (5) marginal lagoons, now transformed into salt flats or salt mines.

The lagoon basin is located in a semi-arid region with low rainfall,[4] an annual mean of 300 mm, and high potential evapotranspiration (close to 900 mm) that results in a deficit of the net annual hydric balance that exceeds 600 mm/m^2 year (Figure 9.3.3). The orographic configuration of the basin, the scant vegetation, the impermeability of marly sectors, and the precipitation concentration all make torrential rainfall a characteristic of the area.[5] Winds show a well-defined and regular pattern during the year primarily from the east (*levantes*) followed by winds from the west and southwest (*lebeches*) (Figure 9.3.4). The annual mean velocities of the weakest winds (west and west-southwest) range from 9 to 12 km/h and the strongest

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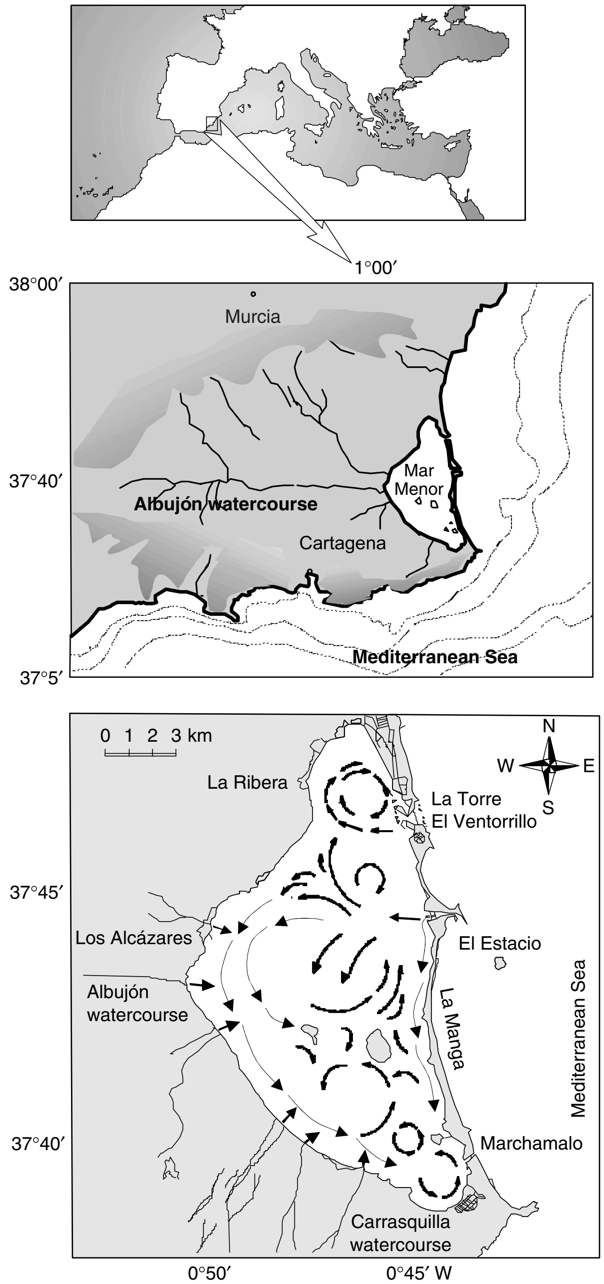

FIGURE 9.3.1 Location of the Mar Menor showing the main channels of communication with the open sea, water courses, and current circulation diagram.

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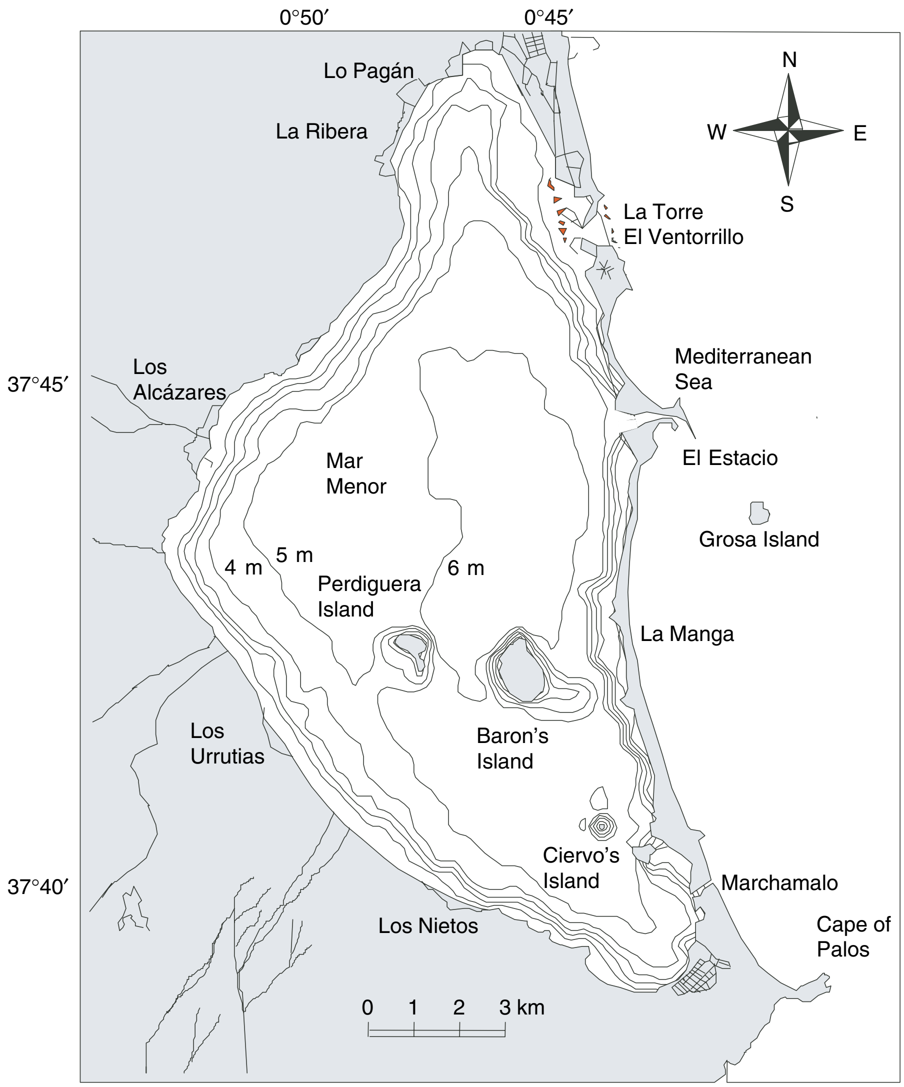

FIGURE 9.3.2 Bathymetry of the Mar Menor.

(northeast, east-northeast, south-southwest and southwest) from 18 to 26 km/h. The highest monthly mean velocities are usually in the range of 30 to 40 km/h.

Climatic and hydrologic features in this area of the Iberian southeast littoral (Table 9.3.1) together with the lagoon's geomorphology cause it to behave like a concentration basin. Evaporation exceeds rainfall and run-off, and, until recent years, there was no permanent watercourse flowing into the lagoon. There are, however, more than 20 cataclinal watercourses on the watershed that collect rainfall water from the surrounding mountains. They get into the plains as real *wadis* but the waters

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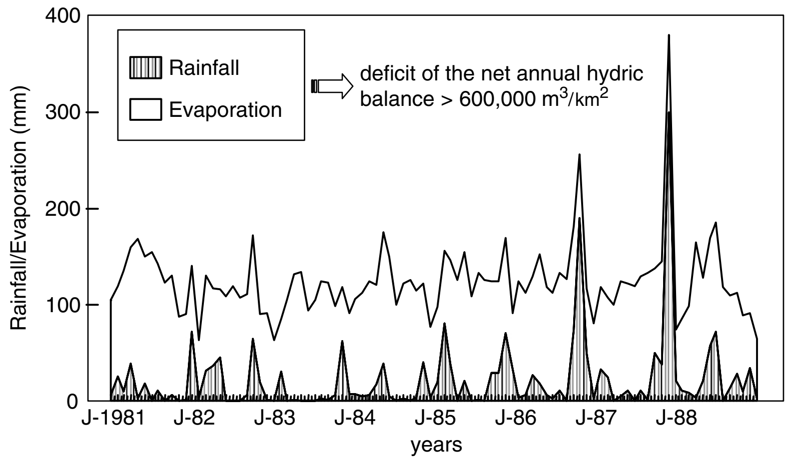

FIGURE 9.3.3 Hydric balance in the Mar Menor area over a 10-year period. Rainfall is scarce and usually concentrated in brief, torrential downpours during the year. (Data from the San Javier meteorological station.)

evaporate and are lost through infiltration and do not reach the lagoon except in instances of strong torrential rainfall.[5] Most of the watercourses discharge in the southern half of the lagoon but that depends on the sporadic and torrential rainfall regime. Among these, the Albujón watercourse, the main collector in the drainage basin, is an exception at present because it maintains a regular flux of water due to changes in agricultural practices, as described below.

Annual total inflow of fresh water through run-off and rainfall into the lagoon range from 27.9 to 122 Hm^3 while 155 to 205 Hm^3 evaporates, resulting in a hydric deficit ranging from 38 to 115 Hm^3 per year. The net loss of fresh water is compensated for by saltwater inputs from the adjacent sea,[6,7] and it is regulated by differences in the sea level between the lagoon and the Mediterranean Sea.[8] The lagoon water budget with the relative contribution of different components to the lagoon volume is shown in Figure 9.3.5.

9.3.1.2 Hydrodynamics

The lagoon hydrodynamics is mainly driven by winds and thermohaline circulation (Figure 9.3.1). The exchange of water between the lagoon and the adjacent Mediterranean Sea is mainly driven by differences in sea level phases,[8] with the Estacio Channel playing the most significant role. The resulting exchange rates lead to residence times of the water bodies in the basin that change from year to year and are responsible for the development of the lagoon water characteristics and hence of the long-term ecological balance in the lagoon. The salinity of the lagoon waters ranges at present from 42 to 46 (with an annual mean value of 44.4) showing a north–south gradient (Figure 9.3.6).[9] Three main gyres can also be identified in a general circulatory pattern along this axis allowing us to differentiate three basins

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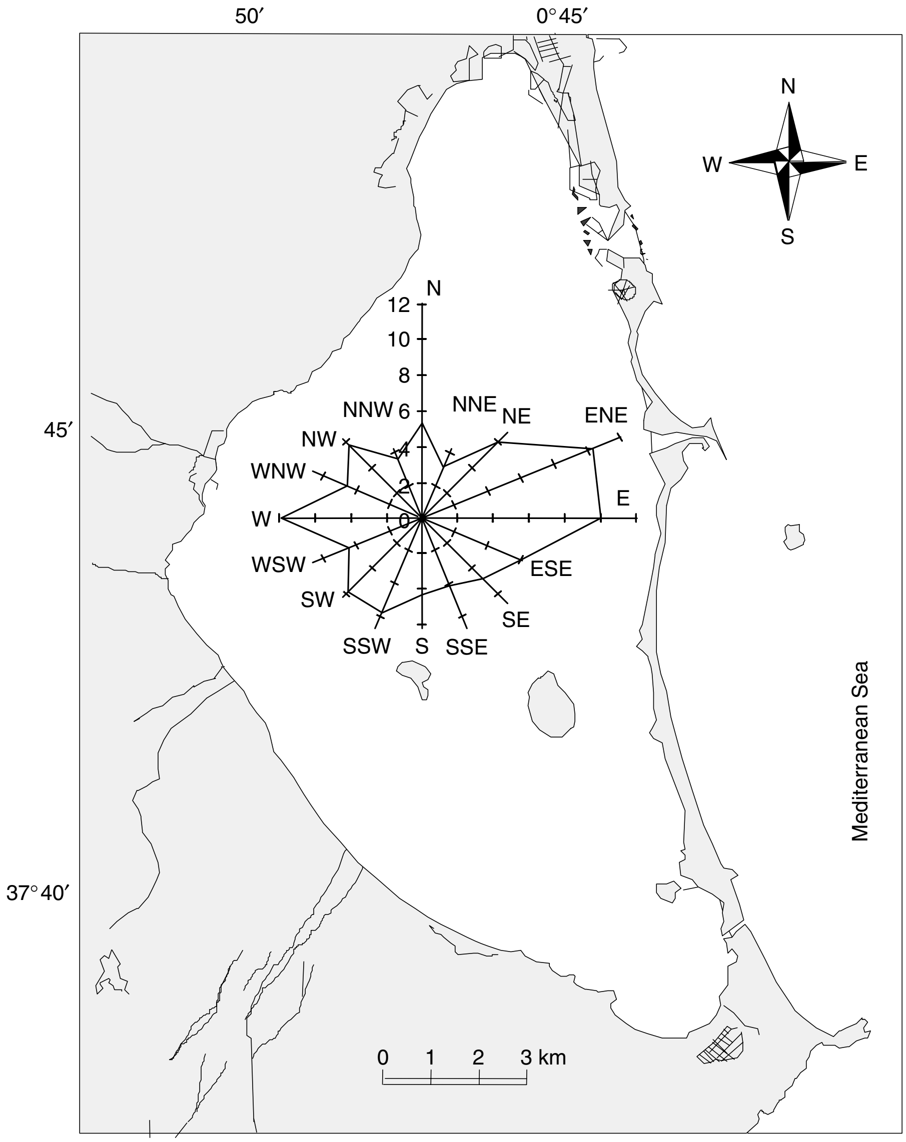

FIGURE 9.3.4 Prevailing winds in the Mar Menor area during the 1980s. (Data from the San Javier meteorological station.)

at the Mar Menor: (1) the northern basin showing the lower mean salinity values; (2) the southern basin showing the most saline waters; and (3) the central basin having intermediate values and corresponding to the mixing area of Mediterranean and lagoon waters.

As in many other coastal lagoons, the water temperature is closely related to the atmospheric temperature.[10–12] The temperature distribution is relatively uniform over

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TABLE 9.3.1
Minimum and Maximum Value of Climatic Variables in the Mar Menor Area (1981–1988)

		Maximum	Minimum
Monthly	Rainfall	300 mm (November 1987)	0 mm (usually in March and from June to August)
	Evaporation	165.5 mm (May 1981)	50 mm (December 1987)
	Solar radiation	280.9 h of sun (July 1981) 623 cal/cm2 * day (monthly mean, June 1987)	110 h of sun (December 1987) 195 cal/cm^2 * day (monthly mean, January 1985)
	Atmospheric temperature (absolute values)	37°C (August 1986)	−3.4°C (January 1985)
Annual	Rainfall	497.9 mm (1987)	113.5 mm (1983)
	Evaporation	1442.9 mm (1981)	115.2 mm (1988)
	Solar radiation	2344 h of sun (1985)	2053.8 h of sun (1982)

Source: Data from the San Javier Aerodrome Meteorological Station on the Mar Menor coast. See Reference 13.

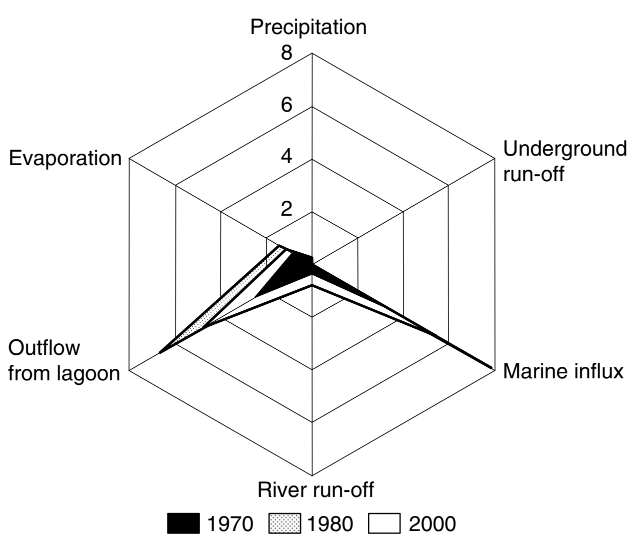

FIGURE 9.3.5 Lagoon water budget rose (meters per year) for the Mar Menor. The diagram represents the relative contribution of each water budget component to the lagoon volume during the recent history of Mar Menor.

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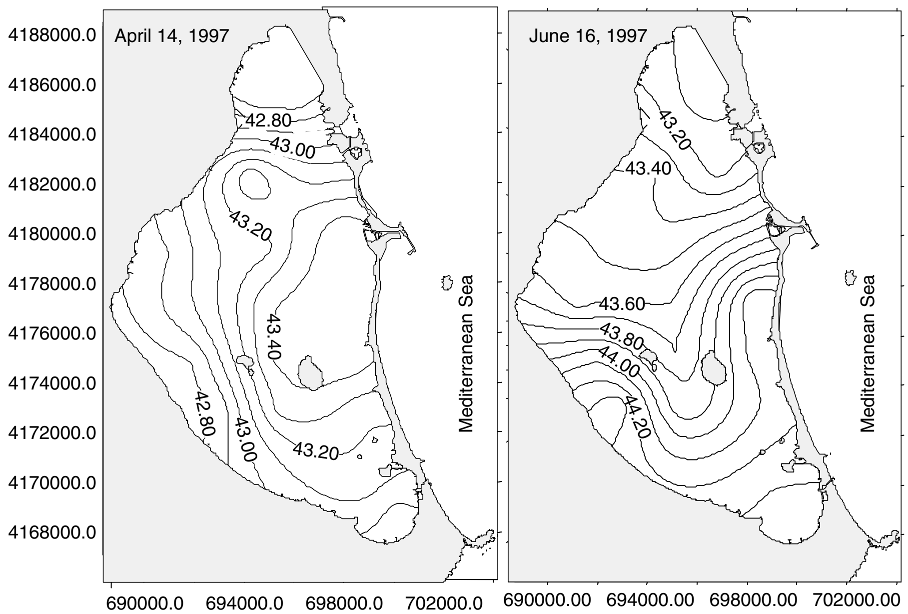

FIGURE 9.3.6 Distribution of surface salinity at the Mar Menor lagoon in two hydrodynamic situations.

all the surface of the Mar Menor with some local differences, mainly related to the shallowest areas. Although the southern basin has warmer waters in summer and cooler waters in winter compared to the others, differences between them are usually less than 2°C at any time of the year.[13] Figure 9.3.7 shows the lagoon hydrological annual cycle using a temperature–salinity (T–S) diagram for mean monthly data.

Turbidity and suspended materials are highly variable depending on many topographical (distance to the coast, depth, nature, and slope of the bottom), biological (planktonic productivity), and climatic (wind and rainfall) variables. Values range from 2 mg/l of suspended solids in calm water conditions on rocky bottoms to 3.88 g/l in shallow waters on muddy or sandy bottoms under the action of the waves. It is possible, however, to distinguish two well-defined situations concerning water clarity: the first is clear waters associated with lower contents of nutrients and chlorophyll spanning along most of the year; the second is turbid water due to the increase of phytoplankton productivity mostly during the late summer.[14] Light is usually not a limiting factor for either phytoplanktonic or benthic biological productivity.

9.3.1.3 Sediment

According to their grain size composition, the bottom of the Mar Menor can be classified into two main sediment categories: muddy and sandy, with some areas of rocky bottoms.[9] On the one hand, muddy bottoms cover both the whole central area of the lagoon and those shallow bottoms that have lower hydrodynamism, being at

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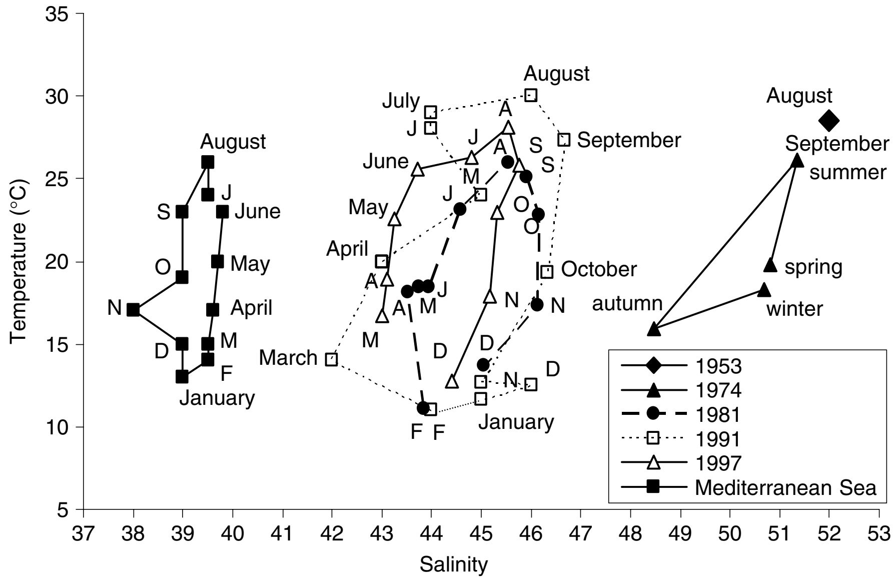

FIGURE 9.3.7 Annual course of T–S index (monthly averaged values) for the Mar Menor during the last decades, compared with the Mediterranean shallow coastal waters of the Cape of Palos. Point at the right of the diagram corresponds to September and August monthly mean values at the Mar Menor according to data from Lozano.[40] The progressive "mediterranization" of the lagoon waters can be noted.

the same time covered by a dense meadow of the algae *Caulerpa prolifera* or patches of the seagrass *Ruppia cirrhosa*. On the other hand, sandy bottoms (with sand content up to 89%) are located on the margins of the basin and in the small bays surrounding the islands in which scant patches of the phanerogame *Cymodocea nodosa* grow.

The organic matter content in the sediment of the Mar Menor is highly variable, ranging from less than 0.34% in compacted red clays up to 8.6% in the *Caulerpa prolifera* areas. An increase in the organic matter content of sediment is observed seasonally, from autumn to winter, both in muddy and sandy bottoms. This increase is explained by the contribution of the fronds of the green algae *Caulerpa prolifera* and the phanerogame *Cymodocea nodosa*, respectively.

Dissolved oxygen values in sediment layers show a high range of variation oscillating between values in the range of 5 to 11 mg/l in surface waters (depending on wave action) to anoxic conditions and concentrations lower than 2 mg/l close to the bottom, in areas with dense meadows on muddy bottoms, high concentrations of organic matter, and low hydrodynamics. The water column shows homogeneous values, usually over saturation, with a small maximum just over the meadow (Table 9.3.2). Such a situation, with saturation levels in surface waters and anoxic conditions at the bottom, has been described previously in deeper lagoons.[12,15]

Submerged aquatic vegetation, rather than physical factors, seems to play a major role in the physical and chemical nature of sediment with only hydrodynamics

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TABLE 9.3.2
Oxygen Values (mg/l) in the Water Column on Distinct Kinds of Bottoms and Statement of the Macrophyte Meadows in a Location off the Los Urrutias 300 m from the Coast (July 1986)

	Dense Meadow of *Cymodocea nodosa*–*Caulerpa prolifera* on Mud	Dense Meadow of *Cymodocea nodosa*–*Caulerpa prolifera* on Rock	Lax Meadow of *Cymodocea nodosa* on Mud
Surface water	5.56	5.56	5.56
1 m	5.64	5.64	5.64
2 m	5.87	5.87	5.87
3 m	5.87	5.87	5.87
3.2 m (bottom)	1.76	4.12	4.04

Note: Profiles are less than 10 m from each other.

retrieving fine particles at the more exposed areas. Although sandy sediment usually show no vegetation coverage, *Cymodocea nodosa* meadows are also related to these bottoms determining slightly higher contents in the fine fraction and organic matter. *Caulerpa prolifera* or mixed *C. prolifera–Cymodocea nodosa* beds, in contrast, determine muddy bottoms with very high organic matter content, which also acts as a sediment trap thus favoring fine particles and organic matter accumulation (as stated in other places by Harlin et al.[16] or Genchi et al.[17]).

The contribution of the macrophytes to the organic content of sediment is a common feature in coastal lagoons, estimated by Mann[18] to be over 60% of the macrophytic production. In the Mar Menor the macrophytic production has been estimated as 165.6 g C/m^2/year[19] implying an input of detritic carbon to the lagoon bottoms of at least 13,400 mt C/year.

9.3.1.4 Biological Assemblages

Biota is characterized by eurihaline and euritherm species also present in the Mediterranean Sea but they usually reach high densities in the lagoon. Many of them are generalist species (*r* strategists) and their high density is the result of both their rapid growth rates and lack of competitors.

From an ecological perspective, the Mar Menor differs from other Mediterranean coastal lagoons in several aspects related to its environmental heterogeneity. Its size, depth, availability of rocky substrates related to the volcanic outcrop and docks, and the mediterranization process related to increased water interchanges account for much of the richness of species and actual bionomic diversity.

Phytoplankton assemblages follow a clearly defined seasonal succession in which four stages can be identified: (1) a winter period dominated by *Rhodomonas* and *Cryptomonas* with *Cyclotella* as the main diatom represented; (2) a spring phase where diatoms (mainly *Cyclotella*) are the dominant group with some monospecific blooms of other diatoms (mainly of *Chaetoceros* sp.); (3) a summer phase characterized by diatoms with blooms of *Niztschia closterium;* and (4) a post-summer and fall phase where diatoms still remained the major group but dinoflagellates increased

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in importance with peaks of *Ceratium furca*[20] with larger diatoms such as *Coscinodiscus* spp. and *Asterionella* spp. also present during the year.

Zooplankton at the nanoplankton (2–20 μm) level is dominated by flagellates eating bacteria. At the microplankton (20–200 μm) level ciliates, both oligotrichs and tintinnids, are well represented by a few species. At the mesoplankton level (>200 μm) copepods are the main group represented with smaller-sized species such as *Oithona nana* and larger ones such as *Centropages ponticus* and *Acartia* spp.[20] Appendicularians can also be found and gelatinous zooplankton is mainly characterized by the jellyfish *Aurelia aurita*. The importance of this trophic compartment has increased during the last few years due to massive proliferation of the jellyfishes *Rhizosthoma pulmo* and *Cotylorhiza tuberculata* in the summer time.

From a bionomic point of view, a number of benthic communities, depending on the type of substrata, wave exposition, and light, shows vertical zonation patterns that resemble the open sea communities but "miniaturized."[9,21,22]

Phytobenthos is represented by 33 species of Chlorophyceae, 20 species of Phaeophyceae, and 33 species of Rhodophyceae.[21] Soft bottom communities are mainly characterized by extensive meadows of the algae *Caulerpa prolifera*, with some areas of the phanerogam *Cymodocea nodosa* and small spots of *Ruppia cirrhosa* in very shallow areas.

Photophilic algae on hard substrates show different biocoenoses related to vertical zonation and the degree of confinement.[22,23] In low confinement conditions, close to the communication channels with the Mediterranean Sea, there is a narrow midlittoral fringe characterized by *Cladophora albida*, *C. coelothrix*, and *Enteromorpha clathrata*. In these areas, the infralittoral community is characterized mainly by *Jania rubens* and *Valonia aegagropila*.

In confined areas, the midlittoral is dominated by *Cladophora albida, Laurencia obtusa,* and *Cystoseira compressa* and the infralittoral by *Laurencia obtusa, Cystoseira compressa*, *Cystoseira schiffneri*, *Padina pavonica*, *Caulerpa prolifera*, and *Acetabularia acetabulum.*

Faunistic assemblages consist of up to 443 species, most of them benthic, included in 11 phyla:[9] Foraminifera (30), Porifera (21), Coelenterea (22), Nematoda (19), Anelida (100), Artropoda-Crustacea (48), Chelicerata (6), Unirramia (6), Molusca (106), Ectoprocta (7), Phoronida (1), Echinodermata (5) and Cordata (Tunicata (5) and Vertebrata-Osteichthyes (67)). Only certain species of each phyla dominate any one community with only rare occurrences of many of the species.[9] For example, the cnidarian *Bunodeopsis strumosa* and *Telmactis forskalii* reach densities of 2,000 individuals/m^2, the polychaete *Filograna implexa* reaches a density of 2,500 individuals/m^2, the amphipod *Caprella mitises* a density of 36,700 individuals/m^2 and the gastropod *Bittium reticulatumes* a density of 39,800 individuals/m^2. Some of these densities are the highest reported for certain species, as in the case of the pycnogonid *Tanystylum conirostre*[24] with 3,600 individuals/m^2, or the ophiuroid *Amphipholis squamata*[25] with 475 individuals/m^2. The diversity of molluscs, taken as an indicator of the communities structure, is rather low (0.5–2.2 bits/ind. on muddy bottoms and 1.7–2.8 bits/ind. on rocky bottoms).[9]

Fishes include mugilids, sparids, singnatids, gobids, and blennids. The benthic fish assemblage of the Mar Menor consists of 23 common species.[9,26,27] The dominant species are *Gobius cobitis*, *Lipophrys pavo,* and *Trypterigion tripteronotus* on shallow

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infralittoral rocks; *Pomatoschistus marmoratus*, *Solea vulgaris,* and *Solea impar* on sandy bottoms; and *Syngnathus abaster*, *Hippocampus ramulosus,* and *Gobius niger* on *Cymodocea nodosa–Caulerpa prolifera* mixed beds.

The lagoon also provides a habitat for many migratory seabirds. Its margins and islands attract nidificate species of international relevance such as *Himantopus himantopus*, *Recurvirostra avosetta*, *Charadrius alexandrinus,* and *Sterna albifron* and others as *Sterna hirundo*, *Tadorna tadorna*, *Anas platyrrhynchos, Burhinus oedicnemus*, *Larus ridibundus,* and *Larus cachinnans*. Marginal lagoons exploited for salt mining give shelter to stable colonies of flamingos (*Phoenicopterus ruber*), which reach concentrations of up to 1000 individuals.

9.3.2 Recent History of Changes in the Lagoon Resulting from Human Activities

The Mar Menor has attracted humans since ancient times, and it has been the target of various types of aggressions during its recent history. Since the early 1970s, tourist development has increased the demand for recreational use, resulting the creation of new beaches, harbors, and channels. On the other hand, mining, urban development, and changes in agricultural practices have increased the waste inputs to the lagoon. Many of these activities led to environmental changes that affected the biota and changed the configuration of the lagoon.

One of the first impacts on the lagoon environment caused by human activities resulted from the input of terrestrial materials which increased the sedimentation rates from 30 mm/century to 30 cm/century as a consequence of the deforestation of the surrounding land for agricultural and pastural use during the 16th and 17th centuries.[28,29] Another ancient activity that developed in the Mar Menor area, beginning in 2000 B.C., was mining (argent, iron, lead, zinc, copper, and nickel among other minerals) in the southern mountains. The maximum extractive capacity occurred from 1960 to 1980 but mining continued until 1990. Waste from the barren mining lands was emptied into watercourses flowing into the south side of the Mar Menor until 1950. It was then diverted to silt Portman Bay (64 ha, 20 m depth) on the Mediterranean coastline facing the south. Although mining waste to the Mar Menor was stopped more than 50 years ago, the heavy metal concentration in sediment, specially at the southern part of the lagoon, still remains high and constant (mean values ≈ 2000 μg/g of lead and zinc)[28–30] (Figure 9.3.8).

Two marginal lagoons are at present used for salt mining. Another four lagoons experienced either a natural process of filling up by sediment or were dried for agricultural use or urban development. This process has contributed to the reduction of the Mar Menor surface (from 185 km^2 in 1868 to 172 in 1927, 138 in 1947, to 135 in 1969 with slight reduction since then (Figure 9.3.9) and a reduction of depth (Figure 9.3.10)).[5,29]

Records of the first tourist settlements date from the first half of the 19th century. Since then the lagoon has attracted an increasing seasonal population. The census of local population that lived year round in the Mar Menor for the year 2000 was 45,584 people whereas the stable tourist population during the high season (July to September) was estimated at about 450,000 people; together with the number of summer

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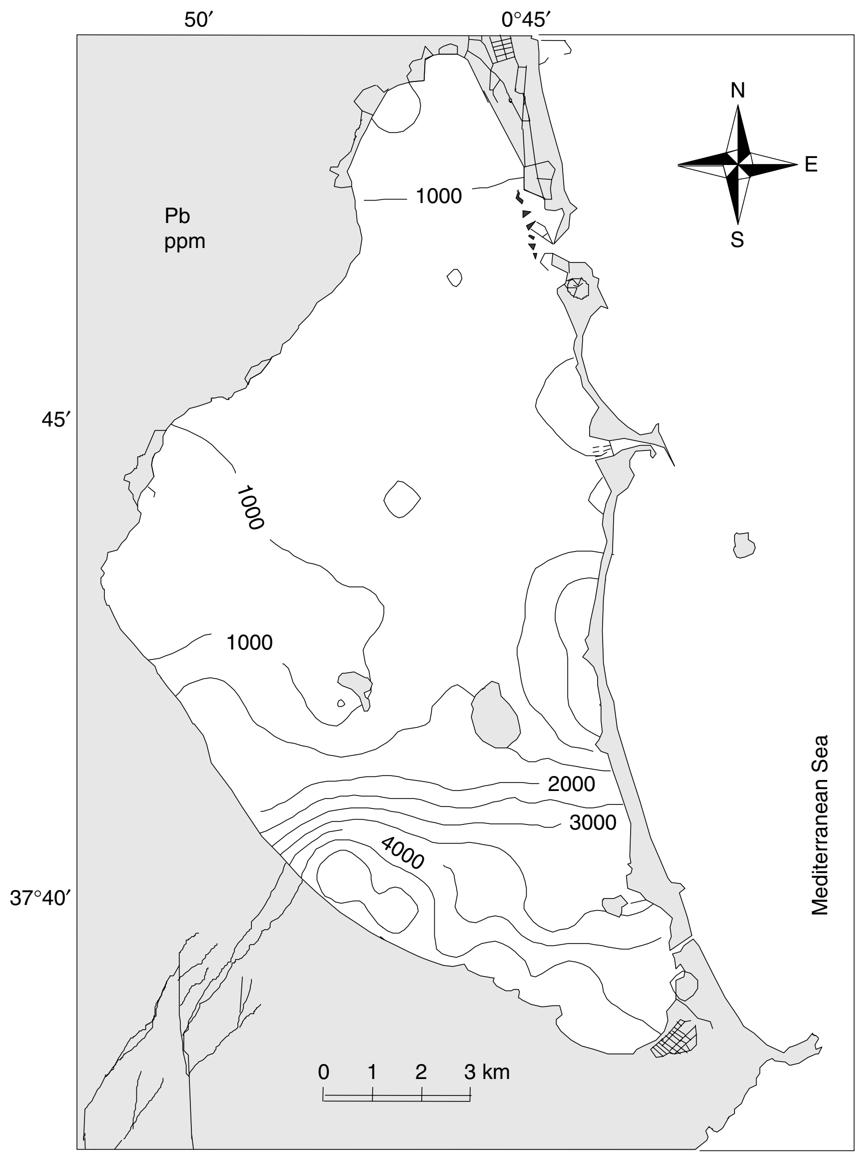

FIGURE 9.3.8 Concentration of lead in sediments of the Mar Menor Lagoon.[28]

visitors approximately 748,211 people generated revenue of 198.4 million €.[31] The construction of tourism facilities has grown in parallel with the seasonal population. New roads, one of which connects Ciervo Island to La Manga, and highways surrounding the lagoon have been constructed recently. Between 1937 and 1976 the built-up lagoon perimeter increased from 12 to 54%, and to 56% in 1986 and 64% in 1994 (Figure 9.3.9). There are nine yachting harbors, lodging 2784 boats, located along the

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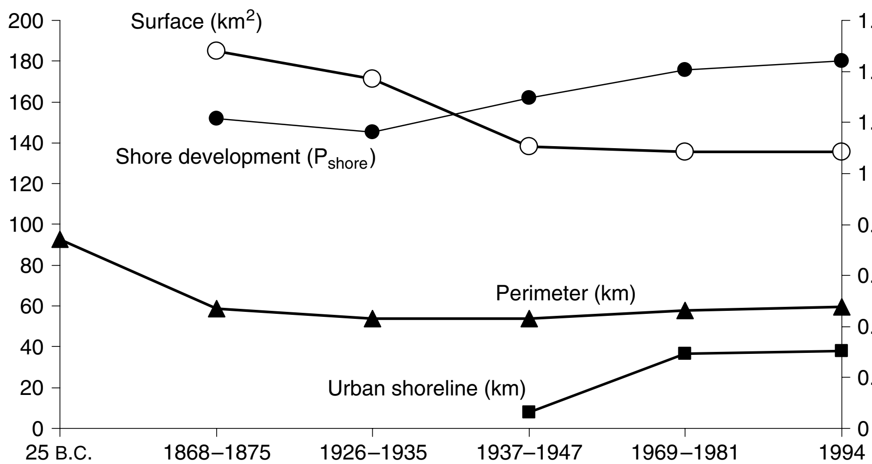

FIGURE 9.3.9 Evolution of the perimeter and surface of the Mar Menor Lagoon from 25 B.C. to the present. Loss of surface and perimeter up to the 19th century probably was related to segmentation processes and fill-up of marginal embayments by erosion of surrounding lands. During the 20th century the surface still decreased but the perimeter increased as a consequence of land reclamation for different human uses. This led to an increase in the shore development index and a corresponding increase in the vulnerability of the system.

lagoon's coastline, some of them less than 800 m away. At present, the major urban development takes place inland, perpendicular to the coastline.

Other tourism facilities include land reclamation for construction of new beaches and promenades, with land reclamation on the order of 270,275 m^2 with 640,456 m^3 of sand, much of it extracted from inside the lagoon during 1987–1988. This action caused an environmental stress exploited by opportunist species such as floating masses of *Chaetomorpha linum* and meadows of *Caulerpa prolifera* in some areas. As a result, clean sandy bottoms were replaced by muddy ones with increased organic matter,[32] causing a change in the species composition of the benthic fish assemblages. At present, a new land reclamation of about 500,000 m^2 is planned to create and expand beaches at the inner part of La Manga.

Only one navigation channel (El Estacio) connects the Mediterranean Sea with the lagoon. That channel was artificially created by dredging and widening one of the *golas* up to 30 m wide and 5 m deep at its minimum section during the early 1970s. Opening this channel caused the major changes recorded for the lagoon dynamic. The modification of the renewal rate of the water changed its physical and chemical properties, mainly salinity and extreme temperatures, permitting access to new colonizer species, thus altering the lagoon's community structure with detrimental effects on fisheries.

On the other hand, the agriculture on the watershed has experienced a deep transformation in the last 15 years by changing from extensive dry crop farming to

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intensively irrigated crops receive that surface waters diverted from the Tajo River, 400 km north, to the Segura River, since 1986. Arrival of surface water for irrigation lessened the aquifer's overexploitation, thus raising the phreatic levels[33] and helping the main watercourse on the watershed maintain a continuous flow (about 24 l/sec) fed by ground water with high nitrate levels to the lagoon. Due to overfertilization with nitrogen and pesticides used in agriculture, this flow is at present the main entrance for nitrate into the lagoon and influences for pesticide into the trophic food web.[34]

Not all human works on the coastline have had negative effects on the biological assemblages. Some of the actions, like building up of small piers made of wood, sometimes on concrete pillars—a component of the traditional Mar Menor landscape—have provided hard bottoms and shadow habitats favoring the settlement and development of sciaphilic assemblages, thus increasing the lagoon biodiversity. Such communities consist mainly of suspension feeders such as sponges, cnidarians, briozoans, and ascidians,[9] which actively contribute to maintaining the water quality.

9.3.3 Main Changes Affecting the Lagoon's Ecology

Two of the above-described human-induced changes have had, and continue to have, significant impact on the lagoon dynamic transformation. On the one hand, changes in hydrodynamics due to the enlargement of the Estacio Channel in 1972 produced an increase in the water renewal rates, decreasing salinity and lower extreme temperature, thus permitting access to new, mainly benthic and nectonic colonizers, in the process of *mediterranization* of the lagoon (Figure 9.3.7, Table 9.3.3). Decreases in salinity values were observed from then until 1988 with the increase in colonizers such as the algae *Caulerpa prolifera*. On the other hand, changes in the nutrient inputs regime are, at present, producing a chain of changes affecting mainly water quality, benthic vegetation, phytoplankton, and gelatinous plankton. A more detailed description of these changes is provided in the following section.

9.3.3.1 Changes Induced by Water Renewal Rates

As mentioned earlier, the hydrographic conditions of the Mar Menor have changed in the course of its geologic history depending on the sea level fluctuations and the development of the sand barrier and communication channels with the open sea with

TABLE 9.3.3
Influence of the Enlargement of the El Estacio Channel on Some Hydrographical Features of the Mar Menor[32]

	1970	1980	1988
Outflow of water to the Mediterranean (m^3)	3.6×10^8	6.1×10^8	6.4×10^8
Inflow of water from the Mediterranean (m^3)	4.5×10^8	7.2×10^8	7.3×10^8
Residence time (years)	1.28	0.81	0.79
Temperature range (°C)	7.5–29	12–27.5	12–30.5
Salinity range	48.5–53.4	43–46	42–45

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the last episode corresponding to the opening of the El Estacio Channel in 1972. Biological assemblages of the Mar Menor have been changing as a function of the degree of isolation and environmental conditions. Salinity increased after the last sea level regression in the Quaternary and the progressive isolation of the 18th century, reaching a maximum of 70 at the end of the century. After that period there were several sporadic storms breaking the sandy bar leading to changes in salinity thus allowing the colonization of several species, mainly fishes (striped sea bream, gilt-head, sea bream).[35,36] The last of these, which occurred in 1869 and was probably reinforced by the opening of an artificial channel of communication with the Mediterranean to be used for fisheries (the Marchamalo gola in 1878), caused a significant decrease in salinity from 60–70 to 50–52. This decrease resulted in a marked change in the lagoon biology with the introduction of several species of submerged rooted vegetation—*Cymodocea* and *Zostera* throughout the basin and occasionally *Posidonia oceanica* in sandy areas of the south—and more than 30 new species of molluscs and fishes that became established in the lagoon.[29] A similar process took place after the opening of the El Estacio Channel. The above-mentioned increase in the renewal rate allowed the colonization of new marine species with a twofold increase in the number of molusc and fish species in the last 15 years.[9,13] As a consequence of the same process the allochtonous jellyfish species *Cotylorhiza tuberculata* and *Rhizostoma pulmo* entered the lagoon from the Mediterranean in the mid-1980s.[9] After an initial period of slow growth, their population grew to massive proliferations. They also became pests as a consequence of the changes in the trophic status of the lagoon, resulting in serious inconvenience to tourism (see below for details).

In this way, an increase in the water renewal or interchange rates with the open sea is thus translated into an increase in the number of species inhabiting or visiting the lagoon (Figure 9.3.11). Related to this, changes in water renewal rates have also

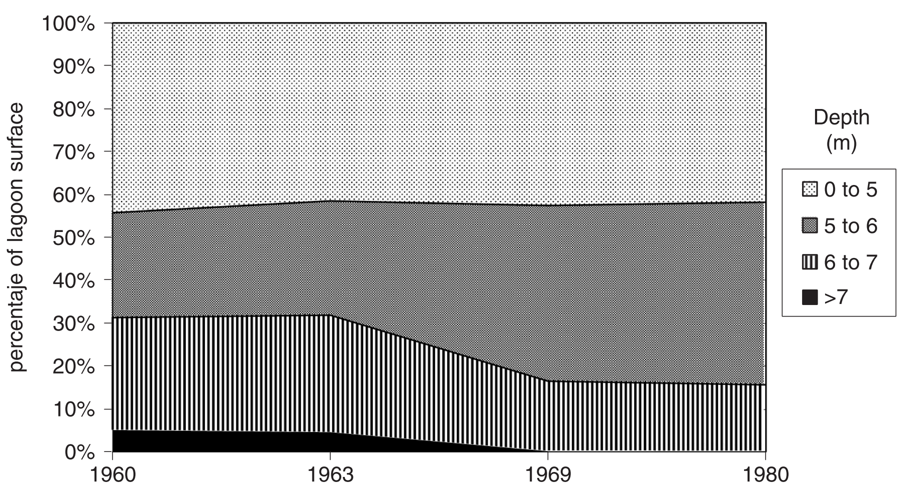

FIGURE 9.3.10 Evolution of the depth distribution in the Mar Menor Lagoon. The maximum depth of 7 m disappeared after 1969 and areas with a depth greater than 6 m now represent less than 20% of the bottom surface.

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provided replacement of some facies in given communities. Assemblages of *Ceramium ciliatum* var. *robustum* and *Cladophora* sp. recorded previously[37] in photophilic community on the rocks were mostly replaced by facies of *Acetabularia acetabulum, Jania rubens, Padina pavonica* and, in some zones, by *Laurencia obtusa.*[21] In recent years, some of these assemblases have been replaced by *Caulerpa prolifera*.

Two main mechanisms operate in these processes: the increase in the colonization rates of marine species (both in larval or juvenile stages and by migration of adults) and a reduction in salinity and the mitigation of extreme temperatures, thus permitting the establishment of alloctonous species to the lagoon conditions[38,39] (see Chapter 5 for a more detailed discussion).

Some of the most important changes affecting the physiography and functioning of the Mar Menor took place at the benthic meadows level. *Cymodocea nodosa* (Ucria) Ascherson, *Zostera marina,* and *Z. nana* meadows dominated the Mar Menor bottoms before 1970[28,40] with scant mats of *Posidonia oceanica* (Linnaeus) Delile found in some small areas. In 1980, however, it was possible to find only a few mats of *Posidonia* close to some of the small islands to the south and close to the mouth of the El Estacio Channel.[9,29] At present, the benthic vegetation on the soft bottoms of the Mar Menor mainly consists of monospecific *Caulerpa prolifera* (Forskal) Lamouroux meadows on muddy and some rocky bottoms, covering more than 80% of the bottoms, favoring high levels of organic matter in sediment and low oxygen concentration. Scarce patches of *Cymodocea nodosa* are now restricted to shallow sandy bottoms and more or less dense spots of *Ruppia cirrhosa* (Petagna) Grande remain in the shallowest and calm zones.[41] (See Figure 9.3.13.)

Spreading of the *Caulerpa prolifera* at the expense of the *C. nodosa* monospecific meadows has been progressive since the Estacio Channel opening, starting in the north basin with intermediate states of mixed *Cymodocea–Caulerpa* meadows.[41] Two related processes seems to be involved in this change: (1) changes in environmental conditions of the lagoon, mainly moderation of salinity and extreme temperatures, permitting the entrance of the algae *Caulerpa prolifera* and (2) and, perhaps, increasing stress in sediment and the increase of nutrients in water, in a second phase, thus giving competitive advantage to the algae over the seagrass *Cymodocea nodosa*.

Before the Estacio Channel opening *C. nodosa* was reported at all depths in the Mar Menor.[28,29,40,41] In the 1990s it was present above the 3.3-m isobath estimated as the critical depth for this species in this ecosystem at that time.[42] After the opening of the channel salinity dropped from 50–60 to 42–45 and the lowest temperatures are usually higher than 11°C, *Caulerpa prolifera* is sensitive to both salinity and temperature and cannot withstand temperatures below 10°C,[43] frequently reached in winter before the enlargement of El Estacio. It has almost continuous growth throughout the year and a high capacity to generate vegetatively a new thallus from any fragment swept away by the water thus conferring a high colonization rate. It seems that most probably *C. prolifera* entered into the lagoon when salinity and temperature were not limiting factors for it after the Estacio opening to settle progressively mainly on muddy bottoms. Instability of sediment also provides a competitive advantage to macroalgae in order to outcompete rooted vegetation. It seems that in the Mar Menor lagoon, both instability of sediment (dredging and pumping of sand, increase in sedimentation rates, increase in organic matter content)

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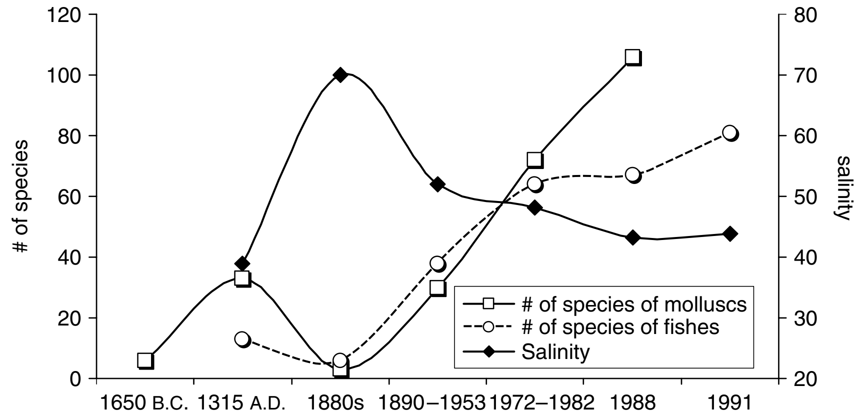

FIGURE 9.3.11 Relation between the number of species of molluscs and fishes and the salinity of the waters in the Mar Menor Lagoon. Mollusc data before 1950 correspond to stratigraphical study of sediments by Simonneau.[28] Data for fishes for the same period come from works on fisheries[35,36] and probably underestimate benthic cryptic species, mainly for median age. Estimation of salinity in ancient time was based on historical data for the open conditions of the lagoon, which maintained a higher water surface level and active commercial navigation through its golas.[62]

and overenrichment of nutrients in the water, in a second phase, acted in a synergistic way on the colonization rate of the *C. prolifera* up to the point of occupying most of the lagoon bottoms (including rocky substrates) at present. Instability of sediment was mainly caused by dredging of parts of the lagoon bottoms, the fill in of some beaches, and the inputs of terrigenous allochtonous materials from torrential rains, whereas nutrient enrichment was mainly due to urban and agricultural waste waters.

Despite, or probably because of, the increased biodiversity in the lagoon there was a decrease in some fish production and catch. The colonization increase at the end of the 19th century resulted primarily in a decrease in grey mullet. The enlargement of the E1 Estacio Channel in 1972 caused a decrease in Mugilidae and *Sparus aurata* (Figure 9.3.12). These changes have been related to the increase in interspecific competition and to changes in sediment properties and the bottom environment.[32,44]

9.3.3.2 Changes Related to Nutrient Inputs

Recent history of nutrient inputs into the lagoon has been closely related to urban, industrial, and agricultural development, either on the coastline or on the watershed, respectively. The eutrophication process, which has been described in many systems with observational rather than experimental data in coastal lagoons, starts with the increase in nutrients following a general trend in which seagrasses are replaced by macroalgae as the first step, and later small phytoplankton cells are replaced by larger ones, that shade the bottom and hinder the submerged vegetation growth with decomposition of benthic organic matter and subsequent production of anoxia at the sediment level and in the water column afterward (see Chapter 5).

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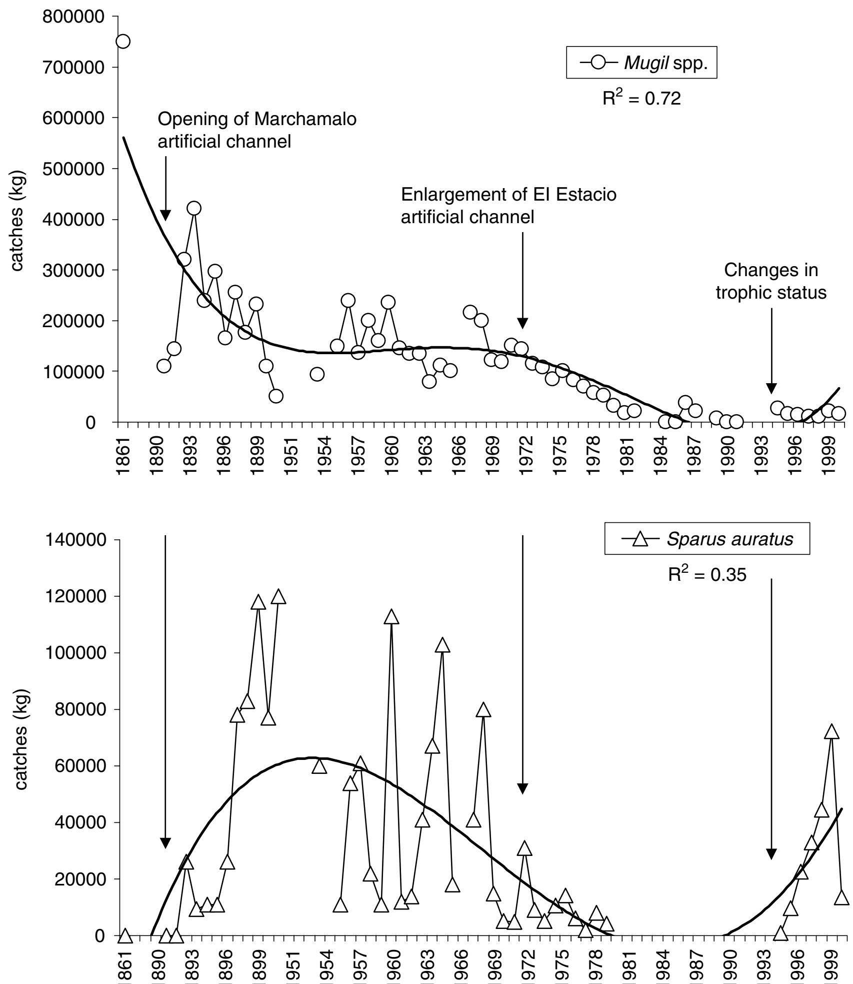

FIGURE 9.3.12 Evolution of catches of *Mugil* spp. and *Sparus auratus* in the Mar Menor lagoon. Fisheries are artisanal and the fishing effort can be considered relatively constant over time.

Physical, chemical, and biological data recorded for many different Mar Menor programs over the years show some deviation from the rather classical pattern of the eutrophication process. As mentioned above, the intensive tourism urban development started in the early 1970s, especially on La Manga. By that time, the Estacio Channel was opened and the largest yachting harbor in the lagoon had been built. Simultaneously, summer residential areas were also built on the lagoon's western coastline. Wastewater treatment plants were installed in the main villages by the mid-1980s, but sewage overflows in many residential areas were, and still continue to be, filtered into the lagoon after primary treatment. Urban sewage is usually considered the main source of phosphorus in

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many Mediterranean coastal lagoons[45] while agriculture is frequently considered the main source of nitrogen. By the time urban wastewater treatment plants were operational, agriculture started to change from dry crop farming with low amounts of nitrogen fertilizers to intensive crop irrigation with nitrogen overfertilization. During the dry agriculture period, nitrogen was the limiting nutrient for both benthic[42] and planktonic primary production in the lagoon with nitrogen entering mainly via run-off and phosphorus entering through urban sewage.[20]

In the 1970s, the Mar Menor was oligotrophic, and primary productivity was mainly benthic with the phanerogam *Cymodocea nodosa* as the main macrophyte. During the early 1980s, after the enlargement of El Estacio, the bottoms were covered by a mixed meadow of *Cymodocea nodosa–Caulerpa prolifera*, with a biomass of about 280 g dw/m^2 (Figure 9.3.13).[21,41,42] By the early 1990s a dense bed of the invasive macroalgae *Caulerpa prolifera* covered most of the bottom, restricting the seaweed *Cymodocea nodosa* to patches in the shallowest areas. The high benthic macrophyte biomass contrasted with the low phytoplanktonic density[46] and the oligotrophy of the waters.[20] Based on data from the mid- to late 1980s it was estimated that 63.18% of the total primary production of the lagoon was due to *Caulerpa prolifera*, 0.42% to *Cymodocea nodosa*, and 0.24% to photophilic algae, with 11.62% due to microphytobenthos, and 24.53% to phytoplankton.[42]

Changes in the trophic status of the lagoon waters can be seen by comparing two extensive time series (weekly sampled): one for 1988 and the other for 1997. The time series of 1988 showed that nitrate concentrations were low thoughout the year, in contrast to the higher phosphate values. It also showed the seasonal variation in the trophic state of the water due to different nutrient input regimes: nitrate mainly in winter via run-off and phosphorus mainly in summer via urban sewage. While nitrate concentration during 1988 (Figure 9.3.14A) was always under 1 µmol NO^-_3/l, much higher concentrations occurred in 1997 (Figure 9.3.14B), particularly during spring and summer (just at the harvest time when larger amounts of fertilizer are used in the lagoon's watershed) entering mainly through the major watercourse (El Albujón) due to the rise of the phreatic levels, as explained above. During 1997 higher nitrate concentrations were usually found on the west coast of the lagoon, close to the mouth of the main watercourses, while lower concentrations were found on the inner coast of La Manga and the El Estacio Channel influence area (Figure 9.3.15),[47] suggesting that nitrate input was related to the agricultural activity.

Drastic changes in phosphate levels were also found between 1988 (Figure 9.3.14C) and 1997 (Figure 9.3.14D). The seasonal distribution of phosphate found in 1988 was not evidenced in 1997, with much lower values probably due to the effect of wastewater treatment plants. The spatial distribution of phosphorus in surface waters, on the other hand, showed maximum concentrations close to the point sources (waste pipelines) of the main wastewater treatment plants in La Ribera and Los Alcázares (in this case through the Albujón watercourse) (Figure 9.3.16) probably due to treatment plant malfunctions. In 1997 the N:P ratio changed drastically as a consequence of higher nitrate load and phosphate removal, with phosphate becoming the limiting factor for planktonic productivity. As a consequence of changes in the nutrient input regime, the water column in the lagoon changed from moderately oligotrophic to relatively

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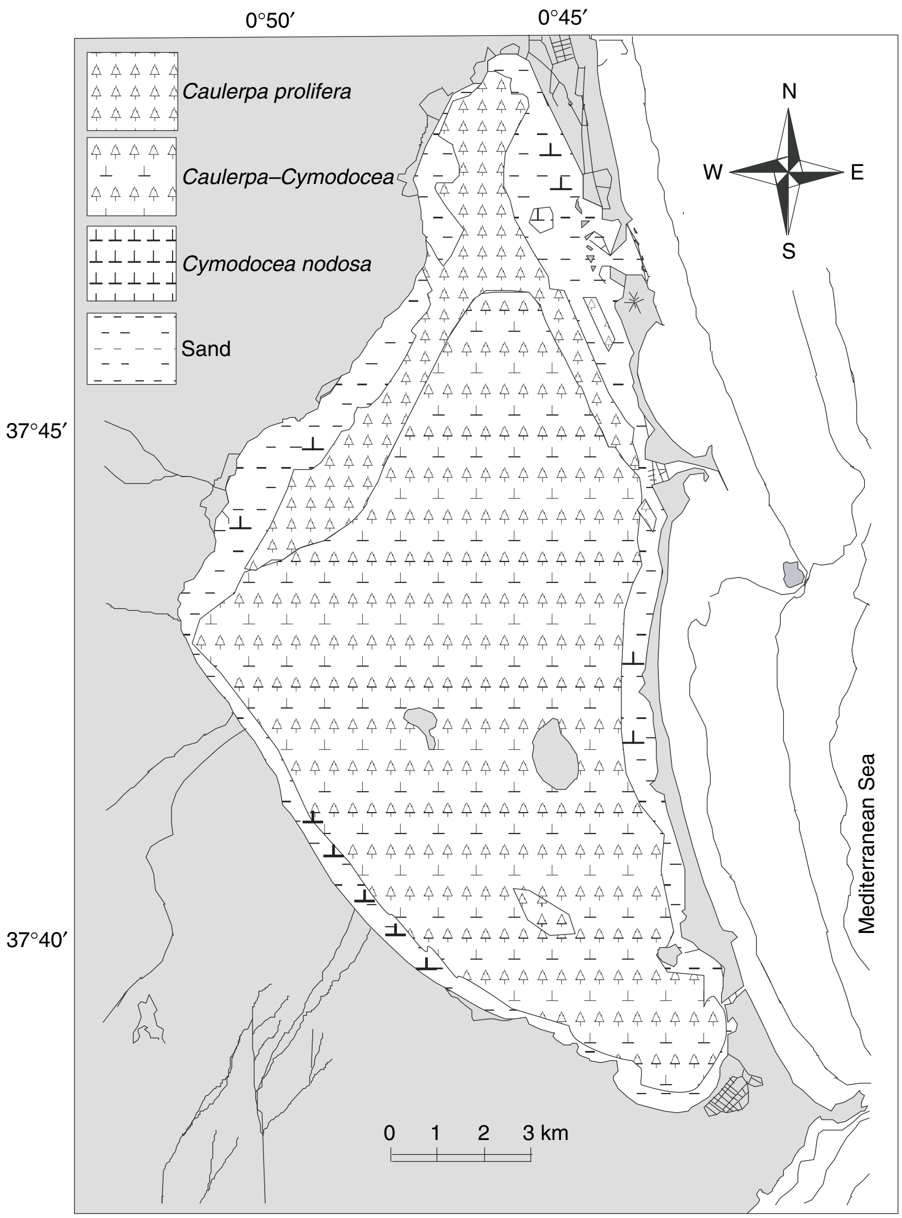

FIGURE 9.3.13 Distribution of macrophyte beds at the Mar Menor lagoon in 1982, showing the broad expansion of the algae *C. prolifera*.[9]

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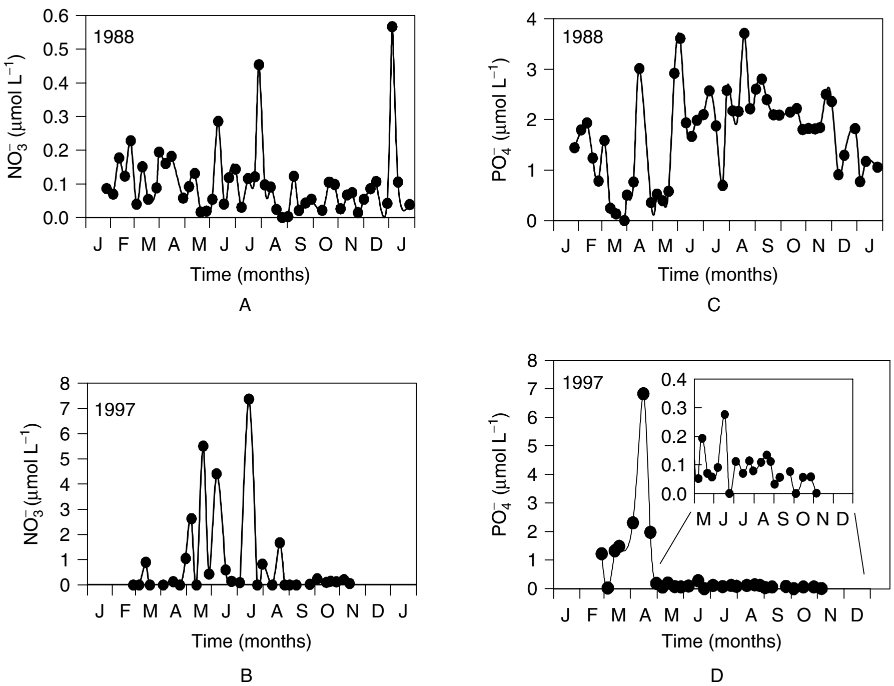

FIGURE 9.3.14 Comparison of nutrient levels in the water column of the Mar Menor lagoon in 1988, under oligotrophic conditions, and in 1997, after changes in agriculture in the surrounding lands. (A) Nitrate concentration, 1988; (B) nitrate concentration, 1997; (C) phosphate levels, 1988; (D) phosphate levels, 1997.

eutrophic, providing conditions for growth of larger phytoplankton cells and subsequent changes in the trophic structure.

Planktonic communities are highly dependent on the nutrient status. As mentioned previously, the seasonal distribution of the main taxonomic groups in terms of density in 1988 reveals that smaller flagellates (*Rhodomonas* and *Cryptomonas*) were numerically the most important phytoplankters in winter, whereas in the period from spring to fall diatoms reached their maximum values with dinoflagellates appearing to be numerically more important in fall.

Although the seasonal pattern found in 1997 in the smaller phytoplankton fractions was relatively similar to the one found in 1988 there were differences in the large-sized phytoplankton cells compartment. Large diatoms such as *Coscinodiscus* spp. and *Asterionella* spp. were present throughout the year. These changes in cell size are in accordance with the ecophysiological theory based on the size-dependent nutrient uptake kinetics[48,49] and diffusion limitation of nutrient transport.[50,51] Similarities in the smaller phytoplankton fractions suggest that both the detritus pathway[52,53] and the microbial loop,[54] characteristic of shallow oligotrophic systems, still played with an important role in transferring energy to larger organisms.

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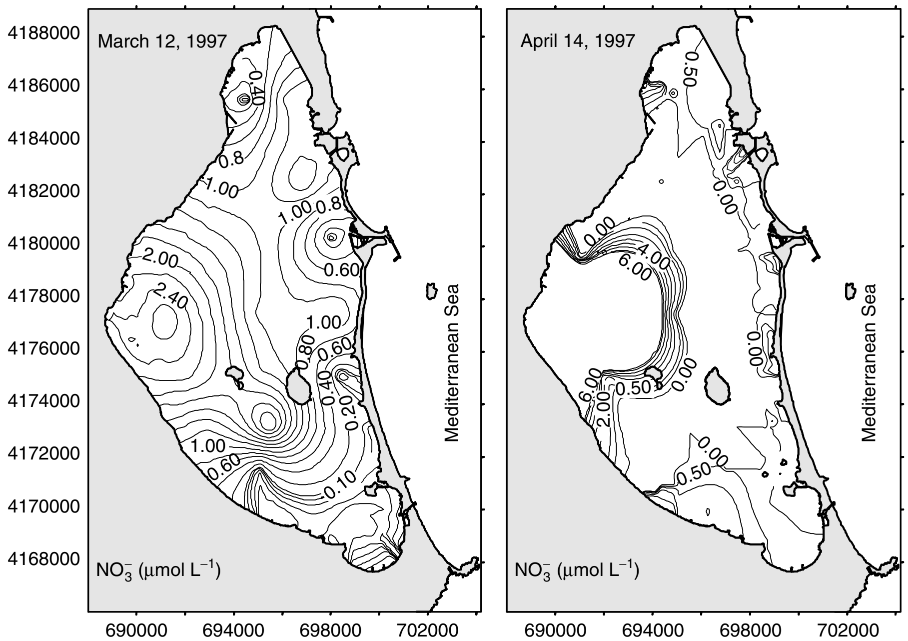

FIGURE 9.3.15 Distribution of nitrate concentration in the Mar Menor surface waters in two situations with different discharge intensity through the Albujón watercourse mouth.

In the zooplankton compartment, small heterotrophic flagellates were numerically the major component in 1988. They showed a seasonal trend with higher values in summer and lower values in spring and fall. At the microplankton level, oligotrich ciliates appeared without showing a clear seasonal trend throughout the year, whereas tintinnids exhibited increases mainly in summer. Eggs and veliger larvae, on the other side, exhibited a strong seasonal trend whereas other larvae of benthic organisms (mainly Bippinnaria and Auricularia) occurred in lower numbers during periods of maximum temperature. Copepods were mainly represented by three species: *Oithona nana, Centropages ponticus,* and *Acartia* spp. (mainly *latisetosa*). They remain relatively constant throughout the year except for the warmer water period in which a steady decreasing trend is observed, which increases later upto the beginning of winter. Massive proliferation of copepods (>1000 indiv./l), mainly due to *O. nana*, may easily take place. Other large zooplankton, such as the appendicularian *Oikopleura dioica,* showed significant well-defined and well-characterized increases both in spring and at the beginning of winter. Again, at the micro- (20–200 µm size) and mesoplankton (>200 µm size) level, seasonal trends in 1988 and 1997 showed no large differences in taxonomic composition except in the gelatinous compartment. During the summer of 1997 there was a bloom of jellyfishes *Rhyzostoma pulmo* and *Cotylorhiza tuberculata.* Figure 9.3.17 shows the temporal distribution of jellyfish species during 1997. Each data point on the plot represents the mean density value estimated from 20 sampling stations spacially distributed. *Aurelia*

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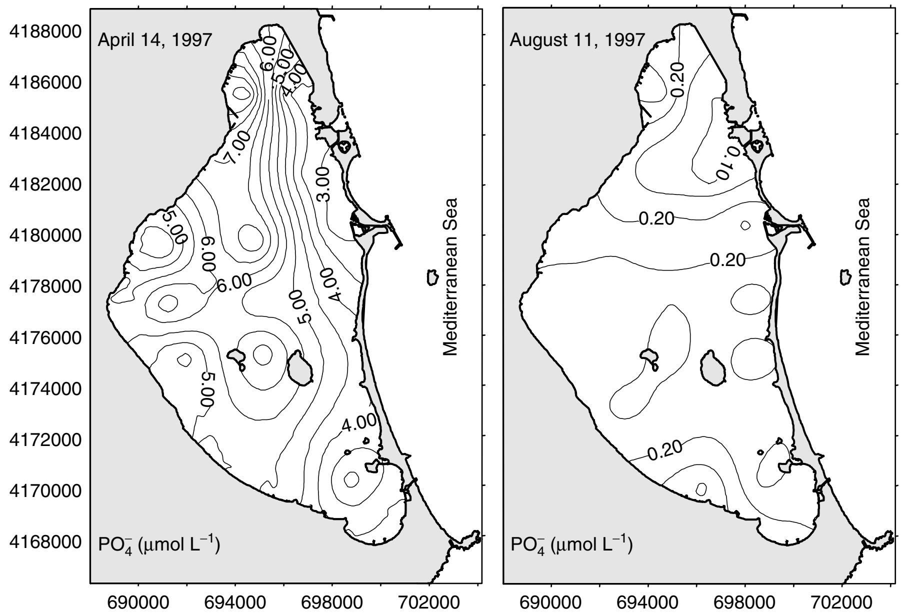

FIGURE 9.3.16 Distribution of phosphate concentration in the Mar Menor surface waters in two situations with different discharge intensity through the urban waste pipelines.

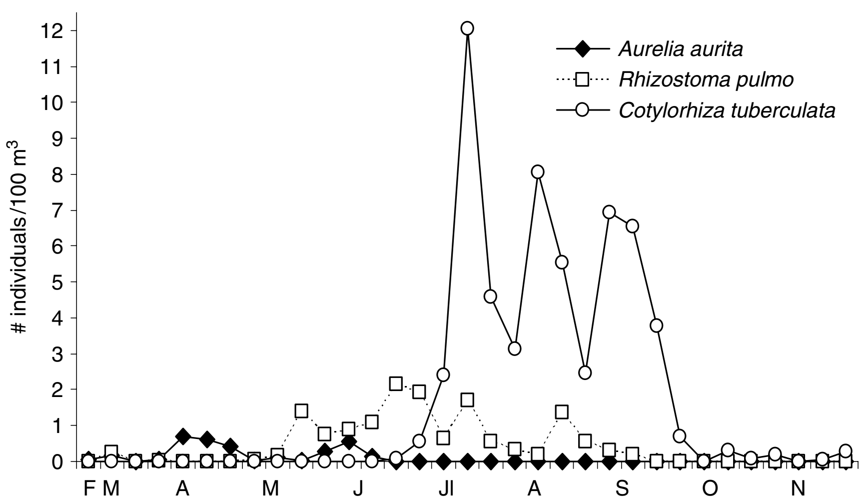

FIGURE 9.3.17 Temporal distribution of jellyfish species in the Mar Menor Lagoon in 1997. F through N = February through November.

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aurita, the only autochtonous species, is the less abundant and has its maximum abundance in spring (April and May). *Rhyzostoma pulmo* started to increase in May, while *Cotylorhiza tuberculata* peaked in abundance in June and July, reaching more than 12 individuals per 100 m^3. The total population of jellyfishes estimated in the lagoon by mid-summer of 1997 was on the order of 40 million.

Presence of large-celled phytoplankton in response to elevated nitrate concentrations has implications for the structure and function of the whole planktonic food web. The distribution of biomass in aquatic systems generally shows a regular decline in biomass with increasing organism size arranged in logarithmically equal size intervals.[55] The spectra slope has been related to the energy flow through the planktonic food web[56–58] and to the trophic state of the ecosystem.[59] Although the seasonal variation of the Mar Menor Lagoon's trophic state was also explained in the biomass size spectra study,[14] it was most interesting, nevertheless, to find that the interannual comparison of planktonic size distribution showed an almost invariable slope within a size range from 2- to 1000-µm equivalent spherical diameter.[47] The size range used for comparison excluded the jellyfish fraction (up to 40 cm in diameter). It can be seen, nevertheless, that this size fraction should play a major role in controlling the biomass spectra parameters. Jellyfish gut contents indicate clearly their preference for large diatoms (62–86%), tintinnids (3–33%), and copepods (1–3%).[47] High removal rates of larger plankton were expected in the Mar Menor Lagoon due to the large number of jellyfishes and their size-selective diet.

It is generally believed that nutrient loads stimulate primary production, thereby increasing planktonic biomass, but that was not completely true in our lagoon because of the top–down control of the planktonic food web by jellyfishes. It was paradoxical to find that chlorophyll *a* (Figure 9.3.18) and the total biovolume considered under the 2- to 1000-µm size range (Figure 9.3.19) was always lower in 1997—with higher nitrate loads, lower phosphate concentration, and very high densities of jellyfishes, than in 1988—with lower nitrate levels, higher phosphate concentrations, and where jellyfishes were not found—both at the same sampling station in the four spectra compared. The size spectra comparison suggests that jellyfishes can be an efficient top–down agent controlling the consequences of a eutrophication process.

In systems where nutrients are scarce, fast-growing small cells can provide available food for certain size ranges of grazers, resulting in relatively high densities of copepods. At higher concentrations of nutrients, large diatoms dominate, which copepods cannot eat. This means that the density of copepods is low to feed the largest zooplankton, such as fish larvae and jellyfish. As jellyfish gut contents indicate, high removal rates of larger plankton are expected in the Mar Menor Lagoon due to the large number of jellyfishes and their size-selective diet. While the origin of large diatoms in the water column can be explained as a direct consequence of nitrate loads, abundance of tintinnids, the second most numerically important of gut contents, feed mainly on bacteria, heterotrophic flagellates, and small phytoplankton cells. The effect of jellyfishes removing tintinnids can be seen as an indirect top–down control mechanism on small size fractions. By eating copepods, jellyfish also act indirectly on small phytoplankton, reducing the top–down control exerted by copepods on this fraction. Trade-offs between direct and indirect effects may explain why some eutrophic systems support viable populations of small-celled phytoplankton and large populations of

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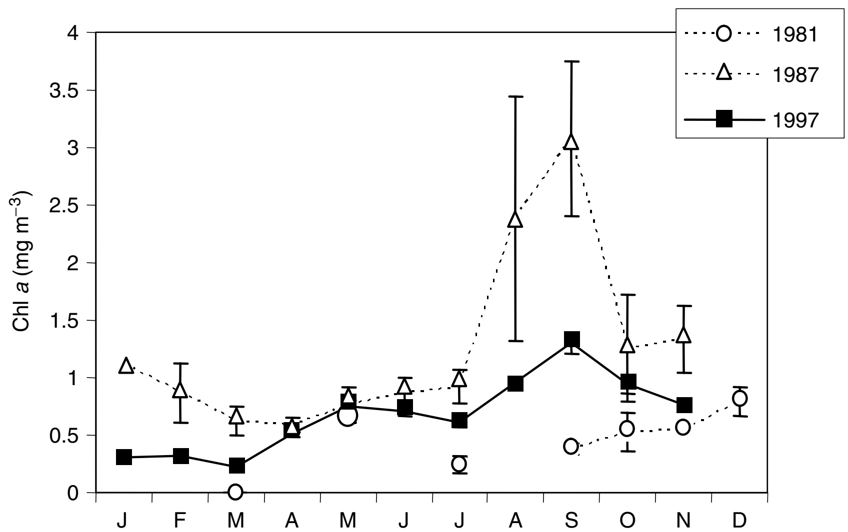

FIGURE 9.3.18 Interannual monthly variation of chlorophyll *a* concentration in the Mar Menor waters in three different trophic states: 1981 oligotrophic state; 1987 oligotrophic state with increasing urban pressure in summer time without urban waste treatments and without jellyfishes; and 1997 eutrophic state with continuous flow through the Albujón watercourse, with urban waste treatments and with top–down jellyfishes control. J through D represent the months of the year.

large gelatinous zooplankton. On the other hand, removing large diatoms has a direct effect on nutrient loads as they uptake inorganic nutrients from the water column, but the simultaneous removal of grazers such as ciliates and copepods reduces the predation pressure on smaller phytoplankton. The feeding preference of jellyfish imposes a combination of direct and indirect effects on the planktonic structure at different size levels. The trade-off between competition for available resources (bottom–up) and predation (top–down) control mechanisms[60,61] results in a planktonic size structure different from that thought to occur under eutrophic conditions.

The presence of such direct and indirect mechanisms controlling the planktonic food web make it necessary to know in depth the nature of those processes in order to establish causal relationships to be included in the eutrophication models. Knowledge about many of these relationships can only be acquired after implementation of long and detailed monitoring and scientific programs.

9.3.4 Suggestions for Monitoring and Modeling Programs

Obviously, to control the processes that lead to the degradation of the Mar Menor or any other natural environment, it is necessary to have in-depth knowledge of the nature of such processes and the causal relationships between them and human activities that cause them. Such cause–effect relationships, in general, are unknown and to establish

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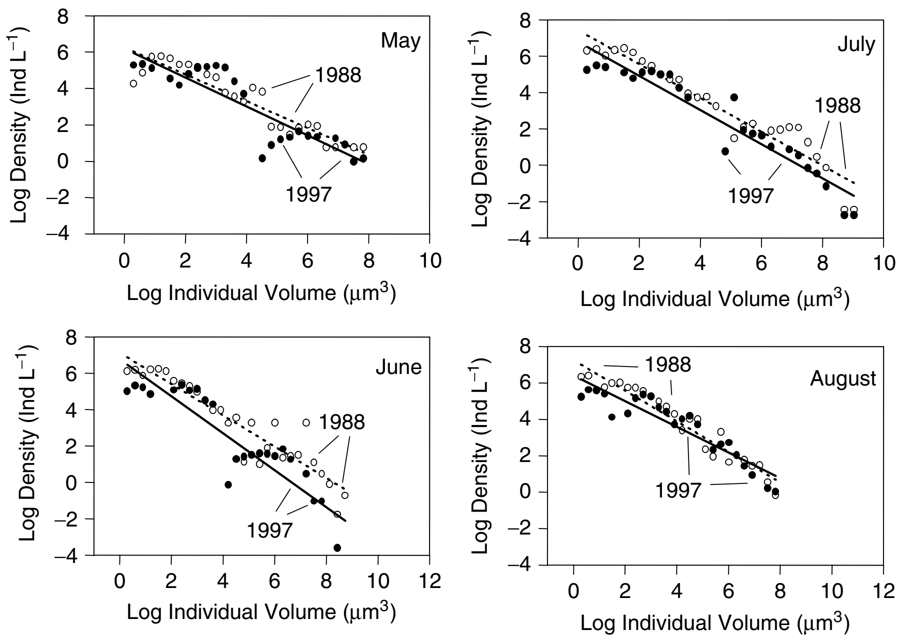

FIGURE 9.3.19 Comparison of biomass size-spectra in the planktonic food web of the Mar Menor between 1988, an oligotrophic state without jellyfishes (open circles, dotted regression line) and 1997, a eutrophic state that jellyfishes control (filled circles, continuous regression line).

them demands detailed monitoring programs, which are sometimes incompatible with the accelerated evolution of the lagoon, forced by human-driven activities.

In the case of the Mar Menor, difficulties in the establishment of such cause–effect relationships have been worsened by the lack of detailed studies and data on the hydrographic conditions and biological assemblages before most human interventions. Furthermore, although in recent years the increasing demands on the Mar Menor coasts has led to the elaboration of *Indicative Plans of Uses of the Littoral* and distinct evaluations of the environmental impact of human activities in terms of the physical, biological, and human environment; however, in most cases, only superficial analyses of the marine environment have been made, and they are focused on satisfying minimum administrative or legal requisites instead of generating the knowledge required for adequate management.

In any case, the large amount of information compiled during the last 20 years permits us to establish general guidelines for such cause–effect relationships in order to draw conceptual models to assign priorities in managerial actions and research lines.

Figure 9.3.20 shows a diagram that relates three of the human activites in the Mar Menor discussed above: the enlargement of El Estacio Channel, the building of artificial beaches, and the building of sport harbors.[13] Many of the consequences of these activities involve potential risks to human use and the local economy. When the Figure 9.3.20 flowchart was created in 1994, the allochthonous jellyfish

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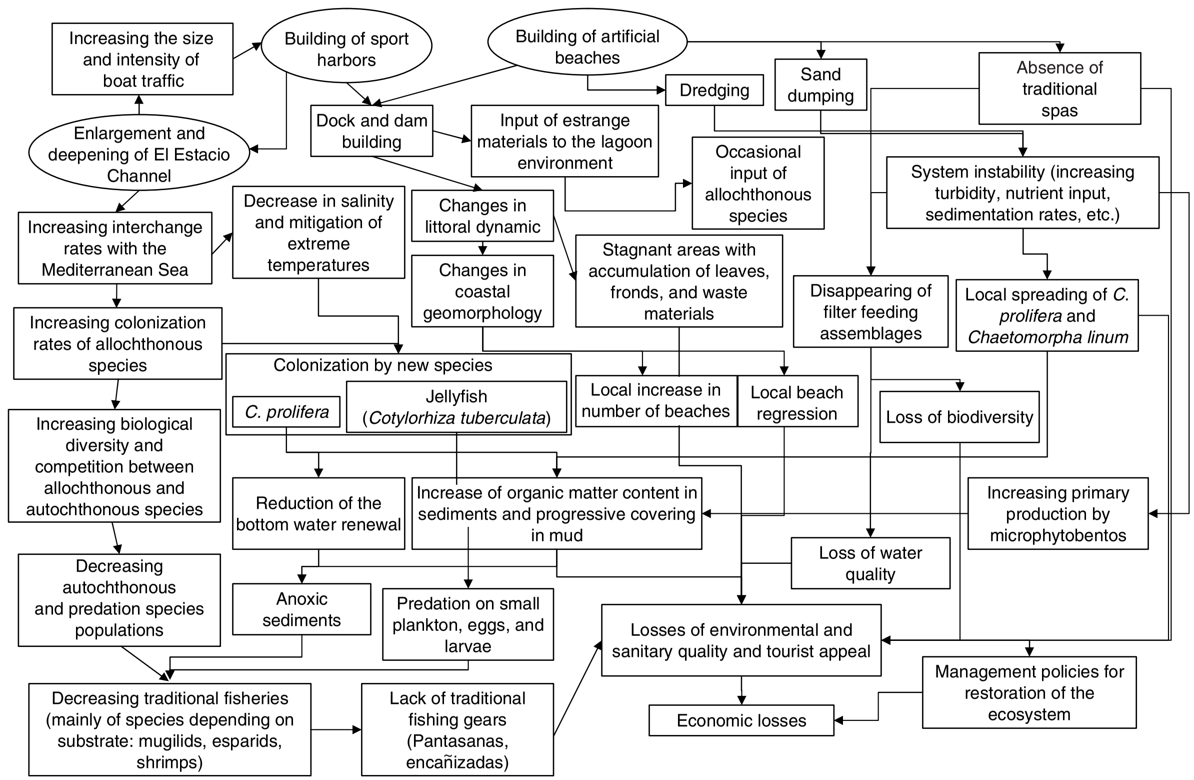

FIGURE 9.3.20 Conceptual model of cause–effect interrelationships derived from three human activities in the Mar Menor Lagoon: (1) enlargement of a communication channel with the Mediterranean Sea; (2) building of artificial beaches; and (3) construction of sport harbors.

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C. tuberculata was very scarce, but its very presence in the chart indicates that it could be a serious threat in the future if nutrient inputs became high enough.

On the other hand, legislation for protection and harmonizing of uses of the Mar Menor (*Protección y armonización de usos del Mar Menor*) or the establishment of specific statutes for protection, such as the one that exists for the salt mines area of San Pedro del Pinatar, will not be sufficient to stop the environmental damage of these singular spaces unless they are supported by a suitable management policy and a clear public awareness. Both must take into account that some urban-planning excesses, although attractive and with high short-term profitability, can shorten the life of lagoon ecosystems.

Any planning measure should define concise objectives for the use and exploitation of these environments; make an inventory of its natural resources; study the processes involved in the functioning of the ecosystem and of different subsystems (terrestrial, marine, interchanges with the open sea and surrounding systems); make an inventory of human activities and their influence on the ecological processes; classify the territory on the basis of previously defined objectives and its ability to sustain the different activities; establish the standards of environmental quality; and design monitoring plans and correction measures.

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