

Chapter 2

Pelagic Zone Subsystem of the Marine Ports Aquatories

In MPs aquatories ecosystems, the water mass is not only an environment in which the transport ways (waterways) for ships are built but also the biggest (by volume) and most dynamic biotope. The water column connects the main subsystems of ports ecosystems (pelagial, benthal and periphytal zones) and creates similar living conditions for the ecosystems' biotic components of MPs. The water volume in the Black Sea ports reaches dozens of million cubic metres and the thickness of the water layer can be 20 m and more.

The peculiarities of MPs ecosystems and their role in the entire marine ecosystem become evident when comparing them with the ecosystems of the adjacent sea zones in both present and past times.

Dredging and construction of hydrotechnical structures increase the depth, water volume and area of artificial hard substrata (HS) in MP, while the area of surface water and bottom sediments remains the same or even reduces. In some ports (Varna-West, Ilyichevsk and Yuzhny), construction of wide and deep permanent access channels, which connect the ports aquatories with the sea, has not only stabilized their hydrological and hydrochemical parameters, but also synchronized all main ecological processes with those of the adjacent sea zones. Major morphological peculiarities of the main Ukrainian Black Sea ports aquatories (Odessa, Ilyichevsk and Yuzhny), as well as Sevastopol Bay, are presented in Table 2.1. Figure 2.1 shows the schemes of Odessa, Ilyichevsk and Yuzhny MPs aquatories.

The ecosystems of all MPs of the Black–Azov Sea basin function in conditions of reduced water dynamics because of the natural or mixed (i.e. natural and artificial) protection of their aquatories. The distribution of organisms' complexes in all subsystems of MPs ecosystems is regulated, first of all, by light intensity, food quantity, hydrodynamics and oxygen content. Except for eutrophication, anthropogenic pollution of MPs aquatories usually has an episodic character and its own specificities in each MP. The food production is mainly determined by illumination. Oxygen content in water can be increased by: 1—adsorption from the atmosphere; 2—production by aquatic vegetation via photosynthesis; 3—input with rain.

Table 2.1 Major morphological characteristics of the main Black Sea ports aquatories of continental Ukraine and Crimea

Morphometric characteristics	Port			
	Odessa	Ilyichevsk	Yuzhny	Sevastopol Bay
Aquatory peculiarities and connection with sea	Divided into harbours with independent ACs	Single, with single AC	Single, with single AC	Single, with single AC
Aquatory length, km	3.0	7.2	7.3	7.0
Aquatory width, km	0.8–1.2	0.2–1.3	0.8–1.2	0.8–1.2
Average depth, m	9.5	7.5	9.0	12.0
Maximal depth, m	16.5	14.0	19.0	20.0
Aquatory area, km ²	2.7	5.7	5.8	7.7
Water volume, mln. m ³	26.0	45.0	50.0	90.0
Length of berths and breakwaters, km	18.0	8.0	7.0	16.0
Sectional area of the passage on aquatory, m ²	11,300	2500	3000	11,000
Areas of underwater surfaces of hydrotechnical structures, m ²	170,000	80,000	90,000	190,000
Ratio of water volume to area of underwater surfaces of hydrotechnical structures, unitless	153	525	535	473

The presence of various equipments and constructions, ships moored at berths of MPs and HTS contributes to the formation of wave, wind and light shadows. This phenomenon directly or indirectly influences the oxygen enrichment of MPs waters via effects on: adsorption from the atmosphere, photosynthesis and equilibration of its concentration in the water column. In MPs, the amount of solar energy per one m³ of water inevitably reduces during dredging.

Forces providing the natural hydrodynamics in MPs and forming currents (water motions) in the seas are usually divided into external and internal ones. The external forces are: 1—wind (wind-induced and drifts currents); 2—changes in the distribution of atmospheric pressure (baric currents); 3—changes in the relative position of Earth, Sun and Moon (tides); 4—influx of coastal and river waters and pile up of seawater, causing changes of the sea level at different shores and of the subsequent drainage flows.

In the Black–Azov Sea basin, the tidal phenomena are weak and do not usually exceed 10–15 cm [16, 108]. The internal forces causing flows are connected with the changes of physical state of water masses and, most of all, with changes of their temperature and salinity (gradient currents). In MPs aquatories, flows are created by moving ships (ship waves).

Flows of exclusively natural origin do not exist in seas. At detailed study, the strongest and most pronounced flows turn out to be complex ones [192].

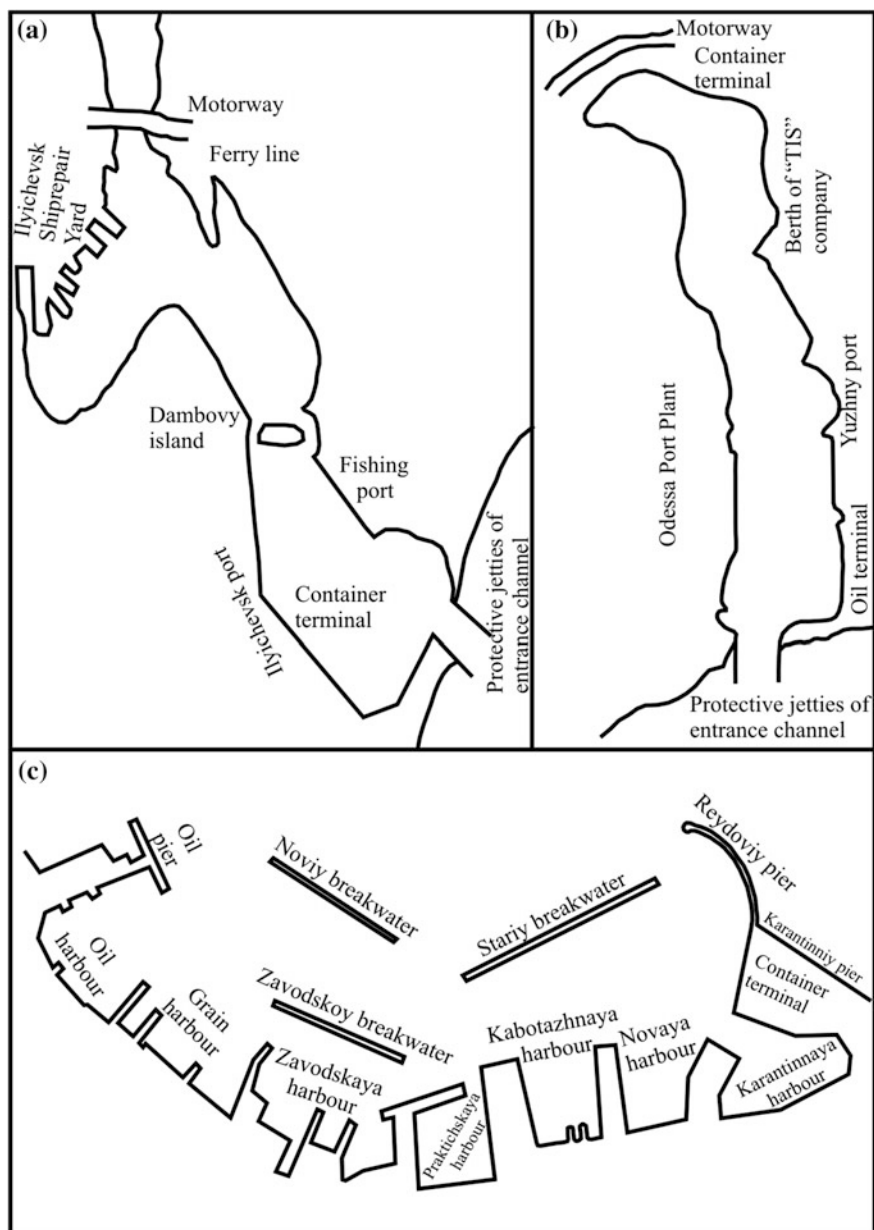


Fig. 2.1 Schematic plan of the main Ukrainian MPs aquatories: *A* Ilyichevsk, *B* Yuzhny, *C* Odessa

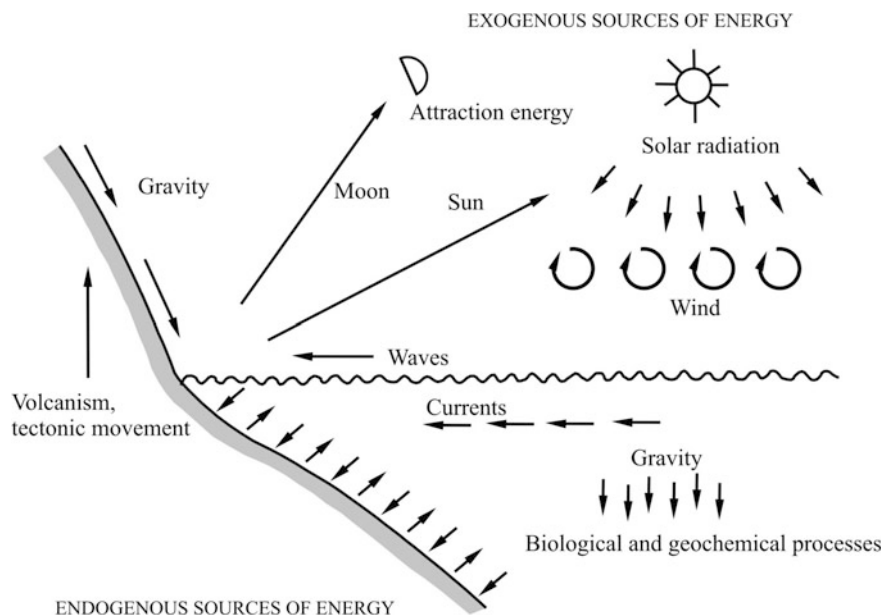


Fig. 2.2 Scheme of main energetic components of marine coastal shallow-water geosystems (according to [114, 133] with changes)

Figure 2.2 shows the main sources of energy controlling the dynamics of water masses in the sea coastal zones, including MPs aquatories.

In aquatories of MPs divided by moles and berths into separate harbours (e.g. Odessa, Novorossiysk, Tuapse and Constanza MPs), habitat diversity for hydrobionts is increased, but water hydrodynamics is much worsened. Each separate harbour has its special flow regime. The farther the harbour is situated from the passage into the MP, the higher is the possibility that its hydrodynamics will slow down to levels critical for hydrobionts. The above-mentioned wind, wave and light shadows contribute to the heterogeneity of conditions in harbours.

In an MP aquatory, a relatively small ship (according to modern standards) with a hull length of about 100 m and a width of 10 m could create a light shadow with an area of 1000–1500 m² depending on the height over water of the ship's hull and of the different Sun positions. Big ships with a hull length of 270–300 m entering the Black Sea ports create the light shadows of 5000–10,000 m².

The illumination of berths' vertical surfaces and of the water column near them depends on the duration of ships mooring at these berths. The more intensively berths are used, the less favourable are illumination and conditions for light-requiring micro- and macrophytes.

The light intensity and hydrodynamics are reduced on the inner side of HTS protecting MPs aquatories.

It was determined that, for a given light intensity, each macrophyte species grows better in a defined and rather narrow interval of water velocity. At lowering or increasing of water speed, biomass is immediately and significantly reduced. The same gradient of water movement exists along the vertical profile and changes not only the biomass, but also the size and age structure of population [2]. Thus, in MPs aquatories, the species composition and biomass of macrophytes, which depend on illumination and water velocity, can differ from those in the adjacent areas of the sea [87]. At the same time, some weakening of the hydrodynamics turns out to be favourable for many planktonic algae, whose development in the open sea and on open shores is limited by storms.

As it was already mentioned, the moored ships, various mechanisms and constructions at the berths and moles in ports form shadow zones that influence light intensity and duration of illumination, thus affecting the speed of photosynthesis and algal growth. In MPs, the light shadows can significantly influence these processes both in the water column (phytoplankton) and at the bottom and HTS lateral surfaces (microphytobenthos, macrophytes). The macrophytes biomass on the smooth-walled, vertical hydrotechnical constructions quite often does not exceed 10–50% of the biomass of the same species on natural HS [72].

In ecosystems, the artificial lowering of the dynamics of water masses always leads to mass development of some phytoplankton species, as it is clearly observed in reservoirs on big rivers. The lowered hydrodynamics of MPs aquatories is characterized by the absence of big waves and strong currents that damage plankton algae, thus frequently allowing them to reach quantities and biomass that cause water “blooms”. The coefficient of relative transmission of solar radiation depends on a number of factors, but water turbidity plays the major role. The mass development of phytoplankton during dredging works reduces amount of energy entering the water column. All other conditions being equal, the division rate of planktonic algal cells is directly proportional to light intensity. The increase of water turbidity in the upper horizon and in the zone of the density gradient (pycnocline), along with the presence of light shadows in MPs aquatories, can modify the depths having the optimal illumination intensity for micro- and macrophytes.

In MPs divided into single harbours, many berths are situated on moles forming various angles with respect to the shore and are quite often surrounded by water on three sides. In Odessa Gulf, the Sary, Novy and Zavodskoy breakwaters protect Odessa port from roughness and are washed from all sides. In general, breakwaters, moles, berths and docks of Odessa MP, as well as the corresponding HTS of other MPs of the Black–Azov Sea basin, can be considered as AR systems.

Constanza, Odessa and Yuzhny MPs have average depths up to 10 m and more and maximal depths up to 18–22 m. In the sea, such depths usually appear at 1–2.5 km distance from the shore. The deep depths are brought directly into the “land—sea” contact zone in spite of increasing gradually as it is usual in the NWBS. The presence of these depths forms preconditions for the development of thermo- and halocline vertical stratification of water masses. At the same time,

big depths directly at the shore prevent excessive heating of the whole water column, which is observed in the adjacent sea areas, during the summer months. MPs aquatories in the Black–Azov Sea basin artificially create conditions typical for the edge of the rocky deepwater shores, but with reduced wave action. The ships movements in MPs aquatories favour water mixing, which plays a positive role during the prolonged periods of calm in summer. However, the deeply immersed ships can also cause remobilization of the bottom sediments.

In MPs, a constant exchange of heat, gases, humidity and chemical substances (airions) occurs between the water mass and the atmosphere through the film of surface tension. The oil film (during oil products spills) and other films of different origin disturb these processes.

The water column is an environment connected with the food resources of MPs ecosystems: seston and dead organic matter (OM) in the form of suspended (SOM) and dissolved (DOM) organic matter.

In MPs aquatories, the most unfavourable conditions for inhabitants of the pelagial zone are found in the near-bottom layer of the deepwater zones and at zones of some harbours, dippers and inlets most distant from the passages and shipping channels. In many MPs aquatories, the hydrochemical and microbiological indexes of the water column are influenced by river run-off and discharges of rain, snowmelt waters, raw wastewaters and insufficiently treated sewage.

Except for the access channels to aquatories, the pelagial zone of MPs is confined on all sides starting from the film of surface tension to the surface of bottom sediments. In MPs, the different layers of the water column move with various speeds relatively to the HTS walls and periphytal. In the whole water column thickness, the water layer adjacent to lateral walls of moles and breakwaters, having a width of about 0.5–1.0 m, represents a contact, or ecotone, zone in which typical plankton organisms, larvae and young individuals of vagile invertebrates from the composition of periphyton and larval, newly hatched and juvenile fish occur. The distribution of various organisms in the MPs aquatories and in the water column is determined by hydrodynamics and by the organisms' ability to move horizontally and vertically as well as by the fear factor. The hydrobionts' communities of hyponeuston, plankton and nekton are distinguished in MPs pelagial. Phytoplankton composition includes phyto-, bacterio-, zoo- and ichthyoplankton.

According to various indexes, the MPs pelagial zone is vertically divided into the following horizons: 1—hyponeustal (0–30 cm)—the layer, immediately below the surface tension film; 2—epipelagial—the layer between the hyponeustal and the upper border of the pycnocline; 3—pycnocline layer; 4—bathypelagial—the layer between the pycnocline and the hydrogen sulphide zone; 5—the zone of hypoxia or anoxic zone—the near-bottom water layer, interested by formation of hydrogen sulphide. Settling, SOM concentrates along the isopycnic surfaces and at the bottom.

The pelagial zone connects all MP subsystems into ecosystems by unifying various general factors, abiotic and biotic connections and relationships.

During the analysis of abiotic and biotic peculiarities of biotopes and ecosystems of MPs of the Black–Azov Sea basin, attention is focused on the main Ukrainian

MPs aquatories: Odessa, Ilyichevsk and Yuzhny, located in the NWBS. Information about ecosystems belonging to the Russian Federation, such as Novorossiysk, Tuapse and Sochi MPs, located in the NEBS, was also used as well as information about Sevastopol Bay (located in Crimea), which serves as a base for military fleet and an aquatory for marine commercial port.

Odessa, Ilyichevsk and Yuzhny ports belong to the biggest MPs of the Black–Azov Sea basin and are located on the NWBS coast, which has an extension of about 50 km. This sea region is strongly influenced by the Dnieper, Yuzhny Bug, Dniester and Danube rivers. Odessa MP was constructed on the open seashore in Odessa Gulf and is protected from the sea by artificial HTS. After their artificial junction with the sea via constantly operating shipping channels, Sukhoy Liman (the aquatory of Ilyichevsk MP) and Grigorievsky (Maly Adzhalyk) Liman (the aquatory of Yuzhny MP) have been transformed into marine bays, with mainly natural protection from wind and wave impact.

According to hydrological and hydrochemical parameters, Odessa, Ilyichevsk and Yuzhny MPs belong to the Odessa region of the NWBS, which is delimited by the near-estuary zone of Grigorievsky Liman to the north and by the near-estuary zone of Sukhoy Liman to the south [20, 154]. Typical average values of hydrochemical parameters in this zone are as follows: salinity—16.3‰, oxygen content $\text{Type}=\text{"General_Pun"}>-6.75 \text{ mg dm}^{-3}$, oxygen saturation—69.5%, pH—8.21, phosphates— $25.3 \text{ }\mu\text{g dm}^{-3}$, organic phosphorus— $26.8 \text{ }\mu\text{g dm}^{-3}$, ammonia nitrogen— $85.2 \text{ }\mu\text{g dm}^{-3}$, nitrites— $2.9 \text{ }\mu\text{g dm}^{-3}$, nitrates— $15.2 \text{ }\mu\text{g dm}^{-3}$, organic nitrogen— $460 \text{ }\mu\text{g dm}^{-3}$ and silicon— $810 \text{ }\mu\text{g dm}^{-3}$ [154]. The temperature regime is very similar along the entire coast from Grigorievsky to Sukhoy Liman. Here, more or less favourable conditions for development of phyto- and zooplankton in the water column are observed during all seasons. Productive–destructive processes decline during the winter period because of the low temperatures, while periodical phenomena of hypoxia and anoxia in the near-bottom layer and at the bottom occur in the summer months [16, 162, 196].

Shallow shores with soft and loose sediments predominate in Odessa region. Because of the relatively shallow water of the region, the aquatories of Odessa, Ilyichevsk and Yuzhny MPs have shipping ACs with lengths of 2.5–3.5 km and freezing of the sea is possible in winter.

Novorossiysk, Tuapse and Sochi MPs located in the NEBS are built on the coasts of Krasnodar Kraiy (a region of Russian Federation). Novorossiysk MP is the northernmost among them and Sochi MP is the southernmost. The ports of the NEBS are located in climatic conditions milder than those in the NWBS, but some climatic differences are also present in this part of the Black Sea. In Novorossiysk region, air temperatures below 10°C can occur in winter, while negative air temperatures are very rare in the region of Sochi MP. During the coldest months (January and February), the superficial waters of Novorossiysk Bay can cool down to 0°C . The sea hydrological regime in Novorossiysk and Sochi regions is close to that of the open sea. The waves' fetch could exceed thousands of kilometres and the roughness is quite often strong, typical for an open sea. The river influence has local character. Because of the high hydrodynamic activity, salinity is less variable and

remains around 18.0–18.5‰. The longshore current is directed northwestwards and, in the area Novorossiysk—Sochi, the longshore drift flow has mainly the south-eastern direction [152, 161]. The NEBS ports are located in a region with deepwater shores and rocky sediments. In the aquatories of these MPs, wind influence and waves are weakened by artificial protective HTS.

Sevastopol Bay is located in the south-western part of the Crimean peninsula and, like Sukhoy and Grigorievsky Limans, is a water basin of estuarine type. In Sevastopol region, the shores are deepwatered with rocky bottoms.

All studied MPs are characterized by significant fluctuations of water level (1.0–2.0 m) caused by the strong offshore–onshore winds.

The ports of Novorossiysk, Tuapse and Sochi, as well as Sevastopol Bay, are located in regions with deepwater shores and, as a consequence, do not need long ACs. Channels with length of about 0.5 km are built in Tuapse and Sochi MPs. The shores here are rocky and edged by rocky bars, so that, unlike in the NWBS, there is no deficiency of HS of natural origin. Besides rocky sediments, clayey, silty, silty-sand, sandy, shell and silty-shell sediments are typical for the aquatories of Novorossiysk, Tuapse, Sochi MPs and Sevastopol Bay. In Novorossiysk MP, liquid silt without macrophytes is registered near the moles and berths at depths exceeding 8–10 m [83]. The black silt is characteristic for Odessa, Ilyichevsk and Yuzhny MPs, Sevastopol Bay, Novorossiysk and Tuapse MPs and, to a lesser extent, Sochi MP.

Only one passage lead into the aquatories of the above-mentioned MPs, except in the case of Odessa port that has three passages. The passages are delimited and protected from the wave action by moles of various constructions. In Sukhoy and Grigorievsky Limans, there are jetties protecting the passage. In Sevastopol Bay and Novorossiysk MP, relatively short moles project towards each other from both shores. The aquatories of Odessa, Tuapse and Sochi MPs are protected by extensive HTS.

Because of the discharge from major rivers, the NWBS is the less saline part of the Black Sea, where the mixing of freshwater and typical Black Sea waters varies according to hydrological situations in the various areas. Location and individual peculiarities of MPs aquatories bring their specificity into this process. However, in the warm period, the upper water layer is usually formed by the less salty and warmer waters. All concerned MPs are characterized by a more or less marked two-layered structure connected with the temperature and salinity differences between water masses. The freshwater and brackish water complexes of hydrobionts play various roles in pelagic and bottom communities of Yuzhny, Odessa and Ilyichevsk MPs. However, the distribution of the freshwater hydrobionts has a local character and representatives of marine Black Sea complex prevail during all seasons. The inflowing rivers have various influence on the aquatories of Sevastopol Bay, Novorossiysk, Tuapse, Ilyichevsk and Yuzhny MPs.

In MPs aquatories, anthropogenic activity artificially creates conditions which are typical for rocky deepwater shores, but with lowered wave action. The presence of depths of 8–20 m is a precondition for the formation of pycnocline and the characteristics of coastal shallow waters are partly or completely destroyed.

When designing new MPs and analyzing the environmental impact of existing ones, it is very important to collect information about the depth at which roughness stops its influence on bottom and ceases to stir up and displace not only sand, but also silty sediments. This depth is the so-called Cornaglia line or silt line [84, 104, 166]. Weakening of hydrodynamics in MPs aquatories leads to changes of Cornaglia line position, or to its disappearance.

Protection of MPs aquatories and OM accumulation in them frequently lower the water oxygen concentration to less than 2 mg dm^{-3} , which causes mass mortality phenomena [17, 40, 45].

Municipal sewage waters enter the aquatories of many MPs and, on average, carry faecal discharges of 75 g dry weight per person per day [17].

2.1 Main Abiotic Peculiarities

The MPs constructed on water bodies of estuarine type such as Varna and Beloslav Lakes, Sevastopol Bay, Sukhoy and Grigorievsky Limans have the largest aquatory areas in the Black–Azov Sea basin. The area of Constanza MP aquatory, located at sea coast, is 26 km^2 . The following important biotopes can be distinguished in the aquatories of all MPs: 1—water column; 2—artificial HS; 3—coastal shallow waters sediments; 4—sediments of the deepwater zones (8–20 m). Ecosystems of MPs aquatories are formed from the subsystems: 1—pelagial; 2—periphytal; 3—benthic.

The large communities of hydrobionts (hyponeuston, plankton—epiplankton and batiplankton—and nekton) inhabit the pelagial subsystem from the surface to the bottom. The population of periphytal and benthic zones is represented by micro-, meio- and macrozoobenthos, and micro- and macrophytobenthos. Bacteria are present in all these three subsystems and larval stages of many benthic organisms can be found in the pelagial. Daily migrations of invertebrates take place from the periphytal and benthic into the pelagial zone.

The periphytal subsystem comprises a permanent component represented by HTS underwater surfaces and a temporary one to which belong the wetted surfaces of ships' hulls. In the benthic subsystem, significant differences are observed between the coastal shallow waters and bars and the deepwater areas with regard to sediments' feature and hydrochemical indices. Because hydrobionts that realize primary and secondary production, transformation and reduction of OM are present in each of the subsystems, matter can be cycled more or less autonomously in each subsystem.

Owing to gravity, dead OM and mineral particles of various origin settle from the pelagial subsystem into the benthic one. Plankton animals, which realize biosedimentation, also participate in the same process. Organisms inhabiting the periphytal zone satisfy their food requirements by filtering seston from the water column. They release metabolites, faeces and pseudofaeces into the water and transform the unused OM and ashes into sediments. In MPs, inhabitants of the pelagial, benthic and periphytal zones interact via numerous links.

The nekton representatives (fishes and dolphins) as well as the large bottom invertebrates that are capable to move from MPs ecosystems into the adjacent sea zones, unite them into larger scale systems and realize the transfer of matter and energy. These links are strengthened by shipping navigation. Aquatic and semi-aquatic birds realize similar functions.

In the ecosystems of MPs aquatories, abiotic and biotic processes are tightly connected and their division has a mainly operational character.

Hydrodynamics, i.e. the totality of horizontal and vertical movements of water masses, is an exceptionally important characteristic for the existence of biotic components in the whole ecosystems in MPs aquatories or in their separate parts.

As for any other fluid, two regimes are observed during the movement of sea-water: laminar (or streamline flow) and turbulent. In laminar flow, the separate water layers move in parallel. On the contrary, the turbulent regime is more complex and comprises separate layers of laminar movement, transition regimes and totally turbulent regimes, i.e. swirling.

The transition from one regime to the other is important for organisms' movement in the flow, flow movement along attached or moving organisms and flow movement and interaction with substratum on which or in which organisms live.

As water flows around solid bodies and surfaces (or bodies move in water), a thin laminar film, often referred to as the boundary layer, forms on their surface. The thickness of this layer depends on roughness height and is usually equal to it. For organisms, the movement in laminar flow is energetically more advantageous than in turbulent flow. Organisms' movement in the water column is hampered by viscosity and facilitated by inertial forces that contribute to advancement. The shear force is always directed opposite to the direction of organisms and water flow.

Water mixing is mainly assured by turbulent motion, while laminar flow contributes to it only marginally. There are two types of turbulent mixing: frictional and convectional. The first one originates at the interface of two layers, which move at different speeds, when whirls caused by friction penetrate from one layer into the other. The intensity of friction mixing depends on the speed differences between separate layers and can occur in horizontal and vertical directions. The second one causes vertical flows and takes place as the result of changes in the specific water density connected with increase or decrease in temperature and salinity.

The transition from one water movement regime to another takes place at limiting, or critical, speeds specific for each layer.

The characteristics of viscous fluid flows can be described and compared using the Reynolds number (Re), which is dimensionless and defined as: $Re = \rho v l \cdot \mu^{-1}$, where ρ is the water density, v is the typical velocity of flow or organism, l is the specific linear dimension and μ is the water viscosity coefficient.

At low Reynolds numbers, pico-, nano- and microplankton organisms live in motion conditions which are close to laminar. The turbulent wind, commonly observed in seas, generates wind waves and flows on the sea surface, creates turbulence, forms a mixed (quasi-homogeneous) surface water layer and also heats or cools it off. In seas, the upper layer combines the paradoxical properties of highly

developed turbulence and homogeneity from one side and complexly ordered movements from the other [101, 137].

In seawaters, one of the convection mechanisms is the formation of the so-called “salt fingers”. It is caused by the contrasting influence of temperature and salinity on water density and by unequal speeds in turbulent heat conduction and salts’ diffusion [36, 60].

Owing to various water movements, the subsystems of MPs ecosystems (pelagial, periphytal and benthal) are functioning as a single whole. At the same time, the pelagial subsystem of MPs is also under the constant influence of the benthal and periphytal subsystems.

2.1.1 Main Peculiarities of the Water Exchange

The processes of water exchange occur between water basins and inside a water basin following the replacement of one water mass by another between its separate zones. Water exchange controls the passive transfer of hydrobionts, the transportation of matter which is necessary for synthesis of primary OM, the mixing, dispersion and removal of metabolites, the transport of oxygen from the upper layers to the near-bottom ones and the diffusion of pollutants.

In MPs with narrow aquatories, deeply cut into the land and with a ratio of about 0.5 between the passage and the aquatory widths, two vertically separated layers with opposite water flows are usually formed in the inlet channel. In MPs with relatively wide passages, an annular longshore flow is most frequently observed. This flow enters MP via AC and exits it at different points. In the semiclosed aquatories of some harbours, proper circulations often originate because of the cumulative influence of wind and differences in temperature and salinity [80].

It is well known that the speed of water exchange in natural harbours and artificially protected aquatories of MPs is closely related with the ratio between the depth of the aquatory incut into land and the width of the passage or passages. Thus, for ratios between 1 and 5, the speeds of water exchange usually allow normal functioning of MPs ecosystems. At bigger ratios, the water exchange could be insufficient.

The fewer are the passages into a MP aquatory, the more independent is its water mass on its regime and vice versa. The proportion between the width and depth of AC and passages into MP is an extremely important characteristic of MPs ecosystems.

The ratio of incuts’ depth into land to the passage width (i.e. the distance between natural delimiting capes or artificial protective moles) can be up to 10–20 in many MPs aquatories of the estuarine type such as Sukhoy and Grigorievsky Limans, Sevastopol, Kamishovaya, Uzkaya, Balaklava Bays and other. MP protecting structures located on the seashore (such as those found in Odessa, Yevpatoriya, Feodosia, Kerch, Berdyansk, Mariupol and other MPs) in fact model

the shoreline of the natural aquatory into land. However, the ratio between the width of their aquatories to the passage width is, as a rule, significantly less than in MPs with aquatories of the estuarine type.

In the artificially protected aquatories of MPs, water exchange processes and generation of upwelling phenomena have regular character at offshore winds and manifest in the same way as in narrow, natural limans and bays deeply cutting into land [105].

The formation of thermo- and halocline (pycnocline) is a self-sustaining process, which interrupts only at significant changes of external conditions. Various studies show that, on average, 90–99% of the produced turbulent energy dissipates and only 1–10% is spent for destratification [101].

The thermocline stops developing and progressively disappears at weakening of the heat flow into the sea (winter period) and strengthening of wind to stormy values (autumn-winter period). Both factors change the energy budget of the mixed sea layer in favour of turbulence whose increase reduces the stratification energy accumulated in the thermocline (pycnocline).

In the most stratified upper part of the pycnocline, the vertical gradients of all parameters (temperature, salinity, flow average velocity, turbulent energy) are so steep that this layer is sometimes compared to the water boundary layer near hard surfaces [101].

In MPs, the processes of water exchange are willingly reduced. Thus, the construction of the Northern and Southern moles in the 1970s reduced the width of the passage into the Sevastopol Bay aquatory from about 1200 to 415 m and the water exchange intensity by 40–70%.

As in other ecosystems, chemical substances secreted by bacteria, protozoans, micro- and macrophytes, metazoans into MPs aquatories could favour the development of some species and depress other ones. When excreted into the water, these substances become factors of the external environment both for the organisms which secreted them and for other hydrobionts. Such chemical communicatory signals regulate intrapopulation, intraspecific and interspecific interrelations. Owing to the confined nature of MPs aquatories, dispersion of these substances is hampered and the biota representatives respond to them in a manner different from that of the adjacent ecosystems.

The internal water exchange depends on dynamic processes and includes horizontal and vertical exchange of water masses between parts of a water body. Water movement, or flow, is one of the main factors determining the behaviour of invertebrates and fish in MPs biotopes (pelagic, periphytal and benthal zones).

A laminar, boundary sublayer about 0.1 cm thick develops on the open surface of the natural basins. This layer originates because, close to the air–water interface, the speed of water mixing reduces from turbulent diffusion down to molecular diffusion. The laminar boundary sublayer is characterized by very high gradients of temperature and concentration. Usually, it coincides with, or is included within, the boundary cold film which is up to 1 cm thick. Both these layers are in turn included into the layer subject to surface microconvection, with a thickness of about 10 cm [1].

Even in the hydrodynamically active open waters of the North Atlantic, the content of labile dissolved organic matter (labile DOM) is nearly eightfold higher in the surface microlayer (about 0.1–1.0 cm thick) than in the underlying layers. This situation confirms that dissolved and suspended OM and living organisms accumulate at the “water—atmosphere” interface [96].

In the protected MPs aquatories, films formed by entrance of various substances of anthropogenic origin (especially oil hydrocarbons) into sea environment are quite often observed besides films of natural origin.

Formation of pollution surface films in MP's protected aquatories causes several serious consequences: 1—reduction of the surface tension; 2—reduction of evaporation; 3—intensification of foam formation; 4—changes in the characteristics of capillary waves; 5—reduction of water surface roughness; 6—reduction of wind tension; 7—disturbance of thermal balance; 8—increase of matter ejection into atmosphere; 9—impact on wave processes and drift flows.

Benthic invertebrates inhabiting in quickly flowing water layers, as well as pelagic ones, are sensitive to changes in water masses dynamics. For them, the flow speed is an ecological factor of primary importance, because it is connected with renewal of the oxygen reserve in the near-bottom layer. The higher the flow speed, the quicker and bigger the inflow of oxygen to bottom-dwelling organisms [107]. For hydrobionts, the intensity of water mixing in water basins sometimes has even more importance than a high level of water oxygen saturation. Cases of invertebrates' mass mortality during the flow's interruption are known in basins with sufficient oxygen saturation. Death occurred as a consequence of poisoning by the organisms' own metabolites [107].

Flow's speed at the sediment–water interface and character of bottom sediments in MPs aquatories play a key role in the distribution of bottom invertebrates in biotopes. Their influence could be direct and indirect. Organisms' quantity and biomass per unit of water volume, bottom area or artificial HTS area depend on flow velocity. It is considered that the highest productivity of invertebrates occurs at water flow velocities between 0.3 and 0.9 m s⁻¹ [107]. Notably, the flow speeds in MPs aquatories are one- to twofold lower [16, 196]. The division of the MPs into separate harbours (such as in Odessa, Novorossiysk and Tuapse MPs) further weakens the internal water exchange.

The surface flows in the Black–Azov Sea basin are mainly induced by the wind pattern. They have the character of anticyclonic circulations and move in the Black and Azov Seas as a peripheral annular flow, which is directed counterclockwise with speeds up to 40 cm s⁻¹. Near the shore, the zone of coastal circulations extends up to 5 miles far from the coast itself. In this zone, the shoreline and shelf bottom configuration determine the direction and velocity of flows. The average flow speeds of the coastal circulations, ranging between 20 and 25 cm s⁻¹, have various impacts on MPs aquatories and on the shelf zones adjacent to them [161].

Wind also contributes to waves' formation on the water surface. Ripples, or ripple waves, appear at wind speeds up to 0.7 m s⁻¹ and are 3–4 mm high and 40–50 mm long. Gravity waves start forming at stronger winds. The size of wind

waves depends on wind speed, duration and fetch, but factors related to water bodies morphometry, coasts configuration, depth and bottom character are also important.

In the Azov Sea, superficial flows originate in the estuaries of Don, Kuban and other smaller rivers. In the Black Sea, the discharge current originating in estuaries of the big rivers (Danube, Dnieper-Bug and Dniester Limans) and in Kerch Strait contributes to the formation of superficial flows.

In the Black Sea, the following systems of flows are distinguished: Anatolian—in the region from the Bosphorus Strait to the traverse of Kolkhida lowland; Caucasian—from the traverse of Kolkhida lowland to Kerch Strait; Crimean—from Kerch Strait to Tendrovskaya spit; Rumelian—from Tendrovskaya spit to Bosphorus Strait. From Cape Kerempe (Turkey) one of the streams of the Anatolian current, going eastward from the Bosphorus, deviates northward towards Crimea. This branch was used by ancient seafarers.

In the coastal waters, wind-induced waves are the main source of energy ensuring water exchange. In MPs, the external sides of moles and breakwaters dampen the waves' strength and, inside MPs aquatories, wind impact on surface water masses is further reduced by different structures such as constructions, storehouses, moored ships, machinery and others. In MPs protected aquatories, the flows velocities are usually below 5 cm s^{-1} and rarely exceed 10 cm s^{-1} [154, 196].

In the NWBS, strong winds are observed all year round, but their frequency and duration depend on season; the strongest winds being registered from November until March. On average, 44–57 cases per year of intensive storm winds (more than 10 m s^{-1}) can be registered. Strong winds last, on average, 18–21 h, but storm duration could reach 5–6 days in some cases and up to 2 days in summer months [188]. Intense, sustained winds mix water masses and weaken the pycnocline. At prolonged calm weather, the pycnocline becomes more marked. Mixing of water masses is closely related with roughness. In the NWBS, roughness with wave height of 0.5 m have the maximal frequency (68% of the time), while storm waves with heights of 1.25 m occur for about 10% of the time [188]. In the region of Yuzhny MP, the storm winds are more frequent in the period October–March, with a frequency of 4–7 days per month.

Comparison of the abiotic components of MPs aquatories ecosystems showed that they have individual peculiarities as to the regime and velocities of flows, but also numerous common features connected with the specific character of their functioning and purpose. It was already said that the main common feature of MPs is the weakening of wind-induced waves. The wave height substantially depends on the strength and duration of wind action and its fetch [77, 191]. For example, possible wave fetch at coastal zones adjacent to Odessa MP could exceed 600 km and its striking energy could be about $5\text{--}6 \text{ t m}^{-2}$. Waves collapsing on the western and eastern coast of the Black Sea have the maximum fetch. Wave action is felt to the maximum extent in the region of Sochi MP on the eastern coast and in Varna-East MP on the western coast.

The aquatory of Odessa MP is protected from big waves' action by a system of moles and breakwaters. In the naturally protected aquatories of Ilyichevsk and Yuzhny MPs, the possible wave fetch is only some kilometres, i.e. two orders of magnitude lower than that of Odessa MP. Inside the aquatories of some harbours of Odessa MP, the possible wave fetch is equal to hundreds of metres and rarely exceeds 1 km. Wave action manifests to its full extent mainly on external surfaces of HTS protecting MPs.

The protective function of moles and breakwaters in MPs is of great importance for navigation and port activity. When correctly positioned, these structures damp up to 90% of the wave energy [153]. As a consequence, aquatories of MPs with 3–3.5-fold artificially increased depths and water volume (e.g. Odessa MP) receive about 10% of the wave energy which enters the shallow zones of the neighbouring shores. The naturally protected aquatories of Ilyichevsk and Yuzhny MPs slightly differ from Odessa MP with regard to this characteristic.

Because the influence of wind and roughness is repeatedly diminished in MPs, oxygen water saturation is not as rapid as in the adjacent sea zones. In Odessa MP, flows speed measured in various harbours at various horizons exceeded 8 cm s^{-1} only in about 10% of the cases [19].

The structure of flow fields in Grigorievsky Liman has a typical two-layered structure in all seasons and the liman water dynamics is characterized by temporary currents. Maximal flow speed does not exceed 27 cm s^{-1} at the surface and 14 cm s^{-1} at the bottom [148].

All harbours of Odessa MP are more or less freely connected with the waters of Odessa Gulf. The total sectional area of all passages into Odessa MP aquatory comprises about $11,300 \text{ m}^2$. Ilyichevsk and Yuzhny MPs are connected with the sea via one channel with cross-sectional areas of 2500 and 3000 m^2 , respectively. The cross-sectional area of the passage into Sevastopol Bay is about 8000 m^2 .

Offshore–onshore winds are frequently observed in Odessa Gulf and give intensive impulse to water renewal in Odessa MP [16]. The same phenomenon contributes to water exchange in Sukhoy and Grigorievsky Limans and in aquatories of other MPs of the Black–Azov Sea basin. Even at relatively weak winds of $4\text{--}7 \text{ m s}^{-1}$, the water exchange could take place during dozens of hours via the deepwater channels of Grigorievsky and Sukhoy Limans. The frequency of onshore–offshore phenomena in the region of Grigorievsky Liman is, on average, five times per season [196] and a similar situation is observed in the zone of Sukhoy Liman. Water exchange between MPs of Odessa region and the adjacent sea zones involves, first of all, the surface water masses (3–5 m) of their aquatories.

During offshore–onshore winds, the highest flows velocities in the surface horizon of MPs aquatories are observed in the access channels. These winds cause also fluctuations in the water level. Maximal fluctuations of the sea level in Odessa MP are mainly connected with nonperiodic changes determined by offshore and onshore winds. Offshore wind phenomena causing a decrease in the water level are more often observed because of the prevalence of north-western winds. These changes do not usually exceed 30–40 cm, but can be very rapid ($20\text{--}25 \text{ cm h}^{-1}$) because of relatively shallow depths in this region. In Odessa MP, the highest decline of sea level caused by offshore wind was 175 cm, while the highest water setup at onshore winds was 100 cm [16].

In Yuzhny MP, the level fluctuations are connected not only with the offshore–onshore phenomena, but also with the run-off of the Dnieper and Yuzhny Bug rivers. During the warm period, fluctuations of water level do not exceed 0.5 m, while they reach 1 m in the cold period. The maximum variation of water level in the Black–Azov Sea basin is registered near the north-eastern coast of the Azov Sea, where fluctuations can reach ± 3 m. In Taganrog Bay, onshore winds prop up river waters during the period of the Don River floods and a significant increase of the water level takes place. At offshore–onshore phenomena, the water level could vary by 1.5–2.0 m at different shores of the Black Sea.

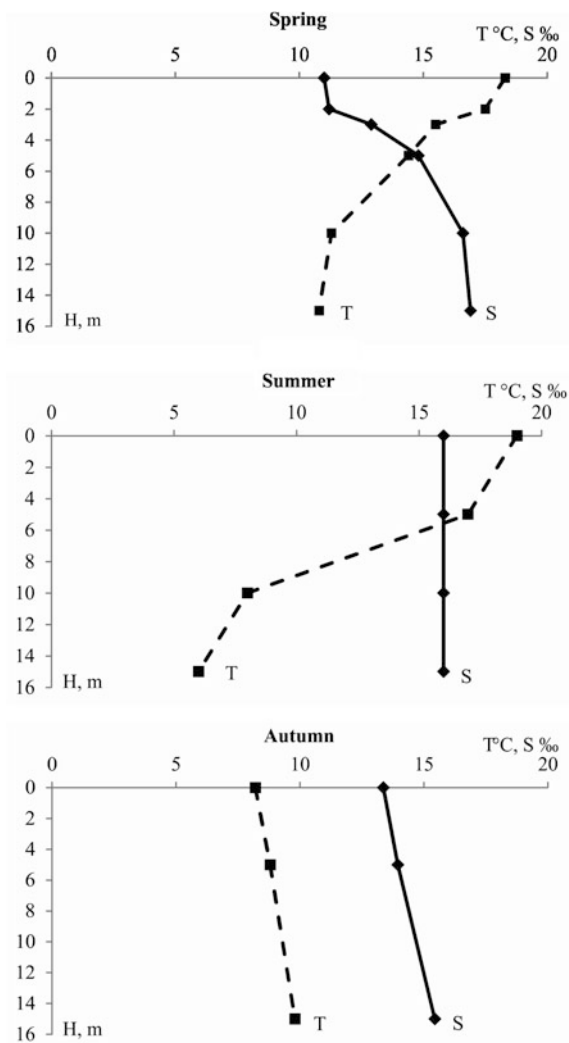
In Odessa MP, seiches (oscillations of the water level) ranging from 2 to 45 cm are registered along with offshore–onshore phenomena. The long-term average seasonal differences in sea level for Odessa MP are 19 cm [16]. The seiches in the aquatories of Sukhoy and Grigorievsky Limans rarely exceed 30–40 cm and have smoother and more lasting character than in Odessa MP because of their morphological peculiarities and protection from winds. In MPs aquatories, the changes of water level have their impact, first of all, on the composition of fouling biocenosis in the near-surface water layer. Internal waves forming in the thermocline layer favour horizontal mixing.

Turbulent mixing of water masses, temperature, solar radiation and sedimentation play a determining role in maintaining the water quality and biological productivity in aquatic ecosystems [145]. The role of these factors in MPs is not less important, but here they are subjected to certain changes. The seawater surface cools constantly. Its first centimetre layer absorbs only 20% of the incoming radiation and, owing to evaporation and long-wave length radiation, gives away 100% of heat absorbed by the boundary layer. In the uppermost layer with the thickness of a couple of millimetres, the water temperature is lower than that of the underlying water by fractions of a degree and sometimes by degrees. This temperature gradient at the water surface creates density instability and microconvection which, in calm water conditions, usually extends down to the depth of 25–30 cm [137]. In MPs aquatories, conditions of calm water develop more often than in adjacent sea zones.

In MPs aquatories, and especially in the access channels to some of them, phenomena of rips and oscillations are observed. They are oscillating water motions which involve a significant part of the water column.

As mentioned earlier, during the summer period, the mixing of surface and deepwater masses in MPs takes place owing to thermal microconvection, which involves the surface layer down to 30 cm [1]. However, the sea warms up not only from above, because of the atmosphere and solar radiation, but also because of the thermal heat flow near the bottom. The deep-sea thermal heat of Earth originates convection with a pulsing character in the near-bottom water layer. A thermal film warms up near the bottom, develops and then tears away from it. In conditions typical of the majority of big MPs of the Black Sea, its thickness is about 1.8 cm and its lifetime about 53 min. Every year the water volume interested by convection mechanisms at the bottom approximately corresponds to a layer of 100 m [1]. Even in the Black Sea ports with maximal depths of 18–20 m, the whole water column could therefore, theoretically, pass through the mechanism of near-bottom convection

Fig. 2.3 Examples of pycnocline formation (T temperature, $^{\circ}\text{C}$; S salinity, ‰) in Yuzhny MP (Grigorievsky Liman) during various seasons



in 2 months. On the flat area of the bottom, at a depth of 10–20 m in the Black Sea, the water velocity varies from 1 to 18 cm s^{-1} in the boundary layer with the thickness of 20 cm adjacent to the bottom [1]. In MPs aquatories, such range of average velocities is registered above the pycnocline layer during most of the year [16, 154, 196].

In Odessa, Ilyichevsk and Yuzhny MPs, vertical water homogeneity is usually registered in mid-winter, after the strong storms inducing wind mixing from the water surface to the depth of 20–25 m in all the NWBS.

In MPs, the vertical water exchange is hampered during most of the year owing to aquatories protection, artificial increase of depths and formation of the pycnocline, which breaks in winter months (Fig. 2.3). The pycnocline obstructs

penetration of oxygen into the deepwater layers and favours accumulation of hydrogen sulphide in the near-bottom horizon.

The pycnocline zone of MPs is enriched by relatively heavy sediment particles, settling down from above, and by relatively light ones rising up from below. However, even at prolonged summer stills, MPs aquatories are not entirely stagnant zones owing to internal waves and convective mixing [154].

Horizontal flows of various origins (surface wind flows, internal flows and seiches) extend into various layers of the water column, but are dampened by HTS and ships moored near berths. These flows have direct influence on internal surfaces which form the periphytal zone of MPs.

Compared with MPs located in other regions of the World Ocean, the MPs of the Black–Azov Sea basin are characterized by a practically complete absence of tides. Where present, tides provide regular mixing, elimination and dispersal of excessive amounts of autochthonous OM and allochthonous BM. The offshore–onshore wind phenomena observed in the Black and Azov Seas do not sufficiently fulfil these functions and OM and BM constantly accumulate in MPs aquatories of the Black–Azov Sea basin. This situation significantly worsens the living conditions of bottom and near-bottom hydrobionts.

Besides the energy sources of natural origin, ships' navigation plays various roles in MPs aquatories. The intensity of navigation varies between periods of a given year and among years. In MPs, ships navigate along defined fairways, usually represented by shipping channels. The disturbing effect of the ships' motion on the various horizons of water masses manifests in different ways. Irrespective of the draft and size of ships navigating at various speeds, waves are initiated at their bow part. These waves mainly propagate perpendicularly to the shipping channel, are usually 10–30 cm high and travel distances from a couple of dozens up to a couple of hundreds metres. In MPs aquatories, these waves come into contact with, and are reduced by, the inner surfaces of berths, piers, protecting HTS and hulls of the moored ships. The upper layer of the periphytal (about 20–50 cm) falls under the influence of these waves.

The movement of the big, deep-draft ship perturbs water masses above, within and below the pycnocline. Passing through a shipping channel, a deep-draft ship favours the mixing of the near-surface and near-bottom layers along with oxygen penetration into the near-bottom layer. Part of the energy flows initiated by ships is assimilated and damped by the slopes of shipping channels. Ships' propellers also create various turbulences and water flows which stir up detritus from the slopes and bed of navigating channels.

2.1.2 Water Motion

The famous hydrobiologist Zernov [79] underlined that life intensity significantly decreases in aquatic ecosystems where water exchange is absent or weak.

Water motion comprises flows and roughness initiated by various phenomena. Energy is spent on the formation of flows which then become a source of energy themselves. In rectilinear flows and horizontal and vertical circulations, the transfer of water masses occurs together with that of small organisms inhabiting them. During wave propagation in the open sea, water particles move on orbits and eventually return back to their initial position. Near the shores, the movement of water particles is disturbed and they are displaced without returning to the initial position.

In the upper part of the shelf, where MPs aquatories are located, wind currents and waves (whose power in MPs is artificially weakened) are the main source of energy ensuring water exchange.

Waves caused by local winds are called wind waves. Wind blowing over the sea intensifies evaporation, carries substances with water droplets and creates surface waves and flows which are usually perceptible to the observer. However, in MPs, water motion also occurs in the water column and is determined by numerous factors which could reciprocally mask their effects.

All flows are divided into laminar and turbulent. When water layers move without mixing we deal with laminar, organized motion. On the other hand, the more widespread turbulent flow is characterized by rapid, irregular motion of water particles along complex trajectories. Heat exchange and mixing are more intense in turbulent flow. The transition from laminar to turbulent flow is quicker than the reverse one. In the surface (mixed) sea layer, turbulence is created by wind-induced shear stress. In aquatories of the Ukrainian MPs, located in the tideless Black and Azov Seas, the following flows are distinguished: 1—superficial (drift), mainly initiated by wind action, river run-off, seiches and ships' waves; 2—deepwater (or inner), having an impact on water the column and resulting from the influence of various natural and anthropogenic factors; 3—near-bottom, mainly compensatory and usually originating at offshore winds, sharp changes of atmospheric pressure, deepwater emission of wastewaters, submarine exit of fresh waters from land and other peculiar processes.

These flows are, in turn, divided into horizontal, vertical and mixed. All types of vertical and horizontal water motions directly or indirectly affect the distribution of biogenic matter, live plants and animals in the water column as well as habitat selection by hydrobionts in the benthal and periphytal zones. Furthermore, water movement redistributes, concentrates and disperses BM and food items necessary for hydrobionts as well as their metabolites and other toxic substances.

As in natural bays and harbours, a fully developed counterclockwise superficial water circulation, with various scales of horizontal and vertical circulations, periodically originates in MPs aquatories during the year (Figs. 2.4 and 2.5).

In MPs aquatories of the estuarine type, wave action can form water run-offs at leeward coasts and water accumulation at windward coasts (Figs. 2.6 and 2.7). The resulting difference in water levels causes compensational flows inside MPs. During winds blowing from the shore, a part of the superficial water mass moves offshore from the MPs aquatory, thus originating a near-bottom compensational flow which propagates into the aquatory along the AC (Figs. 2.8 and 2.9).

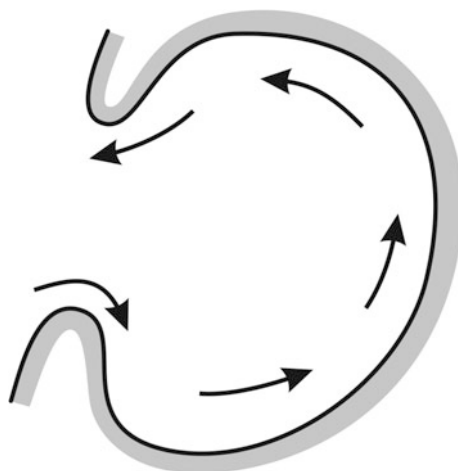


Fig. 2.4 Scheme of the circular flow in a natural bay, located in the northern hemisphere, with a wide passage, in which the incoming and outgoing flows move along right and left shores of the passage

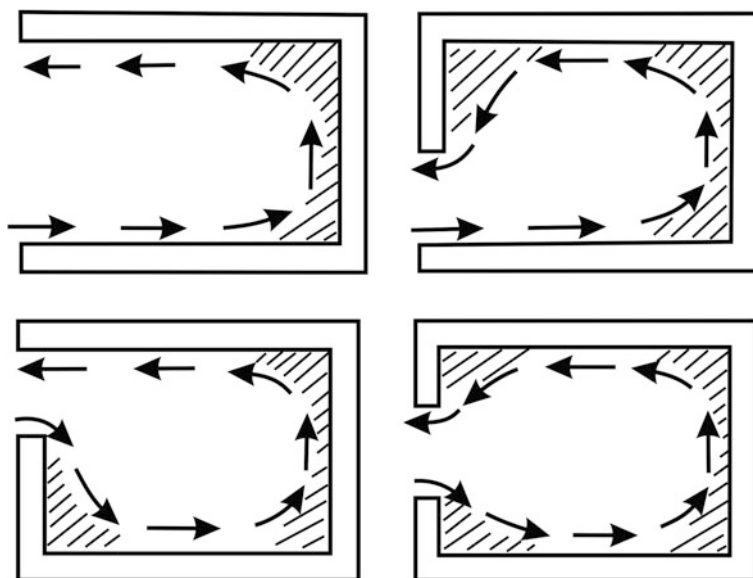


Fig. 2.5 General scheme of water flows and stagnation zones in port harbours having various configurations in the northern hemisphere

Rip currents can occur in MPs aquatories with preserved zones of natural, coastal shallow waters. Rip currents are water flows moving away from the shore through temporal channels which cross zone where waves are destroyed. Rip

Fig. 2.6 Scheme of waves' impact induced by onshore winds on superficial water masses in marine ports

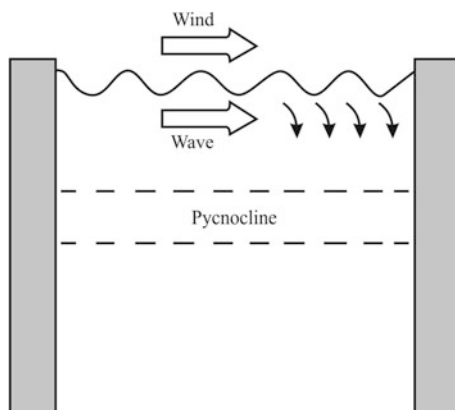


Fig. 2.7 Offshore phenomena in the upper layer of the sea coastal zone

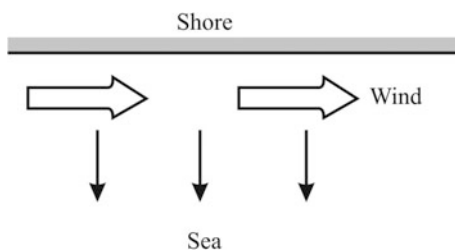
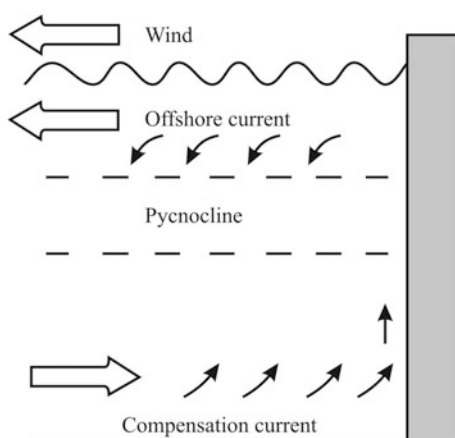


Fig. 2.8 Scheme of the main water flows in marine ports at offshore winds



currents reach high velocities and are formed as a result of water accumulation on the shore. They usually last a couple of minutes, can reach a speed of over 100 cm s^{-1} and are observed up to distances of a couple of dozens metres from the shore (Fig. 2.10).

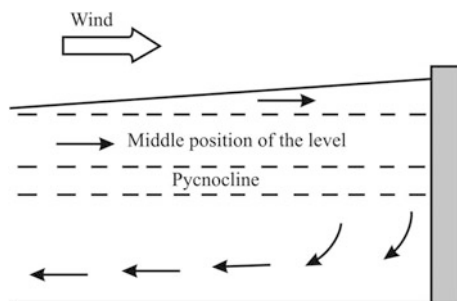


Fig. 2.9 Scheme of water run-on at onshore winds creating circulation and water flows in marine port and access channel

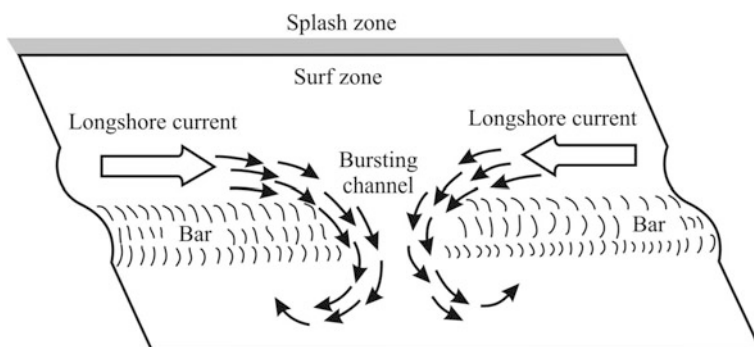


Fig. 2.10 General scheme of formation of a rip channel in the coastal bar zone

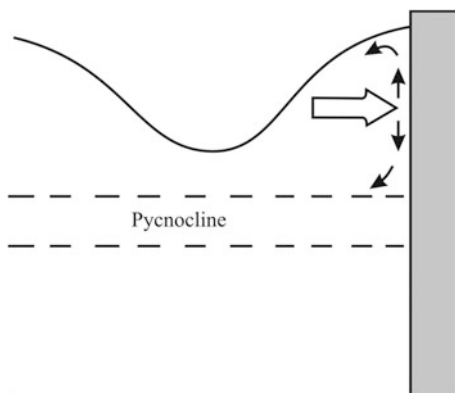
In the deepwatered MPs, waves approach vertical HTS, strike them and are reflected. Reflected waves interfere with the oncoming ones, forming a sequence of standing waves. On the external protection of Sochi MP, the wave force can reach 14 t m^{-2} , while the maximal registered wave force was 6 t m^{-2} in Tuapse port [78] (Fig. 2.11).

The waves' energy grows faster than the corresponding increases in their height and steepness. For example, a twofold increase in wave height leads to fourfold increase in its energy. A wave with a height of 3 m has two- to fivefold more energy than a wave of 2 m height [60]. Waves give up energy when overturning and breaking down.

The smooth ripples, which are slowly rocking ships or running on the shore, are what remain of the waves after they leave the wind influence zone. Even slow changes in the water level of MPs aquatories are waves. When entering natural or artificial narrow passages, such as those into the aquatories of some MPs, waves can significantly increase their height and intensify energy.

Besides the superficial wind waves and ripples, inner waves, seiches and ship waves are also registered in MPs aquatories.

Fig. 2.11 Scheme of waves' energy consumption in marine ports aquatories at collision with hydrotechnical structures



Wind amplifies roughness when blowing in the same direction as wave propagation and weakens it when blowing in the opposite direction. Sea roughness and waves' height and steepness are proportional to wind duration, strength and acceleration distance, i.e. the distance over which the wind and roughness directions coincide. Smaller waves and ripples are superposed on the principal ones. Specifically small waves and ripples are mainly a transmission mechanism of kinetic moment (momentum) from wind to sea. In MPs aquatories, winds, waves and currents are diverted and weakened by natural and artificial obstacles that they meet on their way.

The frequency of wave run up is characterized by the wave period, i.e. the propagation time of two consecutive peaks (or trough) through the same point. Ripples, i.e. waves about 1 cm high emerging under wind influence on a previously smooth surface, have a period of about 1 s. The period of surf waves, having height up to a couple of metres is 4–10 s, while internal waves and seiches have periods from dozens of seconds to a couple of minutes and from a couple of minutes to a dozens of hours, respectively.

The speed of the wind-induced flow on the water surface corresponds to about 3% of the wind speed. Thus at a wind speed of 10 knots (18.52 km h^{-1}), the speed of surface flow is about 0.3 knots (55.5 m h^{-1} or about 1 m min^{-1}) [36].

Dynamic, wind-driven convection distributes energy from the top-downwards. In such situations, mixing is not much determined by the wind itself, but rather by the size and steepness of the waves that form and break, i.e. by gravitation.

Very slow mixing processes connected with the heat motion of molecules (molecular convection) prevail in water masses during calm weather. Flows displacing water masses with hydrobionts from one point to another, accomplish molecular convection, which plays a leading role in functioning and long-term life of aquatic ecosystems.

In MPs aquatories with relatively shallow depths (up to 20 m), the water movement has a three-dimensional character controlled by the energy entering with vortex-type formations (mainly from the upper water layers), the transformation of flows by bottom roughness and the HTS surfaces.

The molecular convection occurs during friction (dynamic) from differences in density, created by evaporation and owing to biological activity of hydrobionts, schools of fish, aquatic birds and mammals. Convective mixing occurs when, for various reasons, the upper water layers become denser than those located below, or vice versa. In both cases, vertical vortexes and currents are created and penetrate from one layer into another, thus mixing the water masses. At density mixing caused by temperature drop of surface waters, the vertical gradient of salinity plays the main role in the process, while in the case of density mixing caused by evaporation, the main role belongs to the vertical gradient of temperature. Mass settlements of filter-feeding invertebrates, schools of fish, dolphins, aquatic birds and other organisms realize biological convection.

In contrast to surface-driven phenomena, mixing connected with compensational flows affects a certain thickness of water over the bottom. The height of this mixed layer is determined, first of all, by flows speed above the bottom and by the vertical density gradients of the near-bottom waters. The higher near-bottom speed gradients correspond to the lower vertical density gradients. In such situations, the vortexes forming near the bottom and mixing the near-bottom layer can rise higher into the water column. Roughness and bottom irregularities contribute to the formation of such turbulent vortexes.

The shallower are MPs aquatories and the stronger is the wind, the easier is the total vertical mixing of waters.

In MPs aquatories bordered by high shores and protected by HTS, the wind force can be significant, but only weak currents and roughness can develop. In such situations, waves have no acceleration although the water level rises up in some zones, and lowers in others, because of wind-induced water accumulation.

At strong winds, a near-bottom flow of variable strength usually forms in MPs aquatories and ACs. At offshore winds, irrespective of direction, part of the surface water mass may press against the right or left bank and form a surface flow (directed into the adjacent sea zone) near the passage. At onshore winds two types of impact could be observed on MPs aquatories: first, part of the surface water masses are shifted to the zones most distant from the passage; secondly, water masses are transferred from adjacent sea regions into aquatories via AC. This transfer of water increases the pressure on the deepwater layers of MPs and originates a backflow carrying part of the near-bottom water mass from MP into the sea. When the wind drops, the opposite situation is observed with the superficial water mass flowing into the sea and a compensation current sucking bottom waters into the MP near-bottom layer. Density stratification, typical of the Ukrainian MPs, increases the transport capacity of compensation currents inside aquatories through ACs. This is why freshly settled OM, accumulating in the near-bottom layer of ACs, is easily stirred up and carried directly into MPs through the passages.

In the Northern hemisphere, the moving bodies, including air and water flows, are diverted to the right under the influence of Earth rotation. This effect was studied by French physicist Gaspard-Gustave de Coriolis and named after him. Coriolis acceleration is perpendicular to the velocity vector and has values of about 0.1 cm s^{-1} for winds and 0.005 cm s^{-1} for major oceanic currents. In the

case of marine currents and flows originating in MPs aquatories, the Coriolis acceleration is one- to threefold lower than in oceans. However, it is a constant force that participates in preserving natural biocenoses on the right shore of MPs and influences periphyton communities on artificial HTS.

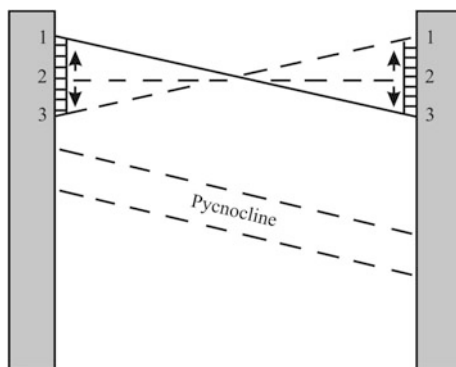
Owing to the Coriolis force, water in MPs located in the northern hemisphere does not drift directly downwind, but is shifted at $30\text{--}35^\circ$ rightwards to wind direction. Wind, blowing parallel to the open shore, either pile up water towards it, or drives it away from it. In the northern hemisphere, the anticyclonic circulations are directed clockwise and cyclonic ones anticlockwise. Vertical gradients of speed are observed in any flow; as a consequence of which the Coriolis force causes some turbulence and transverse circulations in homogeneous surface water masses. If wind direction is perpendicular to the open shore, the pile up and drive off phenomena are not observed.

Zones of flows convergence and divergence exist in water basins. In convergence zones, water sinks down following the convergence of surface flows. The sinking water enriches the deeper layers in oxygen (downwelling). In divergence zones, water rises up from deeper layers towards the surface and enriches the surface layer in BM (upwelling).

In standing waves or seiches forming on sea surface, the water particles do not move on circular orbits as it happens in wind surface waves. The impact of standing waves in the surface layer extends to a depth equal to wave height, i.e. seiches usually affect a water layer from a couple of centimetres up to $20\text{--}50$ cm. Seiches belong to the long “closed” waves. They originate at undulation of water in closed basin, according to vivid expression of Shuleykin [193], “similarly to water poured into bowl to which was communicated a shove”. While water is raising up at one shore of the basin, it lowers down at the other one. The so-called nodal line, at which the water particles stay motionless, passes somewhere in the middle (Fig. 2.12).

Zubov [80] brought an example of a sharp reduction of water level in Sevastopol Bay where the sea level lowered by 58 cm for 50 min during the storm of 25th August 1911 and then raised up to its initial level.

Fig. 2.12 Scheme of changes of sea level due to seiches influence on water masses of marine port (1, 3 seawater level at seiches oscillations; 2 water level position at calm weather)



In the Black and Azov Seas, seiches frequency ranges from 6–7 up to 22–23 h. As it was already mentioned, the wave period corresponds to the propagation time of two consecutive peaks (or troughs) through the same point. Seiches period depends on aquatory length and depth. Inside MPs aquatories, seiche waves usually have periods up to a couple of minutes.

Seiches have various causes: strong blasts of wind, sudden disappearance of wind action, sudden changes of atmospheric pressure, seismic activity, explosion, etc. They are usually observed in relatively closed gulfs, bays, straits and port harbours where the water masses can fluctuate as a whole. In some situations, seiches can be caused by the passage of a big ship.

After termination of force whose action started the seiche, the water level tends to occupy an intermediate position, i.e. an equilibrium position. In practice, under the influence of initial forces, water masses pass through the equilibrium position and causes progressively decaying fluctuations in the form of standing waves. Predominantly low amplitude vertical fluctuations of the water level are observed near the MPs shores and their protection structures.

Seiches cause an oscillatory motion of the whole water mass so that the surface of the entire aquatory acquires an inclination towards one or the other side. In MPs aquatories, each change of surface inclination is accompanied by a change in the inclination of isopycnic surfaces. Even if the position of the pycnocline reacts to seiches, the mixing of different layers of the pelagial zone is weak and most marked in the near-surface layer (about 0.5 m) interacting with the natural shore or with HTS lateral surfaces. Seiches have various influences on the near-surface belt of macrophytes and on barnacles, molluscs and hydroids settlements.

It is known that only surface waves, whose amplitude diminishes with depth, form in homogeneous water masses. In MPs, the seawater is usually a heterogeneous environment where internal waves, not visible at the surface, form between water layers of different densities.

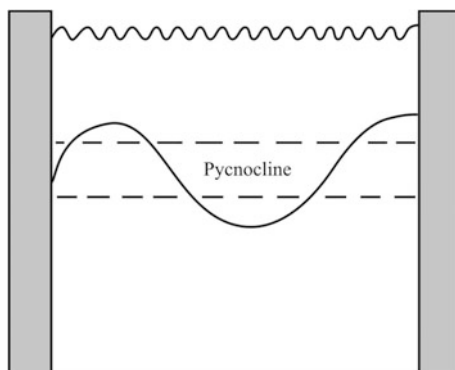
The increase of atmospheric pressure lowers the water level, while its reduction increases the water level. Such fluctuations in atmospheric pressure are transmitted to water masses and induce water movement.

Outside MPs, the inner waves gradually weaken by spending energy in interactions with the water layers located above and below them. In protected MPs aquatories, inner waves are usually abruptly dampened by interaction with the protecting structures, moles, berths and ships. The striking energy of these waves is frequently perceived by the fouling biocenoses.

Internal waves and density currents in MPs are determined, first of all, by non-uniform vertical distribution of temperature and water salinity, both affecting water density. Thus, internal waves are frequently confined to the zones of thermo- and halocline. The summer thermocline forms in MPs when the turbulence minimum appears at some intermediate depths and vertical turbulent diffusion is no longer sufficient to transmit the heat flow to the underlying water layers without the development of a significant temperature gradient.

A change of 1% in salinity influences the seawater density about 5 times more than a change of 1 °C in temperature. In relatively small aquatories of the Ukrainian

Fig. 2.13 Scheme of internal waves impact on water masses in marine ports



MPs influenced by river water discharges, differences in salinity between the surface and near-bottom layers usually influence water density more than differences in temperature. In Yuzhny, Odessa and Ilyichevsk MPs, the salinity of the surface layer (uppermost 3–5 m) could be 10‰ lower than that at the bottom and temperature differences between surface and bottom waters can exceed 10 °C. Under such conditions, the presence of a pycnocline and vertical stratification are steady phenomena.

In the thickness of stratified water masses, the energy of internal or subsurface waves propagates much similarly to that of the surface waves. Internal waves spread through isopycnal surfaces, which form as a result of density differences (thermocline, halocline). Internal waves, propagating from the pycnocline layer, initiate mixing that develops upwards and downwards and gradually fades away.

In the absence of motion, the boundary surfaces and the sea surface are horizontal. Internal waves originate at water masses borders and only in the presence of a vertical density gradient (Fig. 2.13). The density gradient is controlled not only by temperature and salinity, but also by significant inputs of river and drainage waters of various origin (e.g. industrial discharge, rain waters discharge) which are much less dense than seawater.

As shown by the example of Peter the Great Gulf (Sea of Japan), internal waves originate at the upper limit of the thermocline and reach heights ranging from 20 cm during calm weather up to 1 m during storms [118]. Usually, the heights of inner waves range from several dozens of centimetres to 2–3 m and the speed of their propagation from 5.0 to 35 cm s⁻¹ at the depths up to 20 m [100].

In MPs, inner waves are higher than surface waves because the energy required to rise up the water layer in the air is much bigger than that necessary to rise up a water layer in an environment of similar density. The height of internal waves quickly diminishes when moving away (upward and downward) from the pycnocline. The position (depth) of the pycnocline, where internal waves form, changes depending on the height of the internal waves themselves.

Cases when the height of inner waves reached 20–30 m are known for ocean waters. Inner waves with an amplitude of about 10 m usually pass through the pycnocline with a period of about 20 min [36, 100].

The breakdown of internal waves with lengths of a couple of metres, periods of a couple of minutes and phase velocities of a couple of centimetres per second transmits the characteristics of the surface layer through the thermocline zone via vortex formation. Observations in Peter the Great Gulf showed that the characteristic size of visible formations is 3–5 m for internal waves and 5–20 cm of vortices. Moreover, intense vertical descending motions with typical dimensions of 2–3 m were registered in the lower part of thermocline [118]. This phenomenon of “salt fingers” has been previously reported [36].

In protected aquatories such as those of MP, standing internal waves can be observed. The standing waves do not actually transport energy themselves, i.e. they are immobile with respect to the environment. In the water column, water movement is divergent above and below the pycnocline. Inner waves cause fluctuations of pycnocline. Although the amplitudes of inner waves can exceed those of surface waves, inner waves are usually slower. Formation of the standing inner waves is conditioned by size, configuration and depths of aquatories. All these waves are especially marked in aquatories where flows abruptly change their direction and speed. Such phenomena are observed in access channels and passages in MPs divided into separate basins and harbours. In MPs, inner waves originate in water layers with different temperature and salinity. They have heights from a couple of dozens centimetres up to a couple of metres and stretch horizontally from dozens of metres up to a couple of kilometres.

A ship slowly moving in a port aquatory generates internal waves at the border between the surface layer (upper 3–5 m) of strongly desalinated water and the denser deep-sea water. Such inner waves sharply reduce the ship's speed and create phenomena known under the term of “dead water”.

Inner waves influence all components and processes that are affected by changes in temperature, salinity, water density; e.g. hydrobionts distribution, chemical and physical water properties, flows, bottom topography, etc. [100].

The famous oceanologist Zubov [81] emphasized that, regardless of their period, internal waves are particularly important for the periodical “renovation” of deep-waters and bottom water layer of the semiclosed aquatories, thus favouring the development of life in these zones.

In marine ports aquatories, navigation of different types of vessels takes place more or less regularly either autonomously or with the help of tug boats. Ship navigation originates visible surface ships' waves that consist of slanting (or diverging) and transverse waves. The angle between a ship's bow and the slanting waves formed by it depends on the ratio between the ship's speed and the depth and is, on average, equal to 18–20°. The front of transversal waves is perpendicular to the direction of ships' movement [191]. Figure 2.14 shows the scheme of distribution of ships waves in MPs aquatory.

In the stratified water masses characteristic of Ukrainian MP aquatories, ships form not only surface waves but also the so-called internal waves, which are not visible to the naked eye.

When turning around in MPs aquatory, a deep-draft ship causes a turbulent water movement along all the submerged lateral part of the ship.

Fig. 2.14 General scheme of flows created by a ship in motion

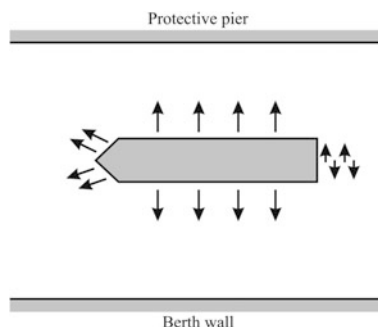
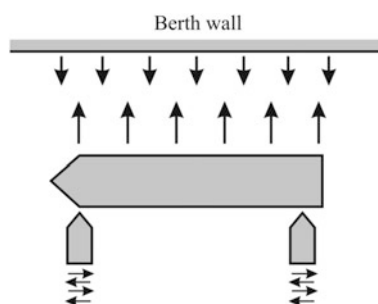


Fig. 2.15 General scheme of flows created at mooring to harbour wall by berthing tug



In particular, a ship pushes a water layer equal to the length of its hull and up to a depth corresponding to its draft. A similar situation takes place during a ship's mooring by tugs to the wharf wall. Pushing a ship with a length of 250–300 m and a draft 10–14 m to the wharf wall, the berthing tug destroys the pycnocline at a distance of a dozen metres from the wall and over a length equal to the underwater part of the ship. Both surface and internal waves form during berthing and, in aquatories with small dimensions compared with the ships' draft, seiches (Fig. 2.15).

The rotation of a ship's propellers forms a strongly turbulent stern wake whose influence on the water mass depends upon many circumstances, such as number and diameter of propellers, the speed of their rotation, the ship's draft and other. The stern wake could initiate surface and internal waves. The stern wake gradually dampens its energy in all directions by forming vortexes of various dimensions. In the stern wake, a dilution up to 1000-fold of the polluted waters discharged from the ship is achieved under the influence of ship's propeller [45]. The stern wake, saturated by oxygen, plunge up to a certain depth. Because the ships in MPs aquatories move along well-defined fairways, the water movements initiated by them propagate towards HTS along defined directions and angles. The angles at which waves approach HTS following navigation in harbours are different during ships' calling in and leaving from the port and such differences could reach 60–70°. In ports, some HTS are regularly subject to the influence of ships' waves, while others experience it only episodically.

A great number of hydrodynamic processes of different spatial-temporal scales simultaneously takes place in natural basins in general and in MPs aquatories in particular. Besides the usual drifts flows, wind creates a series of different scale spiral circulations transverse to its direction and with horizontal axis parallel to its direction. Transverse vertical circulations penetrate the water column up to various depths. Two opposite processes connected with accumulation and dissipation of wave energy take place in the water column. Upon breaking down, the wind-driven roughness originates small-scale movements of vorticity in the water. In open seawaters, the life span of energy containing vortexes could comprise 1–10 min [26].

In seawater, the vertical and horizontal components of turbulence significantly differ on scale and intensity. The largest energy exchange takes place when all water layers are involved into turbulent transition. The energy of turbulent flow is continuously dissipated into heat by the water molecular viscosity. In the ocean, the fluctuations of dissipation speed become insignificant at flow speeds from 1 to 6 cm s⁻¹ which are typical for various water movements in MPs.

At a certain depth, the rate of turbulent energy formation reduces so much, that it is not anymore sufficient to overcome the resistance caused by density differences among water layers. At such depth, at the border of the mixed layer, a transition zone (the pycnocline) forms and a more or less sharp density gradient with low turbulence intensity develops.

The upper mixed layer and the pycnocline, two very important components of MPs aquatories ecosystems, form and evolve under the effect of several mechanisms, including vertical mixing (as small-scale turbulence), thermal (gravitational) microconvection connected with Benard cells, Ekman heterogeneity, collapse of surface and internal waves and Langmuir circulation [147].

With regard to their scale, the main processes of interaction between the sea surface and the atmosphere in MPs could be divided into micro-, small- and local scale. They diffuse to depths of no more than 10–20 m and, horizontally, up to 10–100 m and last no more than a couple of minutes [137]. Small- and middle- (or meso-) scale water movements are usually connected with MPs aquatories. Their spatial sizes range from dozens of metres to a couple of kilometres and their temporal scales vary from hours to days [137].

As already mentioned, the smallest waves, originating under wind influence on previously smooth surface with the height of about 1 cm, are called ripples and their period lasts less than a second. Scales of metres and periods of minutes are typical for the internal waves and seiches.

As it was already said, the sea surface constantly cools down (its topmost 1 cm layer adsorbs only 20% of incoming solar radiation and gives away, due to evaporation and long-wave length radiation, 100% of the energy adsorbed by the border layer with the thickness from a couple of metres up to a few dozen metres). The temperature of the sea surface is lower than that of underlying waters by fractions of a degree and, sometimes, by degrees. This particular feature creates density instability at the water surface and convection which usually propagates up to the depth

of 25–50 cm in conditions of calm water. Thus, thermal, or gravitational, micro-convection is the basis of water motion in the surface layer.

The phenomenon of microconvection originates because the surface tension exists not only between air and water, but also between waters masses of different temperature, i.e. between the cold surface film (0.1–1.0 cm) and the underlying water layer. About 1 cm^3 of colder and denser water sinks from the surface up to the depth 25–50 cm in the form of water thread jets with a diameter of about 1 cm and a speed of 0.2 cm s^{-1} . The masses of heavier water rotate during sinking [1].

Vertical jets arising because of temperature differences create microconvection and gradually acquire the form of regular hexagons in whose centres the water, in the form of concentrated jets, is directed towards the zones of increasing molecular viscosity; i.e. towards lower temperatures. The opposite, compensational water movement in the upward direction takes place along the periphery of the hexagons. Overall, a closed circulation originates in the form of cells known as Benard cells.

Directly in the near-surface layer of MPs, the exchange of matter and energy between the atmosphere and water masses takes place thanks to displacement of microscopic particles of environment, leading to transportation of mass, heat and other physical quantities. Transmission of energy in the form of heat (convective heat exchange) takes place in a non-uniformly warmed liquid medium and is caused by temperature and density gradients.

When the overlying water particles cool down because of the process of evaporation and become heavier than underlying ones, they sink down and lighter ones rise up in their place. This is a gravitational convection phenomenon that often takes place in the form of the already mentioned hexahedral Benard cells. The liquid sinks down along the edges of such cells and rises up in its centre. If a horizontal wind flow is superposed onto cells, cells line up along it and form convergence streaks, which resemble Langmuir circulation discussed below, but are limited to a thinner near-surface water layer [147].

In cases of lasting and stable wind, the so-called Ekman wind-driven currents can develop in a much thicker part of the upper water layer. Under some conditions, the instability of Ekman wind-driven currents also manifests in the form of flows transverse to wind circulations, also resembling Langmuir circulation. The typical time scale of Ekman instability is a couple of hours [147]. However, this time is sufficient for mixing of the near-surface layer over a thickness of dozens of metres.

MPs aquatories have substantially smaller horizontal and vertical dimensions than the seas where they are located. They are placed on the shelf in coastal zones with relatively small depths. In MPs aquatories, the processes of energy supply to the water column are slightly different than in the open sea, owing to deterioration of the macroscopic component of the water motion spectrum. In MPs, movements with a scale up to 10–100 m, connected with the transfer of energy during roughness provoked by winds, acquire a major role.

Water movements in MPs interact with the atmosphere, the bottom, lateral surfaces of hydrotechnical structures, ships' hulls and water layers with different density. Such interactions inevitably generate zones of turbulent flows and form

vortexes of different scales. Displacement effects, determined by vertical and horizontal gradients of flows, the destruction of surface and internal waves, the character of vertical stratification, water density and temperature play an important role in controlling the genesis, size and intensity of the vertical vortexes. In aquatic ecosystems, turbulent flows in the form of small-scale vortexes are more ecologically relevant than laminar flows. Microvortexes with sizes from a couple of millimetres up to a few dozens centimetres have the greatest importance for some organisms. Vortexes with sizes from a couple of metres up to dozens of metres sustain the existence of populations and hydrobionts communities.

In MPs, the strongest “concentration of life forms” occurs in zones characterized by frequently repeated small-scale turbulence such as: 1—under the film of surface tension, 2—coastal shallow waters, 3—the upper part of lateral surfaces of hydrotechnical structures, 4—areas of the bottom with increased roughness, 5—the pycnocline zone.

Microvortexes are connected with feeding of hydrobionts, dispersion of metabolites, reproduction, fertilization and development. They are necessary for the inhabitants of all MPs biotopes to various degrees. The highest biomasses of attached and sediment-dwelling sestonophages and hydrobionts predators are usually concentrated in the zones that are most hydrodynamically active thanks to the presence of microvortexes [68, 139, 145].

In MPs, the water turbulent motion plays an important role in exchange processes (transformation) of momentum, heat, suspended particles, dissolved nutrients and different toxic substances. The marine surface is a transit zone where the exchange of matter and energy takes place between the water mass and the atmosphere owing mainly to processes of molar diffusion, i.e. microvortexes, rather than molecular diffusion.

In the open sea, the strong, wind-induced waves can generate vorticity in a water layer up to 10–20 m thick, i.e. up to the maximum depths of MPs. However, in MPs aquatories, the wind-driven waves usually induce vorticity in a water layer up to 1–3 m thick and the “life span” of energy containing vortexes does not exceed 1–3 min [61, 110, 137].

The turbulent water flow is characterized by complex curvilinear trajectories and vortexes continuously changing direction and velocity in each point of the flow. It causes intensive mixing of water masses and therefore exchange of characteristics. Turbulent exchange takes place in all directions, but vertical displacements are especially important because they favour penetration of oxygen into the MPs water column.

Turbulent vortexes of various sizes form when water flows around isolated obstacles such as HTS, ships or pile foundations. Shadow zones of various sizes, i.e. zones in which water movement becomes less noticeable or even disappears, form behind the obstacle depending on its size and form.

Turbulization of water column by moving ship’s propellers favours vertical mixing [178].

It is considered that productivity of invertebrates is highest at flow velocities of 30–90 cm s⁻¹ [145]. Interaction with the bottom starts at flows velocity of about

7.2 cm s^{-1} [153]. In MPs, turbulization of the flows in hydrobionts habitats depends on the roughness of the surfaces with which they are interacting.

During colonization of HTS surfaces by hydrobionts, bacteria and microalgae form a slimy layer that decreases HTS roughness and weakens turbulence. The appearance of macrophytes and attached invertebrates in fouling increases the roughness of the whole settlement. Owing to bioturbation and accumulation of faecal pellets, the surface of bottom sediments becomes rough and creates turbulence of flows. The increase in surfaces roughness ameliorates the energy supply of both biocenoses and individual organisms.

In the coastal stripe with large-sized sediment components (e.g. stones, pebbles, broken shells and coarse sand) turbulence could be excessive and depress the development of many hydrobionts. In zones with optimal turbulence and corresponding granulometric composition (sand, silted sand), the biomass of bottom population reaches dozens to hundreds of grammes per 1 m^2 . In MPs, the mass development of periphyton takes place on hard substrata located in the zone of optimal vorticity. Organisms of benthos and periphyton of a defined size not only contribute to the generation of turbulent flows, but also create microvortexes of a certain size during their feeding and respiration [209, 228, 234].

Observations in Ilyichevsk, Yuzhny, Odessa and other MPs aquatories showed that, during windy weather, convergence streaks of foam, air bubbles, suspended matter and garbage, fragments of macrophytes, phyto- and zooplankton usually form parallel to the direction of the wind. It turned out that this phenomenon is connected with unusual water movements known as Langmuir vortexes, Langmuir circulation, Langmuir convection and Langmuir effect. Paired convectional cells transverse to wind circulation, also bearing the name of Langmuir cells, form owing to convection processes usually initiated by the wind.

American physicist and Nobel Prize winner Irving Langmuir postulated that the horizontal distribution of live and dead OM on the water surface and in the water column is mainly determined by physical causes. He confirmed his hypothesis that convectional processes are frequently lying at the basis of these phenomena by field surveys [212].

It was found that an ordered convective-drift circulation forms when wind-drift currents having common velocity gradients develop in the convection layer. Such circulation is an important mechanism of heat, kinetic moment and matter transfer, having significant influence on regime formation of all upper layer of water masses [61]. It is considered that Langmuir circulation is the result of a complex interaction between the wind flow and surface gravitational wind waves. The wind blowing over the water surface generates transverse circulations when frequencies “resonating” with water masses of given sizes are present in the wind turbulent spectrum [125, 126].

Langmuir vortexes represent a typical form of highly organized and at the same time randomly variable movement. In particular, it is assumed that Langmuir vortexes (convection) are the prevailing form of wind-driven flows.

Except in still weather conditions, several metres of the upper water column are constantly moving in the form of a vortex-type flow, which consists of small-scale

Langmuir vortexes with a distance of 3–6 m between convergence lines. At moderate to strong winds ($5\text{--}15\text{ m s}^{-1}$), Langmuir vortexes with different scales are observed [101]. In aquatories with sizes similar to those of MPs, Langmuir cells are typically 5–10 m wide, i.e. their size is limited by the depth of the pycnocline [118].

At moderate wind conditions, the coexistence of small-scale vortexes and wind spiral of Ekman type was observed. Langmuir circulations are located at the surface and Ekman circulation is located under it. At large-scale Langmuir vortexes, an Ekman spiral does not form [101]. The transfer of kinetic momentum from wind through the smaller vortexes to the bigger ones creates an effective connection between these vortexes. This type of link explains the quick response of the mixed layer to wind impact. A linear dependence between the wind speed and the water sinking rate was established. Various authors showed that practically any wave motion causes rectilinear translation of water in the direction of wave propagation, although this phenomenon is practically insignificant for flat waves [101].

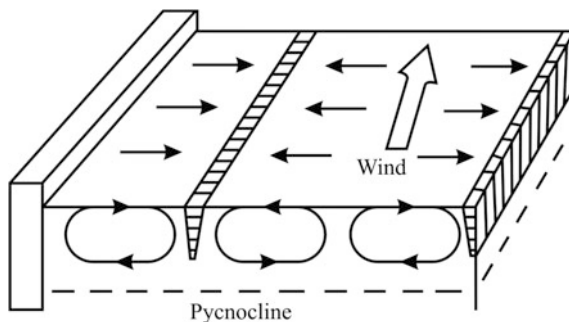
It was discovered that, after some inertial period, the zones of convergence acquire anticyclonic rotation upon occurrence of still weather following a period of moderate winds [101].

Friction force, applied to a horizontal surface, leads to the formation of Ekman flows (Ekman spirals). This effect is a consequence of the Coriolis force action which shifts moving objects rightwards in the northern hemisphere and leftwards in the southern hemisphere. As a consequence, when wind blows over the ocean surface in the northern hemisphere, surface flows diverge rightwards from wind direction. Because of water viscosity, the diverging surface water layer puts into motion an underlying layer, which also diverge rightwards from the above one and so on. The flow weakens gradually with the increase of crook. In the presence of Langmuir vortexes, the conditions necessary for the origin of Ekman spirals are shifted to the lower border of Langmuir flow, which assumes the same role as the wind with respect to underlying waters and can thus form flows of Ekman type in these waters [101].

It was determined that the pattern of transverse circulations and convergence streaks (created by wind and marked by various suspension, bubbles and foam) is tightly connected with the geometry of a water basin. Only vertical circulation of a certain size can form within a specific water basin or in protected aquatories [101, 118, 147].

Irving Langmuir [125, 126] studied values of horizontal and vertical speeds in spiral circulation. At a wind speed of 6 m s^{-1} , vertical descending speeds of about 1.6 cm s^{-1} were observed under the convergence streaks. At the same time, the horizontal speed of water motion at the surface was about 15 cm s^{-1} . It was determined that spiral circulations caused by the wind penetrate as far as the depth of the thermocline layer. Distances between the well-marked streaks of convergence are usually similar to the penetration depth of transverse circulation. Based on numerous data, Langmuir circulations are an important source of turbulent motions in the surface water layer where horizontal and vertical transfer of elementary microvolumes of water simultaneously takes place [118, 125, 126, 147]. These water movements are extremely important for the organisms of the epipelagial zone [228, 234].

Fig. 2.16 Scheme of formation of Langmuir convection cells pair caused by wind influence (*hatched areas* identify the streaks of suspended matter accumulation)



Usually the wind-driven streaks marking flow circulations already become visible when wind speed exceeds $3\text{--}5\text{ m s}^{-1}$ and generates the associated wind flows. The distance between neighbouring streaks ranges from dozens of centimetres up to dozens of metres and more. Thus, Langmuir circulations are vortexes perpendicular to the wind direction and developing in the upper layers of a basin (above the pycnocline). Near the surface, water particles move in the direction of wind streaks where they sink down, creating the so-called downwelling. On the contrary, particles rise up between the windrows thus creating upwelling. At the bottom of Langmuir vortexes, the direction of water circulation reverses with respect to the surface. Two adjoining wind streaks (convergence bars) delimit a two-dimensional circulation cell comprising two oppositely directed vortexes (Fig. 2.16).

On the water surface, each pair of counterrotating Langmuir convection cells forms a stripe of suspended matter in the zone of convergence of surface flows.

In addition, it was found that dissolved OM also concentrates along the convergence line in the thin surface film at the “water–air” interface [36].

Following the pattern of Langmuir convection, flow circulation has opposite directions at depth and at the water surface where regular accumulation of suspended matter can also occur. In convergence zones, the concentration of phyto- and zooplankton can exceed that in the adjacent zones by twofold [36, 209].

In the correspondence of wind streaks, the vertical descending speeds reach about 10 cm s^{-1} and slightly exceed the ascending speeds. Within a circulation cell, vortexes are asymmetrical and thus each cell also has a longitudinal velocity component directed alongside the wind direction, besides the transverse one. The longitudinal component is higher in wind streaks than between them. At sudden changes in wind direction, streaks rearrange along the new direction within a couple of minutes. Typical time scale for this type of circulation spans a couple of minutes, while the corresponding spatial scale is measured in metres as it was already mentioned.

Langmuir circulations originate near the surface and then propagate into the depth. Clouds of air bubbles, which form at wave breaking, concentrate along wind streaks and are carried by Langmuir circulation within the limits of the upper mixed layer. Despite the significant variability in cells' sizes, their dominant dimensions

are well-defined. In small aquatories, for example lakes, the distances between two streaks can be up to 35 m, but distances of 13.5 and 12.0 m are most often observed [147].

It was already mentioned that, at wind speeds of $5\text{--}15\text{ m s}^{-1}$, a whole hierarchy of different-scaled motion cells originates [200]. The width of the average circulation cells is in the range 35–90 and 5–10 m for small-sized ones that are characteristic for MPs aquatories. At cells' destruction, their energy is transmitted to smaller vortexes. This situation occurs when Langmuir cells interact with HTS of MPs.

Thus, in water basins, there are the short-lived zones of flows convergence whose persistence is measured in hours or days. Convergence zones are also characterized by the highest concentrations of neuston organisms, which disperse as soon as the forces that gathered them together stop acting. Such temporary zones of convergence and water sinking are convergence streaks, or storm streaks. They are elongated in parallel lines along the wind direction. The distance between the streaks is proportional to depth and diminishes in shallow water. In convergence streaks, the neuston accumulations represent narrow (less than 1 m), long streaks extending downwind [71].

Planktonic organisms, whose buoyancy is practically neutral, are easily carried down and it is one of the main causes of macrozooplankton abundance in the down flow of convergence zones.

Short-lived and small-scale accumulations of neuston organisms appear under the influence of vortex-type flows formed in the shadow zones of different HTS and ships.

Contrary to turbulent wind mixing, formation of Langmuir convection cells increases the heterogeneity in the distribution of dead suspended OM and dissolved OM in surface water masses on the one hand and controls it for a more or less prolonged time on the other. Functioning of Langmuir convection cells favours the formation of "accumulations" of dead and alive organic matter in mixed layers having relatively homogenous temperature and salinity.

In natural water basins, various hydrodynamical processes with different spatiotemporal scales usually take place simultaneously and superpose one upon another. Nonetheless, it can be surmised that Langmuir circulations and the surface thermal (gravitational) microconvection are the physical driving forces leading to the increased concentrations of phyto- and zooplankton organisms in the hyponeuston and epiplankton layers. The concentration of fish pelagic eggs in convergence zones obviously provides the best feeding conditions to their larvae and fries after hatching.

In MPs aquatories, Langmuir circulations not only form accumulation of suspended OM at the surface, but also create the preconditions for accumulation of SOM and DOM near HTS lateral surfaces.

For small-sized planktonic organisms, the movement of water particles in vortexes with a diameter of about 5–10 m and more practically has a rectilinear and laminar character. Microvortexes with a size of 1–10 cm have a scale similar to the hydrobionts inhabiting the water column, the bottom and the HTS surfaces of MPs.

These microvortexes do not damage the inhabitants of the water column and wash out of their settlements without harming individual organisms.

Numerous studies showed that gas bubbles originated by sea roughness, photosynthesis, decomposition and other phenomena adsorb organic substances and transport them to the surface when rising up in the water column. After this phenomenon, changes of organic matter dispersity take place in the organic coatings of these bubbles. In practice, truly dissolved or colloidal organic substances form particles or aggregates whose composition and size allow their consumption by microheterotrophic organisms [71, 74].

Gas bubbles cover about 3–4% of sea surface at any moment. The number of bubbles increases in the presence of vertical transverse circulations of various scales. The ratio among substances contained in bubbles escaping into the atmosphere considerably differs from the ratio of the same substances in seawater because fractionation of some substances takes place during bubble formation. In exploding bubbles sprays, ammonium concentration is hundreds of times higher than in typical water samples and phosphates can be enriched from 3 to 600 times. OM concentration in bubbles exceeds that in the seawater by up to 2000-fold. A drop forming following the explosion of a bubble of one millimetre is projected upwards with a speed of about 10 m s^{-1} , flies up to 10–15 cm and quite often evaporates in the air, transforming into a salt particle. These particles can then be carried away by the wind. During emersion of inert gases bubbles in the water column, the “dissolved inorganic” phosphate transforms into particulate “organic” phosphate. Such phosphate-containing particles serve as food for some planktonic organisms [110].

In the water column, part of the dead bodies of planktonic hydrobionts, especially crustaceans, acquires positive buoyancy and rises up during decomposition. The above-mentioned flotation process which continuously takes place in the sea also contributes to this phenomenon. The presence of this “anti-rain” of dead bodies causes the constant presence of alive and dead organisms in the near-surface layers. Depending on the different water circulations, the ratio between dead and alive organisms in the upper mixed layer can experience significant fluctuations in convergence and divergence streaks.

As a result of the dead bodies “anti-rain”, which directly affects the hyponeuston layer, a significant part of dead hydrobionts and fragments of their bodies concentrates in the film of surface tension and in foam. The rests of phyto- and zooplanktonic organisms are also found in foam [71].

Zooplankton density under convergence streaks could exceed the density in the adjacent zones by 100-fold [36]. In convergence streaks, concentration of pelagic eggs of fish, passively retained in the near-surface water column, provides favourable foraging conditions to larvae after embryos hatching and exhaustion of yolk stocks.

In the mixed layer, the relatively low speeds of water particles in vertical circulations permit to big-sized diatoms and unicellular flagellates to actively move in water. Flagellates usually swim upwards towards the light, while diatoms (which are mass species in MPs aquatories) strive to go into the deeper layer using the

vertical circulations. Flagellates concentrate near the water surface at weak turbulence and low descending water movement.

Significant accumulation of dead and alive planktonic organisms in the surface layer, as well as rains, hamper the development of roughness and vertical circulations at the surface of MPs aquatories.

Convergence streaks on the surfaces of aquatories are formed from floating particles of different origin such as fragments of macrophytes, phyto- and zooplankton, and dead insects. These streaks constitute peculiar biotopes for some invertebrates, larvae, newly hatched young fries and juvenile fish. The oldest hyponeustal stages of invertebrate larvae and fish fries are common among accumulations of flotsam which, as a rule, are typical for convergence zones [71].

In MPs aquatories, various horizontal and vertical water movements, including Langmuir circulations, favour SOM, DOM, phyto- and zooplankton accumulation in the near-wall layer of HTS and in the harbours most distant from ACs.

Zaitsev [71] described a situation in which the water surface under the foam and in the spaces between its flakes was swarming with hyponeuston. Fries of the leaping mullet and dragonet, larvae of combtooth blennies, sand sole, anchovy, zoeas of decapods and megalopes of crabs, isopods and pontellidae, as well as numerous smaller-sized hydrobionts not perceptible by unaided eye, were swimming among algal fragments, wood chips, land-living insects, seeds and various garbage. Larvae and early fries of garpike raising to the surface were also connected with this biotope.

In MPs, wind and surface flows play an important role in the neuston distribution. Neuston reacts sensitively to the constant and temporary water motions of different scales [71] observed in MPs harbours.

In MPs, interconnection of various phenomena and processes in the pelagial, periphytal and benthal zones and, most importantly, the cause–effect relationship among them are mainly determined by the action of microvortex-type water motions, i.e. turbulence. In MPs, the processes supplying energy to the water column, the HTS near-wall water layer and the near-bottom water layer are slightly different than those in the open zones of the shelf, because the macroscopic spectral components of water movements (wind waves and flows, Langmuir circulations, seiches, inner waves, ships' waves and other) are reduced.

2.1.3 Salinity

Water salinity is a major ecological factor which, in MPs aquatories, is determined first of all by the salinity of incoming water masses and their interactions.

In the open regions of the Black Sea, the salinity of surface waters is 17.5–18.5‰. However, salinity of the surface horizon reduces significantly in the NWBS, in the Kerch pre-strait zone and near the mouths of big rivers, especially during the flood period. In various regions of the Azov Sea, the water salinity of the surface layer experiences strong fluctuations, but its average values are about 12.0–13.0‰.

In Sevastopol Bay, salinity usually stays around 17–18‰ at the surface and it is slightly higher near the bottom. However, salinity can decrease to lower values in the estuary of river Chornaya which flows into the bay [3]. In a significant part of Novorossiysk port, adjoining the Tsemes River estuary, water salinity changes from 8 to 16‰ during the year [51].

Before the digging of a 5 m deep channel in 1909, Varna Lake was a freshwater ecosystem. In August 1911, the superficial salinity reached 11.11‰ and hydrogen sulphide appeared near the bottom. In 1976, Varna Lake was connected to the sea by a second channel with a depth of 10 m. In 1976–1985, the salinity had increased throughout the water column to an average of 14.81‰ (range 11.13–16.31‰) in the surface layer and to 15.86‰ (range 13.91–17.50‰) in the near-bottom layer. The general tendency of increase in salinity was accompanied by the decrease of river run-off which, during summer months, was less than evaporation [144]. In 1990, a salinity of 17.08–17.23‰ was registered in Varna Lake, while values of 16.54–16.94‰ occurred in the connected Beloslav Lake [194]. The yearly hydrochemical regime in Varna Lake is not as distinctly marked as in the sea due to its water exchange peculiarities which are mainly influenced by offshore phenomena. The increase of seawater entry into the lake ameliorates its regime [144].

In Odessa MP, the average monthly salinity minimum of about 11.5‰ occurs in April–May, while the corresponding average monthly salinity maximum is usually registered in August–September with values in the range 15.6–15.7‰. However, salinity fluctuations from 3.4 to 18.4‰ were registered in the period 1999–2001. Such values indicate that water in the Odessa port aquatory is a mix of freshwaters from the Dnieper-Bug Liman and the deepwaters of the Black Sea. Persistent east quarter winds favour the entrance of desalinated waters into the Odessa Gulf and further westwards. During the period of spring floods, the seasonal halocline in the Odessa region of the NWBS is located at a depth of 3–5 m. The halocline further deepens at the beginning of summer before gradually weakening in the second part of summer and disappearing in late autumn. In winter, associated with homothermy, a mild halocline gradually forms at a depth of 7–9 m because of the periodical entry of water from the Dnieper-Bug Liman region [154].

The minimum salinity values (6.0–7.0‰) in the surface horizon of Grigorievsky Liman are registered in spring. In the same way as in Odessa MP, this situation is connected with the entrance of waters from the Dnieper-Bug Liman during the high water period. A two-layer structure is established in the liman. In the upper layer with a thickness of 3–5 m, salinity is in the range 7–8‰ and in the near-bottom layer it is 15–17‰. In Grigorievsky Liman, a weak variability of salinity near the bottom is observed all year round [196]. The desalinating influence of Dnieper-Bug Liman waters in Odessa MP frequently manifests much more strongly than in Grigorievsky Liman, albeit the latter is located noticeably closer to the source of fresh water. Such situation occurs because Grigorievsky Liman is connected with the sea via only one channel with a cross section of about 3000 m², while Odessa MP aquatory and Odessa Gulf are connected to the sea by three passages with a total cross-sectional area of about 11,300 m².

In the central part of Sukhoy Liman, the amplitude of salinity fluctuations is 5.28–18.06‰. In this basin, differences in salinity between the surface and the near-bottom layers reach 10–12‰ and salinity in the near-bottom waters is higher than at the surface throughout the year.

In MPs of the NEBS, similarly to Sevastopol Bay, significant differences in salinity between the near-surface and the near-bottom horizons are not observed.

2.1.4 Temperature and Ice Formation

The temperature regime of the Black Sea is typical for a temperate zone basin. The marine area is characterized by stronger winds than the surrounding land. The prevailing winds blow along the north-western, western and south-western directions, which is connected with the atmospheric circulation at mid-latitudes in the Northern Hemisphere. During the summer months, winds blow from the sea to the land (onshore) during the day and from the land to the sea (offshore) at night. In winter, the surface waters of the north-western and north-eastern regions of the Black Sea cool down to zero and an ice cover can form in the shallow-water shelf zones, bays and limans where ports are located. The coldest area is the north-western part of the Black Sea. Similar water temperatures, or sometimes even lower ones, are registered in the Azov Sea. The Black Sea annual average water temperature varies from 11.0 to 11.5 °C near Odessa to 15.5–16.5 °C in the Sochi region. In the winter period, waters of the northern part of the sea are subject to cooling to zero, while those in the southern part preserve temperatures around 8.0–9.5 °C. In winter, Bulgarian and Romanian coasts are under the influence of much warmer Mediterranean cyclones. The average air temperatures in winter are in the 0–0.6 °C range for the coastal region from Sulina to Mangalia and vary from 0 to 5 °C along the coasts from Mangalia to the Bosphorus strait.

During winter, the deepwater regions of the Black Sea have surface water temperature of 5–9 °C. In summer, the sea surface warms up to 28–30 °C near the shores and to 21–23 °C in the deepwater regions. According to monthly mean data, the annual variations in temperature of the surface water layer are about 17–20 °C in most of the Black Sea coastal regions. In Varna Bay, the maximal range of temperature fluctuations reaches 30 °C [208]. Similarly, in Odessa, Ilyichevsk, Yuzhny, Sevastopol, Novorossiysk MP and others, the water temperature fluctuations are in the range of 28–30 °C, while they are significantly lower (about 15–20 °C) on the southern coasts.

In the NWBS and NEBS, the thermocline starts to form during the period of spring warm up (March–April). In many zones of the Black Sea coast, spring arrives lately because of the slower heating of seawaters in comparison with land. In the same way, autumn is warmer and sunnier in the coastal regions of the Black Sea than in those farther from the coast.

In MPs, the warming up of water to 26 °C is critical for many hydrobionts. However, vagile hydrobionts have the possibility to plunge down into the deeper

water layers to take advantage of the quick decrease in temperature with depth. In all ports with depths above 8–10 m, a two-layer structure of water masses can form in the near-bottom layer. In Sevastopol Bay, the differences in temperature between the surface and near-bottom layers sometimes reach 12–15 °C [3]. In the aquatories of Odessa, Ilyichevsk and Yuzhny MPs, the temperature gradient can sometimes exceed 10–12 °C [154]. In MPs, the formation of the thermocline has various consequences.

The light shadows observed in MPs worsen the warm up of the upper layer and sometimes cause local temperature differences of up to 2–3 °C.

On the northern coast of the Black and Azov Seas, air temperatures up to 30 °C are registered. On the southern coast of the Black Sea, the air temperature in January is everywhere positive with values of 5–6 °C above zero. In the northern regions, the water cools down to 1–3 °C below zero. At such negative temperatures, the water surface in the NWBS, in Dniester and Dnieper-Bug Limans and in the Azov Sea is sometimes completely covered with ice having a thickness of up to 50–60 cm.

The freeze-up period negatively influences the living population of water bodies, including MPs aquatories. The ice cover isolates water from air and interrupts the diffusion of atmospheric oxygen into the water. Furthermore, snowfall on the ice surface decreases the penetration of solar radiation into the water column, sharply slows down oxygen production by photosynthesis and thus decreases oxygen concentration in water. In this context, oxygen consumption by bacteria, aquatic plants and animals for maintenance of their vital activity can contribute to the development of hypoxia and anoxia.

Division of MPs aquatories into separate harbours as, for example, in Odessa MP accelerates the formation of ice covers. To maintain ship-pilotage, ice in the shipping channels and in MPs aquatories of the Black and Azov Seas is periodically broken down with the help of icebreakers and powerful tugs. These measures also ameliorate the oxygen regime in the water column and at the bottom. In places where such operations are not performed, winter mass mortality of bottom fauna is not rare.

The aquatory of Novorossiysk port occasionally freezes in some years, but ice covers do not form in other ports situated southward of it. Mariupol port (Azov Sea) is open all year round, but the average duration of navigation with ice- channelling during harsh winters comprises 86 days from December until March.

In Odessa MP, ice formation does not occur every year and most often is limited to partial freezing of the harbours. The earliest complete freezing was observed at the end of second decade of December and the latest one in the first decade of March. The latest date of final cleaning from ice in Odessa MP was observed in the first days of April [16]. During severe winters, ice in MPs aquatories could mechanically damage hydrobionts-foulers in the near-surface horizon.

The internal variation of temperature in the surface layer of Grigorievsky Liman shows the maximum value in August (peak of the summer hydrological season) and the minimum one in February (peak of the winter hydrological season). This pattern coincides with the average long-term annual variation of temperature in the adjacent

sea region. Maximal temperature near the surface is 26–28 °C, but can reach 30 °C in shallow waters [196]. This feature is also characteristic for the aquatories of other MPs. In Grigorievsky Liman, ice most often appears in December and complete freezing is observed in the second part of January. The cast ice thickness is 40–45 cm during moderate winters and 55–60 cm during severe ones. The aquatory cleaning from ice usually occurs at the end of February, although ice can persist until the end of March in severe winters. Ice formation in the aquatory of Sukhoy Liman follows the same pattern [154].

In Odessa MP, ice formation can sometimes be tightly connected with slack ice carried from the Dnieper-Bug Liman. The presence of three passages into Odessa port favours the entrance of slack ice which, driven by wind and flows into the aquatory, can form a continuous ice cover at low temperatures. The entrance of slack ice from the Dnieper-Bug Liman into Grigorievsky and Sukhoy Limans was not observed.

In aquatories of the NWBS, the slack ice is carried from the Dniester Liman and from the near Danube region. It does not usually diffuse farther south than Kaliakra Cape, even if it may be found up to Bosphorus strait in very cold winters.

Near the Crimean shores, ice can be formed up to Tarkhankut Cape and slack ice can reach Yevpatoriya port. The slack ice carried out from the Kerch strait may float up to Anapa to the east and up to Feodosiya to the west.

Seawater ice contains less salt than seawater before freezing. Salinity of the lower ice layer, submerged into the water, is higher than that of the upper layer, even for the freshwater ice carried into the sea because its lower part is soaked with seawater. Ice melting leads to reduction of water salinity in the surface layer of MPs aquatories.

2.1.5 pH

In the Black Sea surface waters, the pH value ranges from 8.1 to 8.5 units. The pH value depends first of all on the quantity of carbon dioxide dissolved into the water and on the content of hydrogen sulphide. At relatively high hydrogen sulphide contents, such as those observed in the near-bottom water layer of MPs during periods of phytoplankton die-off after mass vegetation, the pH value can decrease to 7.6. In pore waters, the pH value sometimes reduces to 6.0. With the increase in temperature of the water surface layer and intensification of photosynthesis, the pH value increases because the water carbon dioxide content decreases.

In the eastern part of Varna Lake, the pH value varies from 7.20 to 9.85 (average 8.10) [144].

In Sevastopol Bay waters, pH ranges from 8.23 to 8.53 in the surface horizon and from 7.91 to 8.49 in the near-bottom layer. Average pH values of 8.20–8.30 are typical for bay waters in the winter–spring period, which could be also connected with river run-off influence [3].

In 1998–2001, the pH values in the surface layer of Odessa MP aquatory have changed from 7.80 to 8.90 during different seasons [16].

The range of pH fluctuations in Grigorievsky Liman waters is quite considerable: 7.50–9.20. The pH values in the surface horizon of liman waters reach maximal values of 8.80–9.20 in zones with active photosynthesis, during the warm period at mass development of phytoplankton and water “blooms”. In the near-bottom horizon, the pH value reduces to minimum values for marine environment (7.50–7.80) during OM destruction and hypoxia. In the cold period, pH values are relatively stable at 8.30–8.40 from the surface to the bottom [196]. In Sukhoy Liman, the pH values are in the range 8.18–9.19 [154].

In MPs, water usually preserves the slightly alkaline milieu near the lateral surfaces of HTS under the vegetal fouling in the near-wall. Fouling by animals, especially by molluscs, is accompanied by the formation of acidified waters in the near-wall zone because of the release of carbon dioxide.

2.1.6 Vertical Water Exchange and Vertical Stratification of the Water Column

Vertical and horizontal gradients play an important role in coastal marine ecosystems, including MPs aquatories that experience strong freshwater inputs from rivers, land run-off, and industrial and municipal drainage. Because flows and general hydrodynamics in MPs aquatories are weakened by artificial protections, the importance of vertical water exchange increases. Owing to gravity and other factors, the near-surface and near-bottom water layers, adjacent to the film of surface tension and directly overlying bottom sediments, play a particular role in functioning of MPs aquatories ecosystems with regard to the distribution of live and dead OM. Isopycnic surfaces in the water column are also involved in the same processes.

Significant vertical gradients exist in the coastal part of the Black and Azov Seas, and in MPs aquatories with depths up to 20 m, for many important parameters such as temperature, salinity, redox potential, concentrations of gases (e.g. oxygen and hydrogen sulphide) of importance for hydrobionts, and biogenic substances such as phosphates, ammonium and others. The position of gradients in the MP water column vertically reflects the interaction of hydrodynamic factors, first of all the vertical and horizontal motions of water masses. In MPs, anthropogenic activity, mainly connected with ships movement (draft, velocity, number, frequency, etc.), has a mitigating effects on gradients. The smaller are vertical density gradients, the easier mixing extends to higher depths and vice versa.

In MPs, vertical stratification (i.e. division of the water column in temporally stable pelagial layers) is determined by a series of factors. In spite of the relatively small depths, a thermocline and halocline can form in MPs aquatories of the Black–Azov basin because of the significant differences in temperature and salinity between the surface and the near-bottom water layers. A water density jump, called pycnocline, is observed in correspondence of such gradients. Along with other consequences, the pycnocline hampers oxygen penetration into the near-bottom

layer, thus favouring the accumulation of hydrogen sulphide near the bottom. In MPs, detritus accumulation occurs in the water column at the isopycnic surfaces. The lowered hydrodynamics and the presence of natural and artificial aquatories, along with deep ACs, speed up the pycnocline formation compared with the adjacent sea zones. In MPs, the pycnocline formation is usually determined by temperature differences and has a seasonal character. However, in some aquatories, e.g. the Donuzlav Liman, the halocline could be preserved throughout decades.

In the Black–Azov Sea basin, many MPs represent, properly speaking, temporary or permanent meromictic aquatories. These aquatories have a two-level stratification of the water column with the water of the lower layer being colder and saltier (and therefore denser) than the water of the upper layer. In such aquatories, the circulation usually takes place only in the less dense surface water layer.

In marine waters, density-related water stratification is stable and resistant to vertical mixing. Under stability is intended a vertical density gradient and correction for adiabatic temperature change. In surface layer and in the coastal waters adiabatic correction in comparison with vertical gradients of density is very small and it can be neglected [81]. The value of conditional density is a number derived from temperature and salinity and it is usually lower in the surface than in the near-bottom layer.

In the NWBS open waters, vertical density gradients could exceed 6 units of conditional density per metre of water thickness and even winds with speeds of $15\text{--}17\text{ m s}^{-1}$ cannot destroy the existing pycnocline [75]. In Grigorievsky and Sukhoy Limans, as well as in Odessa Gulf, the density gradient could reach 8–10 units. In the coastal desalinated regions of the Black Sea, the average water density is about 1.0115 g cm^{-3} with variations between 1.0100 and 1.0105 g cm^{-3} near the rivers mouths and in the surface layer of MPs during the summer period. As a rule, the water density is notably higher in the AC and in the near-bottom layer of an MP than near the surface. Owing to such differences, the near-bottom layer is characterized by a maximal vertical stability and gravitational mixing of heavy and light water masses becomes impossible. Densities of water layers in MPs are primarily determined by temperature and salinity, wind-related factors, input of river and surface run-off and water discharge from land.

During periods of strong offshore–onshore phenomena, both strong floods and artificial weakening of river run-off entering MPs aquatories could contribute to the penetration of saltier deepwaters into the near-bottom layer as a compensation flow. In such situations, the pycnocline position in the water column raises and its thickness decreases. As a consequence, vertical gradients of density and stability of water masses increase.

As it was already mentioned, the mixing and homogenisation of MPs water masses result from temporally and spatially variable turbulent motions. Weakening of such movements leads to vertical stratification of the water column. In MPs, the primary sources of micro- and mesoscale turbulent energy, which play the most important ecological role by influencing vertical water exchange and stratification of water masses, are mainly located at the sea surface. Generation of turbulent energy originates from dispersion of ordered average velocity of flows [1] fading

with increasing of water depth. In the aquatories of MPs of the Black–Azov Sea basin having various levels of protection, the temperature of the surface waters is usually 1–3 °C higher than in the adjacent zones during spring, summer and autumn. In summer, the surface waters temperature decreases to some extent because of evaporation and of the increase in salinity caused by wind mixing. As a consequence, the density of surface waters could be even higher than that of the underlying layers. In spring and summer months, which are hotter and less windy than the average, a more marked development of the thermocline is observed, resulting in maximal stability of the MPs surface and near-bottom water layers.

During windless days in summer months, the nearshore and MP waters can warm up to 25–26 °C and, occasionally, to 28–30 °C in the surface layer. In AC and at MP bottom, water temperature can be around 10–13 °C [16, 154, 196]. Concrete and metallic construction, mechanisms and ships heat up during the day and give away heat to air and water masses during the night; which can influence the local distribution of temperature in MPs aquatories.

Water basins heat up owing to inputs of solar energy to the water surface and into the water column. Heat exchange with the near-bottom water layers depends on the temperature of the water surface. As a result of differential heating and cooling of water, the water column stratifies at various depths of the water basins. Stratification is firstly caused by physical characteristics and then by chemical and biological ones. Changes in water temperature along aquatory and depth are diurnal, seasonal, annual, and long term. They depend, first of all, on inflow regime and absorption of solar energy. The warmed-up superficial water layer is mixed with the deeper layers owing to various hydrodynamical processes [79, 85, 89, 145].

The temperature regime of water basins includes periods of daily and spring–summer warm up and night and autumn–winter cooling. These temperature fluctuations trigger the dynamic mixing of water masses. The artificial shading of various zones of MPs aquatories causes water temperature gradients. In MPs, the presence of light and wind shadows contributes to uneven water heating, formation of microflows and convective mixing. Convective water motion is connected with energy transmission in the form of heat.

As already mentioned above, such motion is observed in the near-surface water layer (0–30 cm) owing to interaction between the atmospheric air and solar heat and also in the near-bottom layer (0–20 cm) owing to geothermal processes.

MPs aquatories located in the NWBS are largely influenced by large rivers such as the Danube, Dnieper, Yuzhny Bug and Dniester. In these cases, the role of salinity in the pycnocline formation is extremely important. In spring, marine water from the regions near river mouths is desalinated by river waters and spreads over the surface of the saltier, colder and denser seawater, gradually mixing with it. Spreading of such waters takes place rather quickly. Under favourable wind conditions, the desalinated waters from the Dnieper-Bug Liman, reach the Odessa Gulf and enter the aquatory of Odessa MP within 2–3 days. A desalinated layer of about 3–5 m can be stable for most of the year and only autumn–winter storms will cause its mixing with the lower, saltier water layer.

In the Black Sea and in the NWBS, the pycnocline position changes during the year. Thus in the NWBS and in MPs, the pycnocline lowers to the bottom and disappears in winter due to the reduction of temperature in the upper water layer, the decrease in river run-off and the intensive mixing. In the aquatories of Odessa, Yuzhny and Ilyichevsk MPs, the differences in temperature and salinity between surface and near-bottom waters could exceed 10 °C and 10‰ during the summer months, but become very small in winter. The water column becomes more homogeneous. In the NWBS, the seasonal pycnocline extends over a layer of 5–15 m and regularly forms in MPs aquatories. In Sukhoy and Grigorievsky Limans, the pycnocline can form earlier, and disappear later, than in the adjacent zones of sea because of several factors. A seasonal pycnocline is registered in Sevastopol and Novorossiysk Bays and in other MPs with depths above 8 m and which receive inputs of river water to a different extent.

The oxygen concentrations in seawater usually range from 1–2 to 9–10 mg dm⁻³.

The processes leading to seawater enrichment in oxygen are distinguished in O₂ diffusion from the atmosphere, the so-called “old” oxygen which enters the water column due to mixing of the near-surface water layer, and O₂ production during photosynthesis in the near-surface water layer, the so-called “young” oxygen. Processes lowering oxygen content of the whole seawater column include O₂ evasion to the atmosphere, its consumption for oxidation (biological and biochemical processes), organisms respiration and oxidation of various contaminating substances of natural and anthropogenic origin.

In semiclosed MPs aquatories, the formation of a sharp pycnocline hampers oxygen diffusion into deepwaters and favours its almost total or total depletion in the near-bottom layer. The absence of oxygen leads to diffusion of hydrogen sulphide from the bottom sediments into the water column.

The absence or presence of a certain degree of hypoxia in the lower water horizons is an indicator of the intensity of vertical water exchange in MPs. In recent decades, in the NWBS, hypoxia starts to develop in May and persists until September in the near-bottom layer. Hypoxia extends from the bottom up to depths of 12–15 m, for areas with total depths of 17–23 m, and up to depths of 5–6 m for areas with total depths of 10 m. In the middle of this period, the thickness of the near-bottom water layer contaminated by hydrogen sulphide varies from 2 to 6 m and H₂S concentration reaches 0.95 ml dm⁻³ [75]. In general, the thickness of the water column with conditions favourable for hydrobionts reduces to a couple of metres of the epipelagial zone.

In Odessa region, a strong pycnocline forms regularly in spring–summer because of the warming up of surface waters, the influence of river run-off (in spring) and the weakening of wind action (in summer). This pycnocline blocks mass and gas exchange between the surface and deep layers. Under such conditions, the wind-induced coastal upwelling of waters, which develops at offshore winds, acquires an important ecological role [82, 172].

In the NWBS, hypoxic zones coincide with zones of suppressed vertical exchange in 73% of cases. In other cases, the differences can be ascribed to inertia of the physico-dynamical and biochemical processes [75].

In Sevastopol Bay, the difference in water density between surface and bottom waters was reported not to exceed 0.4 units of conditional density in spring during the period of pycnocline disruption. At the beginning of summer, the whole water column was weakly stratified and well mixed. In July, the difference in density between the surface and the near-bottom layers had raised to 2.4 units of conditional density and the possibilities for mixing worsened [123].

Balaklava Bay serves as an interesting and illustrative example of water masses behaviour in relatively deep aquatories with limited water exchange. Its length (incut depth into land) is about 1400 m with a width of about 300 m in the middle part and less than 200 m near the entrance. The bay is 34 m deep at the entrance and 2–4 m in its apex part. The salinity in its apical zone is 0.2–0.5‰ lower than that in the major part of the aquatory due to the influence of river Balaklavka run-off and surface land run-off. The Georgievsky source (a submarine discharge of fresh waters) is located at the south-western coast of Balaklava Bay, while a municipal collector of sewage waters, which locally causes desalination, is located on its south-eastern coast near Balaklava Cape [105, 106].

In warm months, the temperature profile shows a marked vertical stratification in most of the bay's aquatory. In the apical part, with depths of 4–5 m, the temperature of the water column remains uniform. On the other hand, in the rest of the bay's aquatory, the typical situation consists in the presence of an upper quasi-homogeneous layer (about 10 m thick and with an average water temperature of 19.8–20.0 °C) overlying a pycnocline showing a 0.5 °C m^{-1} gradient between the depths of 10 and 15 m. During the cold half-year period, the vertical stratification of the temperature profile is smoothed by convective flows. Vertical stratification of the temperature profile appears in April–May, remains stable until autumn, and disappears in October–November [105].

During offshore phenomena with associated upwelling, the nutrients' concentration in Balaklava Bay can decrease, by one to twofold during 0.5–17 days, to the concentrations typical for the Black Sea surface water thanks to turbulent diffusion. This happens even in extremely rare situations of heavy nutrient pollution (floods, heavy showers, dredging). The time to homogenize, via mechanisms of turbulent diffusion and processes of biological degradation, the concentration of nutrients in water masses interacting during upwelling processes varies from 0.2 to 11 days in situations of extreme pollution and from 0.2 to 2 days—for reference situations. In Balaklava Bay the whole upwelling cycle is completed within 1–10 days [106]. These observations provide information on the time scale of upwelling phenomena and confirm that they represent an important mechanism for reducing biogenic matter concentrations in MPs aquatories with depths of 8–10 m and more via water exchange, mixing and diffusion.

The upwelling phenomenon is also observed in the open sea, in particular, in the region of cape Kaliakra [62]. On the 28th of August 1986, the water temperature at the surface was 26 °C in spite of the strong south-western wind. After three days, the water temperature was only 7–8 °C. At the same time, all metal objects and dredges immersed in water turned black, which testified the presence of hydrogen sulphide. Oxygen was indeed lacking in the whole water column.

The pycnocline hampers the diffusion of oxygen into the near-bottom layer, weakening vertical mixing during warm months. In ports of the NWBS, NEBS and in Sevastopol Bay, the months of July, August and September are the most critical with respect to this aspect. The period of temperature stratification, during which the vertical circulation of the waters does not take place, is called stagnation period. During stagnation, an oxygen dichotomy phenomenon appears and oxygen content in the near-bottom layer is lower than above the pycnocline. Destruction of the pycnocline facilitates water exchange in the near-bottom layer and favours the increase of dissolved oxygen concentration into it.

During the spring–summer–autumn period, the high position (at 10–15 m depth) of the thermocline in the Black Sea ensures the increased stability of water masses in the upper part of the eutrophic zone and sustains development of diatom populations in well illuminated conditions [161]. Accounting for the presence of lower depths, this regularity also manifests in MPs aquatories.

In MPs, the processes connected with excessive eutrophication are exacerbated by protective structures, lowered horizontal water exchange, and formation of the pycnocline. This is why the worsening of vertical water exchange and prolonged stratification of the water column causes extremely negative, long-lasting consequences in their ecosystems.

Deepening of MPs aquatories to 8–20 m by dredging creates conditions for prolonged stratification of the water masses. In MPs, the presence of the deepwatered ACs favours the entrance into their aquatories of “tongues” of saltier seawaters, with thickness of a couple of metres, during the offshore phenomenon. In some situations, this phenomenon can contribute to the onset of upwelling and also intensify vertical stratification. When the low water layer is denser and the vertical mixing is hampered, less oxygen enters into the layer below the pycnocline and conditions become favourable to the formation of hydrogen sulphide, first within the sediments and then in the water column. The intensity of vertical water exchange is one of the major factors regulating hydrochemical and biological processes in the near-bottom water layer and in the benthal zone, particularly in MPs aquatories. The intensity of vertical gradients of water masses in the NWBS is one order of magnitude higher than in the open sea [154].

In the 2000s, the oxygen minimum in the NWBS was registered in the water layer having a thickness of 2–3 m and located directly below the pycnocline [174]. Hypoxic and anoxic layers can extend through the whole water column below the pycnocline. Such situations were observed in Mariupol port [85], in Varna Lake [142, 143] and in other MPs. In 1998–2001, regular phenomena of prehypoxia and hypoxia were registered in the near-bottom layer of Odessa MP from June to August [127].

2.1.7 Colour, Transparency and Illumination of the Water Column

The presence of ships of various sizes and in variable number inside MPs aquatories decreases the total area of the water surface impacted by sunlight and through which matter and energy can be exchanged. At the same time, the bottom area remains constant.

In MPs, the colour of water depends on season, depth, sediment character, quantity and characteristics of the suspension, transparency and illumination as well as on the port geographic position. The prevailing water colour usually has greenish-yellowish tints in ports of the NWBS and the Azov Sea, while blueish- and blueish-green tints are more common in ports of the eastern and southern parts of the Black Sea and at Crimean shores.

The NWBS coastal waters, particularly those of MPs aquatories, generally have greenish, yellow and yellow-green colours throughout most of the year; which is usually an index of high phytoplankton production. In MPs aquatories, the inflowing rivers, the discharges of waste and drainage waters, and the surface run-off carry differently coloured sediment particles which have various influences on the colour of water and on some hydrochemical and hydrobiological parameters. Many MPs are surrounded by cities and industrial constructions. An artificial increase of MPs aquatories protection increases the influence of the superficial flow from the drained areas into their ecosystems. Such influence reaches its maximum during floods, heavy showers and snow melting. During such events, the amount of sediments entering port aquatories is higher than during other periods. The Bolshoy Dalnik river waters flow into the aquatory of Ilyichevsk port, the Maliy Adzhalik river into the aquatory of Yuzhny port, the river Chernaya into the aquatory of Sevastopol Bay, the Tsemes river into Novorossiysk port aquatory, and the Tuapse river into the eponymous port. The suspended and dissolved substances of different origin entering MPs aquatories with the river run-off change the water colour and its transparency.

The ability of water to transmit sunlight depends on the characteristics of the water itself and on its transparency. The water in MPs aquatories can have various colours depending on season and meteorological conditions. The colour of water directly depends on the colour of substances dissolved into it as well as on suspended mineral and organic particles and microorganisms (ultranano- and nanoplankton) inhabiting the water column. In MPs, the mass development of small-sized planktonic hydrobionts, usually planktonic algae and protozoans, is quite often observed and causes water “blooms” phenomena. During planktonic blooms, water sometimes acquires a brown or reddish colour along with its usual green and yellow shades.

In MPs, the stirring of bottom sediments caused by strong storms, dredging, hydrotechnical construction and movement of deep-draft vessels causes changes in water colour and transparency that can last up to 2–3 days. In such cases, water acquires grey, yellowish or brown shades. During erosion of shores in the NWBS, the water acquires a reddish colour because of the presence of red clays and usually clears up over two days after the storm has ceased. Pale blue and grey clays give a corresponding colour to water.

In Sevastopol Bay, the water colour changes from blue-green (or green) at the bay entrance to yellow in its apical part [3]. In the river Tsemes estuary, located in Novorossiysk port aquatory, and in the adjacent north-western part of the port, the water has a constant lemon-yellow colour [51]. Water in Odessa, Ilyichevsk and Yuzhny MPs aquatories generally has a yellow, green or dimmed-yellow colour, although blue tints appear in winter [16, 154, 196].

Seawater often turns toward yellowish colours in the presence of high concentrations of the so-called “yellow substance” which is a mixture of dissolved OM of various origins; mainly dead cells of phytoplankton organisms [63, 161, 181]. In MPs, the water transparency depends on the concentration of suspended particles of various size and origin and on the presence of the aforementioned “yellow substance”.

In the Black Sea coastal zone and in MPs aquatories, upwelling is frequently accompanied by a water “albication” phenomenon. It occurs when, in the presence of surface run-off phenomena, the cold deepwaters (which during anoxia become slightly acid and contain hydrogen sulphide) react with bicarbonate, forming carbon dioxide and water. During the subsequent upwelling episode, the deepwaters bring a high quantity of dissolved carbon dioxide and calcium ions towards the surface where the water heats up. Upon heating, carbon dioxide evaporates into the atmosphere, thus increasing the water pH and forming numerous fine crystals of aragonite (CaCO_3). These crystals gradually sink to the near-bottom horizon, where they dissolve again in the slightly acid environment of the near-bottom water, or settle onto the sediment. The seawater with the suspended aragonite fine crystals is opalescent.

In MPs aquatories, the water transparency has a seasonal character. The highest transparency is registered during periods of slow phytoplankton development, no release of reproductive products of molluscs-foulers and absence of strong storms. The relative water transparency in the open part of the Black Sea varies from 10 to 18 m in winter and spring, from 15 to 25 m during summer and from 15 to 18 m in autumn. In the coastal zone, water transparency for the same seasons ranges from 6 to 10 m, from 10 to 15 m and from 5 to 10 m, respectively. In the NWBS, near the estuaries of big rivers such as Rioni, Kizilirmak, Yesilirmak and Sakarya, transparency usually varies between 2 and 4 m during the whole year [161, 189]. It is considered that the highest recorded transparencies in the Black and Azov Seas were about 25 and 6 m, respectively [73].

In waters with reduced hydrodynamics such as those in MPs, mineral suspended particles usually sink to the bottom quicker than the other components, so that the bulk of suspension comprises living vagile forms and relatively recently died cells.

In MPs, the vertical distribution of waters with different transparency is connected with the position of the pycnocline where plankton, detritus and other organic and inorganic suspensions accumulate. In the near-bottom layer under the pycnocline, the water transparency can sometimes exceed that near the surface by twofold.

In various ports of the Black–Azov Sea basin, the water transparency varies widely; from 0.5 to 7–8 m. The water transparency in the Azov Sea and in the NWBS ports is usually lower than in Crimean ports, the NEBS and near the coasts of Turkey.

In Sevastopol Bay, the water transparency changes in the different zones of the bay, but it is usually less than that in the open sea. The gradual reduction of transparency towards the upper part of Sevastopol Bay is a general feature during summer and autumn. Thus, transparency is 7.5–6.5 m near the entrance into the bay, 5.5–4.0 m in its central part—and about 1.5 m in the apical part. In the zone adjacent to the bay entrance, the average concentration of total suspended matter in surface waters is 0.57 mg dm^{-3} (range $0.02\text{--}1.8 \text{ mg dm}^{-3}$). Inside Sevastopol Bay, the average concentration of total suspension in the surface layer is 1.14 mg dm^{-3} , with a range of $0.3\text{--}5.0 \text{ mg dm}^{-3}$ [44]. In a significant part of Novorossiysk port aquatory, the water transparency often does not exceed 0.5 m [51]. In Odessa, Yuzhny and Ilyichevsk MPs, the water transparency varies between 2 and 5 m, sometimes dropping to less than 1 m [16, 154, 196].

As already mentioned, the variability of seawater transparency is substantially connected with the quantitative distribution of pico- and nanoplankton along with ‘net phytoplankton’ and composition of its dominant species. There is a direct and indirect link between transparency, illumination of the water column and phytoplankton development, so that a certain autoregulation of primary production is achieved in the photic zone [119, 161]. This autoregulation mechanism, along with others, is also present in MPs aquatories ecosystems. In MPs, clarification of the water column occurs during intensive grazing of phytoplankton by zooplankton which, in turn, becomes food for mass fish species (anchovy, sprat, horse mackerel, whiting, etc.).

The sunlight represents one of the energy forms that enter MP aquatories. Besides the natural sources, artificial light sources (e.g. coastal and ships’ illumination) are present in MPs. Most of the light energy absorbed by seawater transforms into thermal energy, increasing water temperature. A relatively small share of the incident light is used by plants for the transformation of inorganic carbon (CO_2) into organic carbon during photosynthesis; which maintains life in the marine environment. Because the photosynthetic process is initiated mainly by solar radiation, the amount of light energy available to pico-, nano-, micro- and macrophytes determines the quantity of OM primary production.

The amount of light energy entering aquatic ecosystems is determined, first of all, by illumination, i.e. the light quantity per unit of surface, and transparency, i.e. the ability of water to transmit radiation, including visible light. Light is required for the normal photic activity of autotrophs as well as for the normal development of reproductive products, reproduction, development and growth of heterotrophic organisms. In MPs, illumination decreases quickly with depth and the intensity of oxygen production by photosynthesis weakens accordingly.

In MPs, the seawater is a polydisperse system of chaotically oriented, heterogeneous organic (living and dead) and inorganic particles; all of them with the ability to disperse and absorb light. Accumulations of particles, frequently observed in the pycnocline zone, can cause dispersion of light upwards, thus increasing light exposure in the epipelagial zone. Phytoplanktonic organisms, actively migrating according to diurnal rhythms, order this process to a various degree. Part of the light energy directed from the water column upwards is subject to various degrees of refraction and does not go out from water, but it is again reflected downwards from the water surface although with weakened intensity.

A flow of radiant energy from the sun and sky reaches the sea surface. Sunlight comprises the main part of total radiation. Light enters the water surface in a form of direct and diffused radiation. A ray of light falling on the water surface is subject to diffraction, polarization and spectral separation, besides reflection and refraction. Furthermore, while passing through the water column, light is absorbed and reflected from different particles suspended in water, so that a different amount of light energy reaches the different water horizons. In MPs water column, the light spreads not only in the top-down direction, but also bottom-up and horizontally, also getting to the lateral surfaces of HTS in a weakened state. Thus, only a part of the light entering water becomes a source of energy for hydrobionts.

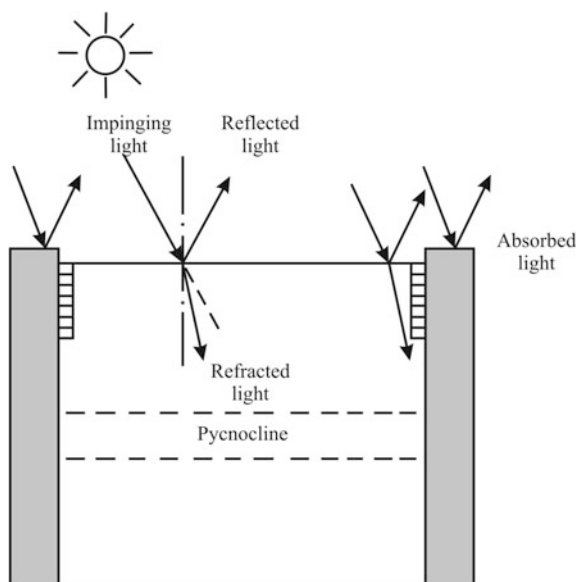
In the water column of MPs, the sunlight penetrates in the same way as in the adjacent regions of the Black and Azov Seas, i.e. half of the radiant energy is absorbed in the upper half metre of the water layer. In MPs the process can be affected by light shadows formed by mechanisms, various constructions, warehouses located on piers and berths as well as protecting HTS, berths and ships. Thus, the concentration of various suspensions and live planktonic organisms is often higher in MPs aquatories than in the open sea.

The major part of the energy falling onto the sea surface is transformed into heat. In MPs, part of the heat is spent on heating the big mass of HTS and ships. At night, this heat partially returns to the water masses and to the atmosphere.

The light rays are refracted at the interface between two different milieus. In seawater, this phenomenon occurs near the surface. Falling onto the water surface, a ray of light is partially reflected into the atmosphere and partially penetrates into the water. According to the laws of optics, the incident and reflected rays form identical angles with respect to the normal to the reflection surface, while rays that enter into the water are bent towards the normal by a certain angle. The angle between the direction of the refracted ray in water and the normal to the water surface is called the angle of refraction. This angle is always lower than the incidence angle that is the angle between the ray direction in air and the perpendicular to the water surface at the point of the ray penetration into water. A refraction angle never exceeds 48.5° which causes the formation of shadow zones (Fig. 2.17).

Thus, upon crossing the water surface, a light ray refracts and enters into the water at an angle of no more than 49° . At such an angle between light and the vertical, the border between light and shade already appears. Passing from a water layer with one salinity value into another, the rays of light are again refracted. The refraction index is different for rays with different wavelength and has the lowest

Fig. 2.17 Scheme of light transmission in the central part of MP aquatory and in the zones adjacent to HTS (hatched area: shadow zones of periphytal)



value for red light. Rays of this part of the spectrum, which is necessary for photosynthesis, are already absorbed in the upper water layer (about 5 m thick), yellow ones around the depth of 10 m, and green ones around 15–20 m. In general, the salinity of seawater does not markedly reduce light intensity. On the other hand, sea roughness changes illumination because of the formation of a water layer with a high quantity of air bubbles on the sea surface and can cause losses up to 15% [85]. In MPs aquatories, roughness is artificially weakened and illumination is slightly ameliorated compared with the open sea. The roughness causes fluctuations of the rays' propagation directions in water column because rays are refracted by a disturbed water surface. The roughness influence on the interaction of light with the sea surface becomes noticeable at a sun height below 20°. At low sun height, the reflection coefficient drops sharply because of roughness and more light enters into the water column.

Near all the infrared and the major part of the ultraviolet radiation of solar emission are already absorbed in the first metre of the water column. Since the long-wave part of spectrum (red, orange, yellow colour) carries the highest amount of energy, its absorption causes a more marked warming up of the upper metre of the water column. At lower depths, the role of light and chemical energy increases and the role of heat decreases sharply [36, 60, 63, 85].

In the relatively thin, but turbid layer of sea coastal waters inside MPs, complete (100%) absorption of long (infrared) as well as short (ultraviolet) wavelength is observed because of the presence of various suspensions. The minimal absorption occurs in the blue sub-spectrum near 0.47 μm . In the open ocean, a water column with a height of 10 m absorbs from 33 to 80% of the blue light, while the corresponding figure for the coastal waters in MPs is 94–100% [36].

The rays of light often refract and disperse repeatedly while diffusing from one water layer into another. Suspended live and dead particles and also the fine bubbles of gases constantly present in water favour light dispersion. Since accumulation of suspended particles takes place at the border of layers with different densities, layers differing in their degree of transparency and light dispersion appear in the water column.

When water is turbid, i.e. of little transparency, a strong dispersion of light takes place and water has a green colour. Clean, transparent water dissipates light weakly and has a blue colour.

Light dispersion in the marine environment is caused by the cumulative action of two different processes: dispersion by the water itself, which is a constant and main factor in determining light attenuation in the sea, and dispersion by the particles of organic and mineral origin suspended in water. Direct diffusion by water varies relatively little and only because of changes in temperature and pressure. On the other hand, dispersion by suspended particles depends on variations in their concentrations [63].

It is generally agreed that during summer the layer of optimum illumination in the Black Sea is located at the depth of 5–7 m. Above this depth, the photosynthesis of planktonic algae could be inhibited by excessive illumination and below it by lack of sufficient light [161]. In MPs, the optimum layer is close to surface because of poor illumination due to a variety of causes.

As it was previously mentioned, a significant part of the solar energy penetrating into water is already absorbed in the upper water layers. The amount of light energy absorbed by a water layer with a thickness of 1 m is about 92% for a water transparency of 0.7 m and a sun altitude of 12° , up to 76% at water transparency of 1.2 m and sun altitude of 39° and up to 46% at a water transparency of 1.6 m and sun altitude of 58° . At water transparencies of 2 and 7.5 m, the photosynthesis is most intensive at the depths of 1.5 and 6.3 m, respectively [145]. In MPs, because of the peculiarities of their ecosystems, depths from 0.2–0.5 to 1.5–3.0 m are optimal for photosynthesis.

Exposure to solar irradiation from above is a function of the sun elevation. Scalar irradiance in MP depends on sun altitude, light wavelength, water transparency and depth, presence of light shadows, orientation of the HTS rising out of the water and presence of ships standing at berth. In the winter period, the presence of an ice cover, possibly covered by snow, weakens the light penetration into the MP water column. The amount of solar energy entering the ecosystems of MPs aquatories depends on daylight duration and irradiance rate. The span of time during which aquatories are exposed to solar radiation depends on shores' height and harbours' orientation, especially at low sun elevations in the morning and evening hours. These conditions are different in each port.

The lower the sun elevation above the horizon, the more light rays are reflected by the water surface and do not enter the water column. At a sun height of 10° , less than two thirds of the light energy enters into the water. At such height, the distance that a ray must cross to reach a certain depth is 1.5-fold the value of that depth, compared with values of 1.32-fold for a sun height of 30° and 1.15-fold at a sun

height 50° [85]. All other conditions being equal, the longer is the path of a ray, the more it is weakened.

The irradiance of berths, moles and breakwaters, which usually have vertical surfaces, represents the so-called horizontal irradiance constituent and change within limits of 75–85% of total irradiance [63]. Light shadows in MPs aquatories cause even more reduction of HTS lateral surfaces irradiance. This circumstance permits to consider that, in MP aquatories, inclined HTS surfaces, oriented southward, south-east and south-west, and to a lesser degree, eastward and westward are a priori more favourable for macrophytes foulers. Heliophobic macrophytes can be found at shallower depth in MPs than outside them.

2.1.8 Oxygen and Hydrogen Sulphide

The film of surface tension is the border between air and water. Water surface tension can be explained by forces of inter-attraction among the molecules in surface layer molecules, owing to which water experiences additional pressure.

An intensive exchange of gases usually occurs from the atmosphere to the marine environment (top down) and exchanges of water and salt take place from the aquatic environment to the atmosphere (bottom-up). Dilution in seawater of gases (e.g. oxygen, carbon dioxide, nitrogen, ammonia and hydrogen sulphide) that affect hydrobionts is determined by pressure, temperature and salinity.

Intensification of gas exchange occurs at breaking of wind waves and formation of water mist and sprays, as well as at appearance of ripples on the surface of seawater. The latter causes periodical tension and compression of the surface film and changes in the thickness of the viscous boundary water layers and air [137].

In the open sea and near natural shores in MPs, a multitude of “water–air” boundary surfaces is formed during strong storms, collectively creating a cloud of sprays and water mist with thickness up to a couple of metres. In such situations, gas, heat and moisture exchange are particularly active. In MPs aquatories, such effective mechanism of exchange is generally strongly weakened and is limited to the HTS zone.

In MPs, the appearance of various films, due to oil products and other substances, on the water surface influences gas exchange as does the accumulation of various small particles (suspension from live and dead planktonic organisms) that disturb the film of surface tension.

In MPs aquatories with reduced hydrodynamics, diffusion and submersion of surface waters (downwelling) provides partial entrance of oxygen into the near-bottom water layer. In the aquatories of many MPs, the superficial horizon is desalinated so that salinity could be 10‰, or more, higher in the near-bottom layer. In such cases, it is important to consider that oxygen in desalinated water is dissolving quicker than in saltier ones.

Oxygen and hydrogen sulphide play an extremely important role for hydrobionts inhabiting MPs aquatories. In these ecosystems, as well as in open sea regions,

oxygen enters the seawater column via diffusion from the atmosphere, mixing caused by wind and wave action, rain water and as a result of the photosynthetic activity of micro- and macrophytes. In coastal regions of the Black Sea, where MPs are located, the value of daily oxygen production is 1.5–2-fold higher than in the deepwater regions [161]. In MPs aquatories, reduced hydrodynamics along with reduced wind and wave action hamper the diffusion of oxygen from the atmosphere. However, the same peculiarities favour mass development of some planktonic algae. In ports, conditions for photosynthetic activity of micro- and macrophytes in the near-surface layer remain quite favourable despite lowered water transparency and weakened illumination.

Atmospheric air is a main source of oxygen to water. Plants excrete a significant amount of oxygen during the photosynthetic process, during which water oxidation and reduction of carbon dioxide occur. Oxygen is essential to the absolute majority of aquatic hydrobionts from various systematic groups and ecological complexes. Furthermore, not only the presence of oxygen, but also its actual concentrations are important for hydrobionts.

Solubility of atmospheric oxygen in water depends on temperature, salinity and atmospheric pressure. Oxygen exchange between the aquatic environment and the atmosphere has a dynamic character and consists of two processes: invasion (entrance of oxygen from air into water) and evasion (passage of oxygen into the atmosphere following its oversaturation in the surface layer because of the plants' photosynthetic activity). These processes speed up at turbulent exchange between water masses and wind influence on the water surface.

The maximum oxygen water saturation cannot exceed 100% due to diffusion alone. However, oxygen saturation can exceed 100% and reach values of 150–200% and more as a result of algal photosynthesis. The brackish waters of the Azov and Black Seas can reach 250–300% oxygen oversaturation. This phenomenon appears when an especially high number of live phytoplankton concentrates in the surface layer at calm weather. Intensification of water mixing leads to the disappearance of oversaturation and even to partial under saturation [85].

Values of oxygen water saturation below 100% indicate unfavourable conditions for its diffusion, reduction of the intensity of its formation due to photosynthesis and significant consumption for oxidation and biological decomposition of OM. All these conditions can be found in the ecosystems of many MPs aquatories. In aquatic ecosystems, oxygen is indispensable for the decomposition of DOM, died plants and animals (detritus). During the normal decomposition process, the complex organic compounds are transformed into simple ones (carbon dioxide, water, nitrogen) and are cycled back into the sea matter turnover. In aquatic ecosystems, decomposition of OM mainly takes place owing to bacteria and fungi.

Bacterial degradation of OM depends on dissolved oxygen concentration. It proceeds normally at oxygen concentrations of 8 mg dm^{-3} and higher. The speed of decomposition reduces by 10% at a concentration of $6 \text{ mgO}_2 \text{ dm}^{-3}$ and by 25% at $4 \text{ mgO}_2 \text{ dm}^{-3}$. At $2 \text{ mgO}_2 \text{ dm}^{-3}$, the decomposition speed is only 40% of the corresponding value $8 \text{ mgO}_2 \text{ dm}^{-3}$ [145]. In the MPs near-bottom layer, oxygen content often drops to less than 1 mg dm^{-3} , especially in summer months. In

ecosystems of MPs aquatories, the production of primary and, often, secondary OM is higher than in the adjacent regions of the sea and the elimination of excess OM is hampered. The combination of such conditions hampers the aerobic bacterial destruction of OM and favours the formation of zones of hypoxia and anoxia close to the MPs bottom.

Near the steep shores of the Black Sea (as it is the case in MPs), the onshore–offshore wind phenomena can cause the rise of coldwaters with low oxygen content from under the pycnocline up to the water surface. The rise up of waters from the depth of 20 m occurs during a couple of hours [85]. These phenomena are observed in many ports of the Black–Azov Sea basin. During offshore winds, waters from the depth of 10–20 m are pulled up to the shore and into MP aquatories via ACs. Rising bottom waters are always saltier than the surface ones and, in summer, also colder. In the warm period, water temperature near the shore can decrease by 10–12 °C within a day under the influence of offshore winds. During such days, water with an odour of hydrogen sulphide can approach the shores in summer and autumn [74]. This phenomenon is even more distinctly observed in MPs aquatories.

Two processes are the source of hydrogen sulphide in MPs: decomposition of sulphur-containing organic substances and reduction of sulphates (sulphurous compounds) by bacteria. Either process can dominate depending on specific environmental conditions.

Production of hydrogen sulphide during the decomposition of proteins also leads to the formation of sulphur-containing compounds such as mercaptans. In the absence of oxygen, the oxidation of hydrogen sulphide is done by sulphur bacteria and thiobacteria.

In Sevastopol Bay, the measured content of dissolved oxygen is in the range 4.94–8.28 ml dm⁻³ (78.0–143.7% saturation) in the surface layer (0–1 m) and 3.81–7.11 ml dm⁻³ (66.2–113.7% saturation) in the near-bottom layer. High levels of surface water saturation by oxygen were registered from May until September. The lowest content of, and degree of water saturation by, oxygen in the near-bottom layer were registered during the same months, which testifies about excessive amounts of suspended and dissolved OM along with insufficient water dynamics. Oversaturation of water by oxygen in May–June indicates an increase in the intensity of production processes and trophicity of bay waters [3, 88].

Various factors create preconditions for an oxygen deficit in the near-bottom waters of Sevastopol Bay during the summer period: reduction of wind mixing intensity, decrease in the horizontal water dynamics, relatively high water temperature, discharge of waste waters into the surface layer, unfavourable chemical and biological factors (increased BM content in surface waters, oxygen consumption for the oxidation of excess OM) [3].

In the middle part of Varna Lake, in 1976–1985, the oxygen concentrations varied from 4.36 to 13.31 mg dm⁻³ (average 7.30 mg dm⁻³) near the surface and from 0 to 9.81 mg dm⁻³ (average 4.37 mg dm⁻³) at the depth of 16 m. In the same period, the corresponding values for water oxygen saturation varied from 60.6 up to 212.5% (average 109.2%) at the surface and from 0 to 122.8% (average 59.4%) near the bottom [126]. In Varna and Beloslav Lakes, the oxygen content in the

near-bottom layer is frequently reduced practically to zero during warm months [126, 189, 194].

A reduction of the oxygen concentrations to $1.0\text{--}2.0 \text{ mg dm}^{-3}$ was registered in the near-bottom layer of Sukhoy Liman in 1970–1980. In 2001–2003, the maximal value of oxygen in the surface layer of Sukhoy Liman was 15.7 mg dm^{-3} (189.1% saturation). In some periods, oxygen content decreased to $0.80\text{--}1.10 \text{ mg dm}^{-3}$ (10.0–15.0% of saturation) in the near-bottom layer [154].

In different periods of various years, for example in August 1995 and at the beginning of October 2007, a series of offshore winds reduced the oxygen water saturation to values not exceeding 30% in the near-bottom horizon of practically all the Grigorievsky Liman aquatory, creating a critical situation for many benthic animals [196]. During the period of intensive photosynthesis, the content of dissolved oxygen reached $15\text{--}16 \text{ mg dm}^{-3}$ and up to 190% of saturation in the surface layer of the liman (Fig. 2.18). Oxygen concentration can change very rapidly during the same day. Thus, in August 2005, the measured oxygen concentrations decreased by 2 mg dm^{-3} 2 h after sunset. The oxygen content further decreased almost linearly with a speed of 0.4 mg dm^{-3} per hour overnight. Minimum water saturation was registered at 6 a.m., but had already increased by 12% 30 min after the sunrise [196] (Fig. 2.19).

Fig. 2.18 Water oxygen saturation in Yuzhny MP (Grigorievsky Liman) in various seasons and at different depths

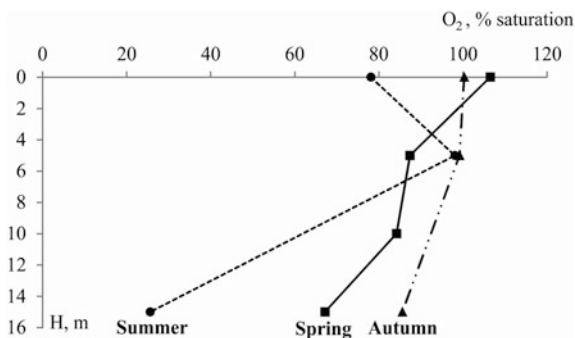
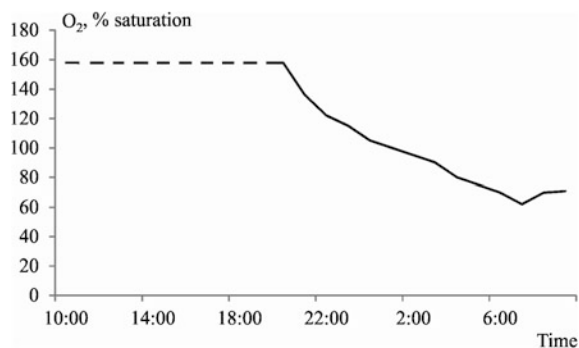


Fig. 2.19 Diurnal dynamics of saturation of the upper water layer with oxygen in the frontal zone of Yuzhny MP (Grigorievsky Liman)



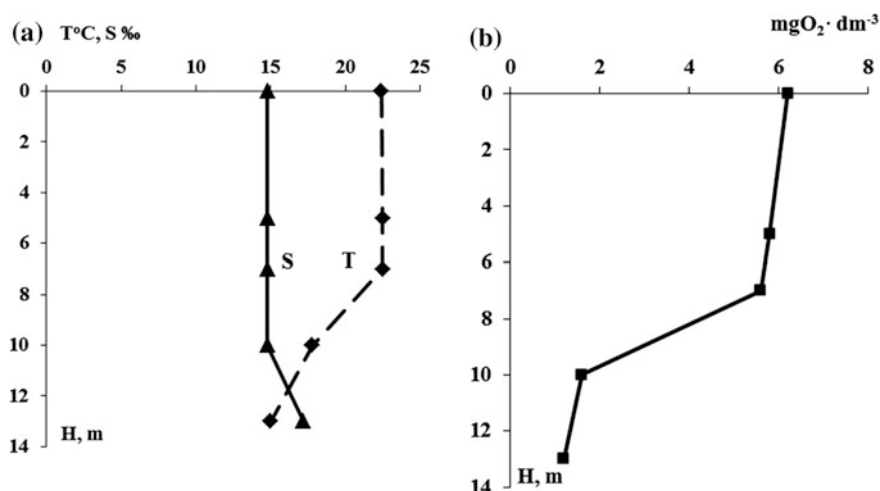


Fig. 2.20 Pycnocline formation (a) and the near-bottom hypoxia (b) in the Voennaya harbour of Odessa MP in August 2001

In the near-wall water layer, oxygen content increases during the day and decreases at night owing to the photosynthetic activity of micro- and macrophytes present in the composition of periphyton on MPs HTS.

The temporary presence of ships near berths in MPs can create wind shadows that reduce the possibility of oxygen penetration into the water column. Light shadows formed by ships also weaken the illumination of the water column and HTS lateral surfaces, thus influencing oxygen production by micro- and macrophytes to different degrees.

In many MPs (Odessa, Ilyichevsk, Yuzhny, Mariupol and others), the presence of hydrogen sulphide in the water column is observed after oxygen has disappeared in the near-bottom water layer. In the near-bottom layer of Odessa MP, dissolved oxygen content decreases to $0.5\text{--}1.0\text{ mg dm}^{-3}$ in certain periods, which leads to hypoxia and to the presence of hydrogen sulphide at concentrations of $0.5\text{--}1.0\text{ mg dm}^{-3}$ [16] (Fig. 2.20).

In eutrophic aquatories such as those of many MPs in the Black–Azov Sea basin, physical and chemical characteristics of the environment change significantly. BM and OM content increases, while the level of water saturation by oxygen decreases and anaerobic zones appear in the near-bottom water layers. At the same time, turbidity increases and water transparency decreases. The extent and rapidity with which eutrophication develops are determined by the inputs of biogenic elements as well as by other parameters including illumination and intensity of vertical and horizontal water exchange, water basin depth, water volume and degree of oxygen saturation. In MPs, depths are artificially increased and the water exchange weakened. In deep basins with intensive water exchange, eutrophication is slower than in shallow basins with low hydrodynamics.

In water basins, the anaerobic decomposition of OM accumulated in bottom sediments is a source of hydrogen sulphide. In the absence of oxygen, the sulphate-reducing bacteria use sulphates as the final electron acceptors of their metabolism to obtain energy and discharge hydrogen sulphide into the surrounding environment. Sulphate reduction consists in the reduction of sulphate ions (SO_4^{2-}) to hydrogen sulphide (H_2S) without oxygen participation. These processes are characteristic for practically all basins with high biological productivity where bottom silty sediments accumulate and water exchange is reduced. In aquatories with a good degree of oxygenation, sulphate reduction occurs only in the thickness of silty deposits and hydrogen sulphide is not registered in the near-bottom water layer.

Sulphur is an essential element for the synthesis of proteins in animal organisms and during the formation of sulphur-containing OM in plants. Thiobacteria are able to oxidize hydrogen sulphide to sulphur while releasing energy that can be used for metabolic processes; as it occurs with the use of solar energy during photosynthesis. Hydrogen sulphide belongs to the easily oxidizable compounds and it does not accumulate in waters where oxygen can easily diffuse.

Sulphate-reducing bacteria oxidize OM in the absence of free oxygen. They use the oxygen included in sulphate compounds for OM oxidation. These bacteria transform the sulphate ions (SO_4^{2-}) into sulphide ions (S^{2-}) and oxidize OM to carbon dioxide (CO_2) and water. When reacting with protons (H^+), sulphide ions form hydrogen sulphide. Slowly moving up in the oxygen-containing part of the water column, hydrogen sulphide oxidizes to sulphate. BM is released during OM decomposition by sulphate-reducing bacteria.

The process of hydrogen sulphide formation is most intense in the topmost 1–2 cm of silts, where the most active and numerous populations of sulphate-reducing bacteria also occur. Deeper into the silt bottom layer, their quantity and activity quickly drop [160]. The silt thickness 5 cm deeper under surface is often sterile [160, 161]. At a depth of 10 cm within a silty bottom layer, sulphate-reducing bacteria are usually absent.

At hydrogen sulphide concentrations of about 0.3 mg dm^{-3} in water, there is practically no oxygen left. In 2000, the hydrogen sulphide concentration in the NWBS was $1.7\text{--}2.0 \text{ mg dm}^{-3}$ not only in MPs zones, but also in the near-bottom layer of other areas [174].

Hydrogen sulphide generation from sulphates starts when the oxygen level in the near-bottom boundary water layer becomes less than 0.14 mg dm^{-3} ; which occurs at low circulation, stagnation and abundant input of OM; i.e. typical conditions in MPs. The redoxcline moves from the sediments surface into the water column, leaving below itself an almost lifeless space containing hydrogen sulphide and ammonia [1]. In MPs, the upper level reached by the redoxcline in the zone of various berths can be inferred by the depth at which fouling hydrobionts are no longer present. The upper border of hydrogen sulphide dynamics determines the living vital water volume for oxybionts. Besides the long-term, annual and seasonal fluctuations, diurnal fluctuations of hydrogen sulphide level also occur under the influence of internal waves [143].

Academician Knipovich [85] described a situation that was already registered in Mariupol MP near the coal pier in the 1930s. The intensive formation of hydrogen sulphide was taking place in the silt which covered the bottom and silt was having a strong odour of this gas. In summer months, the oxygen content of waters having a total depth of 7.75–9.0 m was already reduced at a depth of 5.0 m and totally absent near the bottom. Sometimes, already at that depth, water was having a hydrogen sulphide odour. It was determined that a real hydrogen sulphide layer of local origin with a thickness up to a couple of metres can form in the waters of MPs aquatories.

Over the years, hydrogen sulphide in bottom waters of Varna Lake usually appears in summer and disappears at the end of autumn, although it sometimes persists through winter. In 1976–1985, the average near-bottom concentration of hydrogen sulphide was 1.38 mg dm^{-3} with an absolute maximum of 4.25 mg dm^{-3} . The total depth of Varna Lake reaches 18–19 m, but hydrogen sulphide was already registered at a depth of 10 m. In Varna Lake, the offshore rise up of waters containing hydrogen sulphide towards the surface is also observed at the lee shore and is often accompanied by fish mass mortality [144].

In Beloslav Lake, the lowest oxygen content was registered in summer close to the berths of Varna-West MP. As a result of summer stratification, oxygen is exhausted near the bottom and hydrogen sulphide appears. Hypoxia and anoxia lead to summer mass mortality of bottom organisms [194, 195, 225].

The river waters flowing into Varna and Beloslav Lakes favour vertical stratification by density. This stratification hampers vertical water exchange, especially in summer, when the less salty surface water has the highest temperature. Stagnation in the near-bottom layer leads to complete use of oxygen. Hydrogen sulphide is present in the near-bottom layer of lakes in summer and during warm winters and even all year round at low wind activity. In the deep part of Varna Lake, the bottom is covered with black silt containing hydrogen sulphide [189]. In Varna Lake, a biocenoses of hydrogen sulphide silt, where life is possible if hydrogen sulphide is absent, can exist at depths of more than 10 m during winter and early spring.

For most of the bottom black silts of Odessa, Ilyichevsk and Yuzhny MPs, oxidizing and reducing conditions alternate each other seasonally or over the years, which hampers the development of long-lived hydrobionts. In some seasons, the oxygen content in the near-bottom layer of Odessa MP reduces to $0.5\text{--}1.0 \text{ mg dm}^{-3}$ and hydrogen sulphide concentrations increases to $0.5\text{--}1.0 \text{ mg dm}^{-3}$ [16].

As a consequence of the redoxcline rise from the bottom, the thickness of MP water column suitable for the normal existence of hydrobionts diminishes, i.e. the water volume for oxybiont organisms practically becomes lower than the total volume.

When the diffusion depth of vertical flows and water exchange in MPs are limited by temperature and salinity stratification, oxygen under the pycnocline is consumed without the possibility to replenish its stock. As a consequence, oxygen concentration drops to values insufficient for hydrobionts respiration. Anaerobic bacteria develop below the pycnocline after total oxygen consumption.

2.1.9 Biogenic Matter

Living organisms, generally use about 40 elements for protoplasm synthesis; with carbon, nitrogen, oxygen, hydrogen, phosphorus, silicon, sulphur and iron being the most important ones. Substances containing these elements participate most actively in the vital activity of aquatic organisms. They are called biogenic matter (BM), from the Greek *bios*—life—and *genos*—birth. The remaining elements are contained in seawater and are required in lower amounts with calcium, potassium, magnesium and sodium being the most important. The named elements alternately pass from inorganic matter into living one and then into dead OM, participating in biogeochemical cycles of various complexity [111, 210, 231].

In general, the BM turnover in MPs aquatories ecosystems takes place in the same way as in the coastal marine ecosystems adjacent to them. However, there are some peculiarities that are specific to MPs. With regard to biogeochemical cycles, the atmosphere serves as the main reservoir in the turnover of gases (carbon, nitrogen, oxygen, water vapour). Elements included in the composition of sediments (phosphorus, sulphur, iron, silicon, etc.) are carried to the sea via surface and river run-off in both dissolved and particulate form. In the latter case, elements can accumulate in bottom sediments and return back into the biotic turnover following various processes.

The hydrobionts require carbon, hydrogen, oxygen, nitrogen, phosphorus, silicon and iron in relatively large amounts. The living organisms modify the content of phosphorus, nitrogen and silicon in seawater to the maximum extent. The turnover and distribution of these elements in aquatic ecosystems are controlled, first of all, by photosynthesis and OM decomposition [37, 95, 146, 202].

In seawater, BM is mainly present in a form of phosphates ions (PO_4^{3-}), nitrates (NO_3^-) and silicic acid (SiO_3^{2-}). In particular, nitrogen and phosphorus ensure the normal functioning of marine ecosystems, but at the same time they trigger various negative processes and consequences at extremely low and at extremely high concentrations. In BM compounds composition, the biogenic elements participate in the synthesis of OM via primary production, i.e. in photosynthesis and chemosynthesis. Biogenic matter (BM) comprises the mineral compounds of nitrogen (NH_4^+ , NO_2^- , NO_3^-), phosphorus (H_2PO_4^- , HPO_4^{2-} , PO_4^{3-}) and silicon (HSiO_3^- , SiO_3^{2-}), as well as the organic compounds of nitrogen (N_{org}) and phosphorus (P_{org}), forming during the processes of vital activity of hydrobionts and during destruction of dead OM [146, 199].

In water, nitrogen also occurs as the molecular form N_2 , whose importance is not high. As in the case of most terrestrial plants, marine plants are usually unable to directly assimilate molecular nitrogen, diffusing into water from the atmosphere and released during OM decomposition. This chemical form of nitrogen can be directly used only by some bacteria. Photosynthesis requires 1 part of phosphorus and 8 parts of nitrogen. During formation and decomposition of living organism's tissues, nitrogen and phosphorus are incorporated or released in a ratio close to 16:1. These elements are present in clean seawater at approximately the same ratio. According

to the classical scheme, nitrogen and phosphorus are absorbed from the sea surface layer by phytoplankton and macrophytes. All other organisms use the primary production of phytoplankton and macrophytes, including nitrogen and phosphorus incorporated in their composition after uptake from water, via food chains of various complexities. The cycle ends when hydrobionts die and BM is released from OM during the process of decomposition by microorganisms and fungi. In the classical scheme, the role of micro- and mesoplankton in BM turnover is underestimated [159, 198, 213, 222, 223].

In MPs, the development of biological activity in the surface water layer is accompanied by uptake of BM and decrease in its concentrations. At a later stage, the formation of dead OM leads to BM enrichment in the near-bottom water layer and bottom sediments. At the same time, biological utilization of oxygen near the bottom for the decomposition of dead OM lowers its concentration. This is the reason why the continuity of biological processes in MPs aquatories directly depends on oxygen supply to the whole water column, i.e. on vertical water exchange.

The dead OM (accumulated in bottom sediments or present in the water column in suspended (SOM) or dissolved (DOM) form) is a potential source of mineral compounds of nitrogen and phosphorus. Destruction of the dead OM occurs both in the presence and absence of oxygen. The scheme of OM decomposition is presented below [46].

(1)	Aerobic oxidation $(\text{CH}_2\text{O})_x(\text{NH}_3)_y(\text{H}_3\text{PO}_4)_z + (x + 2y)\text{O}_2 \rightarrow x\text{CO}_2 + y\text{HNO}_3 + z\text{H}_3\text{PO}_4 + (x + y)\text{H}_2\text{O}$
	Nitrification $\text{NH}_3 + 2\text{O}_2 \rightarrow \text{HNO}_3 + \text{H}_2\text{O}$
(2)	Denitrification $(\text{CH}_2\text{O})_x(\text{NH}_3)_y(\text{H}_3\text{PO}_4)_z + 0.8\text{HNO}_3 \rightarrow x\text{CO}_2 + y\text{NH}_3 + 0.4x\text{N}_2 + z\text{H}_3\text{PO}_4 + 4\text{H}_2\text{O}$

Aerobic mineralization of dead OM occurs at oxygen concentrations above 0.3 mg dm^{-3} and produces nitrates and orthophosphates. In anaerobic conditions, OM decomposition leads to the formation of ammonia nitrogen and nitrites [46].

In the last decades, a conception was elaborated based on fact that, in marine ecosystems, a large amount of BM circulates in the water column over prolonged periods (i.e. without settling onto bottom sediments) owing to nutrition and vital activity of pico-, nano-, micro- and mesoplankton [10, 11, 29, 55, 161, 198, 210].

The quantity of nitrogen and phosphorus compounds entering into MPs aquatories depends on many conditions, including the degree of development of plant cultivation, cattle and poultry stockbreeding and population density in the coastal zone. On average, each inhabitant introduces 2–4 g of phosphorus per day into aquatic ecosystems [45]. It is commonly believed that 1 g of phosphorus can provide an algal production equivalent to 50 g of organic carbon. Bacterial decomposition of dead OM requires 150 g of oxygen per 50 g of carbon [45].

In MPs aquatories, several zones offer abundant food for various uni- and multicellular hydrobionts, namely: the coastal zone of preserved natural shores, the HTS near-wall water layer, the near-surface water layer adjacent to the film of surface tension, the isopycnic surfaces in the zone of density jump, the surface of bottom sediments and the associated nepheloid layer.

Hydrogen sulphide (H_2S), which forms in bottom sediments under conditions of oxygen deficit, belongs to the strong reducing agents during OM decomposition. While reducing nitrites and nitrates, hydrogen sulphide causes the liberation of free nitrogen, thus explaining why some degree oversaturation by nitrogen always occurs in the reducing zone of MPs [232].

Ammonification of MPs aquatories, i.e. the accumulation of ammonium ions (NH_4^+), takes place when an aquatic environment enters a stable reducing state due to oxygen deficit [40, 68, 139, 157]. The nitrite ion (NO_2^-) acts as an intermediate compound in the chain of reactions transforming NH_4^+ into NO_3^- . The nitrite ion is a product of the reduction of nitrate (NO_3^-) or of the oxidation of nitrogen-containing compounds in lower redox states; i.e. NH_4^+ , NH_2OH , N_2O , NO . Nitrite ion is very toxic [12].

Offshore wind phenomena can initiate the development of hypoxia in the near-bottom layer of the coastal zone, particularly in Odessa region [82, 171].

In summer, the development of hypoxia in the near-bottom layer favours the intensification of ammonium and phosphates fluxes from bottom sediments, slows down nitrification and causes a decrease in nitrates levels via denitrification processes. As a result, maximal concentrations of phosphates and ammonium are registered in the near-bottom water layer during the summer months [82].

In Odessa region, during the spring-summer period, concentrations of nitrogen and phosphorus organic compounds are exceeding those of their mineral compounds by, on average, two to threefold for phosphorus and three to sixfold for nitrogen. In autumn, the ratio between organic and mineral compounds of phosphorus reduces to one or less, while it remains the same for nitrogen. The maximal concentrations of organic nitrogen ($730 \mu\text{g of N dm}^{-3}$) and phosphorus ($27 \mu\text{g of P dm}^{-3}$) in the coastal waters are observed in autumn. Over a year, the average ratio between the concentrations of mineral compounds of nitrogen and phosphorus in water ($N_{\text{min}}: P_{\text{min}}$) is 10:1, while it increases up to 30:1 for their organic compounds ($N_{\text{org}}: P_{\text{org}}$) [13, 82, 171].

In coastal waters in general and in MPs aquatories in particular, the process of nitrogen regeneration from OM to mineral forms available for aquatic vegetation is slower than the process of phosphorus regeneration.

The regime of BM in MPs aquatories depends on the inputs of these compounds from natural and anthropogenic sources (external and local) and, in particular, from bottom sediments. Water temperature, illumination and hydrodynamics play an important role in determining the intensity of vital activity of aquatic organisms and the related processes of formation, transformation and destruction of OM. In eutrophic ecosystems, to which MPs aquatories belong, seasonal differences in BM content disappear because they offer the necessary conditions for an almost year-round mass production of primary OM by phytoplankton [154, 196].

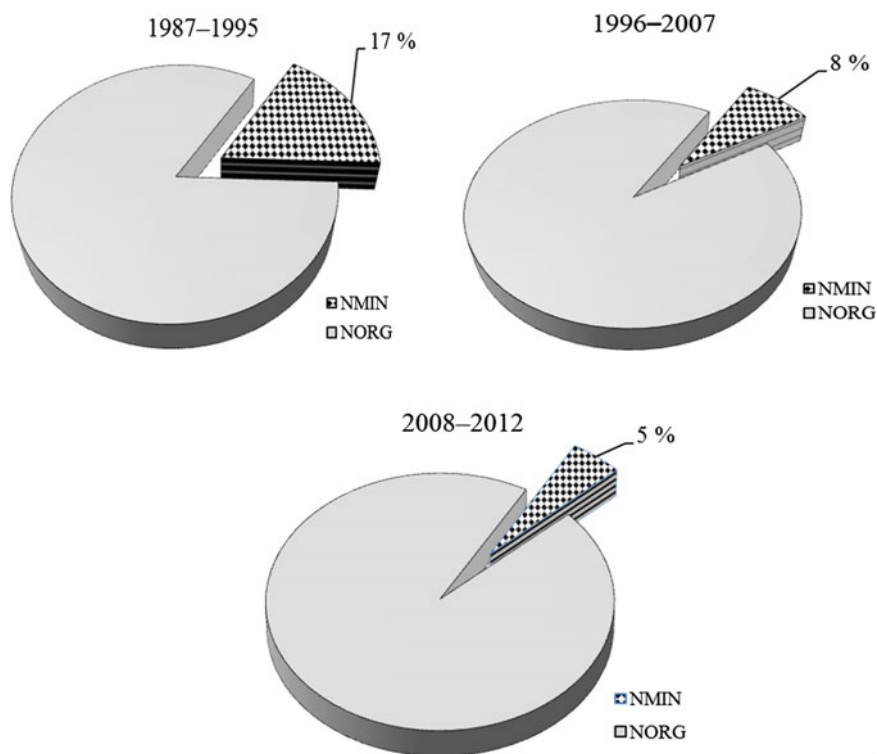


Fig. 2.21 Increase in the content of organic compounds of nitrogen (N_{org}) along with decrease in mineral forms (N_{min}) during eutrophication of Yuzhny MP aquatory (Grigorievsky Liman)

The major forms of nitrogen determining the biological productivity of aquatic ecosystems (i.e. the vital activity of micro- and macrophytes) are the inorganic ionic forms of nitrogen: ammonium (NH_4^+), nitrates (NO_3^-) and nitrites (NO_2^-). The total amount of nitrogen compounds is an indicator of the eutrophication level of an aquatic ecosystem. In MPs, organic nitrogen (N_{org}) is the dominant form and can account for up to 90% of the total as in the case of Grigorievsky Liman [196] (Fig. 2.21). The ratio between the mineral and organic compounds of nitrogen characterizes the relative rates of OM production and destruction processes. In Grigorievsky Liman, the average content of N_{org} had increased nearly sixfold towards the middle of the 2000s compared with the 1990s. Maximal values were registered during the warm period in the whole water column. The decrease of temperature slows down OM destruction and leads to its accumulation in the near-bottom horizon and in sediments [196].

The concentration of nitrates (NO_3^-), i.e. the oxidized mineral form of nitrogen which is more actively used by micro- and macrophytes during the formation of new OM, has slightly increased in Grigorievsky Liman waters during the last decades. This phenomenon can be connected with various processes, but it confirms

the constant accumulation of nitrates in MPs aquatories ecosystems having limited water exchange with the adjacent sea regions. The content of nitrites (NO_2^-), unstable and toxic forms of nitrogen, in the liman is insignificant. Nitrites are registered in the most polluted zones of the MP and in the near-bottom horizon during OM destruction under hypoxia conditions encountered in reducing environment [196].

In 1976, nitrates dynamics in Varna Lake showed a regular increase of their concentration in winter and decrease in summer [144].

Phosphorus compounds (–dissolved, –mineral PO_4^{3-} and organic P) pass through all the links of food chains until total destruction of OM. The lack of phosphorus can limit photosynthesis, because the three dissolved mineral compounds of nitrogen (NH_4^+ , NO_2^- , NO_3^-) are always present in seawater. In aquatic ecosystems, a constant turnover or recycling of phosphorus takes place from mineral forms into organic ones (plants), transformation along food chains and destruction owing to bacterial activity. The recycling speed of phosphorus depends on water temperature, content of dissolved oxygen, and activity of micro- and macroorganisms (i.e. the correlation between primary and secondary OM production; the latter causing biochemical oxidation of OM). This speed can vary from a couple of hours up to a couple of days [196].

In MPs ecosystems, orthophosphates (PO_4^{3-}) are the main phosphorus form and their concentrations, as well as those of nitrates, usually have a more or less marked seasonal character, with minimum levels in spring and summer and maximum ones in autumn and winter [16, 196].

In Varna Lake, over the period 1976–1985, phosphates showed a regular and, in the case of MPs, typical reduction in spring and summer, i.e. during the period of intense photosynthesis [144].

In the Black Sea, the surface layer contains an average of 3–4 mg dm⁻³ of dry OM [161]. In coastal waters, and especially in MPs aquatories, the content of dry OM could be one to twofold higher [154]. When OM decomposition occurs via aerobic oxidation, the decrease in oxygen concentration in seawater is directly connected with the increase of BM inputs into the water column [215, 226].

In the anionic form of silicic acid (SiO_3^{2-}), silicon is an important element in marine ecosystems, because it is necessary for the vital activity of diatoms and peridinin algae as well as of some zooplanktonic organisms. Diatoms and dinoflagellates use silicon for building their shells and exoskeletons. The river, rain and snowmelt waters, as well as the products of the decomposition of dead algae, are the main sources of silicon to marine waters. In some cases, diatoms and peridinin algae in marine ecosystems incorporate all the silicon available from the surface waters, thus slowing down their further development. Other microalgal species, which have no need for silicon, can then develop. This is an example of a self-regulation mechanism in aquatic ecosystems. Theoretically, in MPs surface waters, silicon could limit mass development of some microalgal groups such as diatoms and dinoflagellates. However, river waters, which are one source of silicon renewal, flow into many MPs, thus making the occurrence of silicon deficit

unlikely. Furthermore, silicon accumulates in the sediments of MPs aquatories ecosystem and can return back into the water column from this reservoir.

A certain seasonal variability of silicon content is observed in the waters of MPs aquatories. This variability is closely linked to the development of diatom microalgae which are its main consumers. In Grigorievsky Liman aquatory, the ranges of silicon concentrations are larger than in the adjacent sea region because production–destruction processes are more active in the liman. According to the results of long-term observations, the silicon content in Grigorievsky Liman waters is higher than in the adjacent sea zone and ranges from 2.3 to 4.8 mg dm⁻³ during the year [196].

In 1998–2001, an increasing trend of silicon content was found in the waters of Odessa MP [127]. In Sevastopol Bay, the silicon content varies within 30–1500 µg dm⁻³ (average 382 µg dm⁻³) in the superficial waters and 150–900 µg dm⁻³ (average 450 µg dm⁻³) in the near-bottom layer. These values are significantly higher than the typical concentrations in the 0–20 m layer of open sea zones where silicon content is in the range 0–390 µg dm⁻³ [3].

In 1977–1985, the silicon content in the western part of Varna Lake varied from 0.5 to 6.12 mg dm⁻³ (average 2.08 mg dm⁻³). In Varna Lake, the silicon concentration decreases in spring and summer and increases in autumn and winter in most cases [144].

In coastal aquatic ecosystems in general, and in the MPs aquatories ecosystems in particular, bottom sediments reflect the processes that take place in the water column. The solutes contained in the bottom sediments interstitial waters also characterize the state of bottom sediments and are an indispensable component in the BM balance of ports ecosystems. Studies in Odessa MP and Grigorievsky Liman showed that OM of allochthonous and autochthonous origin accumulates in the bottom sediments and, therefore, in interstitial waters.

Benthic organisms are particularly important in delivering OM to bottom sediments during their vital activity. They also transfer, use and convert OM, assist the aeration of the sediments upper layer, and participate in decomposition of OM and its diffusion into the near-bottom water layer. The OM destruction in bottom sediments of MPs takes place both in the presence and absence of oxygen. In Grigorievsky Liman, the main amount of labile BM (93–98%) in pore solutions is located in the upper ten centimetres layer of bottom sediments. This situation creates significant gradients of concentrations at the sediment–water interface and controls migration of BM from the bottom sediments into the near-bottom water layer [58, 196].

In bottom sediments, as well as in water, the aerobic mineralization of dead OM leads to the formation of nitrates (nitrification) and orthophosphates. Under hypoxia or anoxia conditions, OM decomposition takes place under reducing conditions with formation of ammonia nitrogen (ammonification) and nitrites. The speeds of OM destruction and BM turnover (recycling) in bottom sediments, as well as in water column, depend on temperature, oxygen content and vital activity of micro- and macroorganisms.

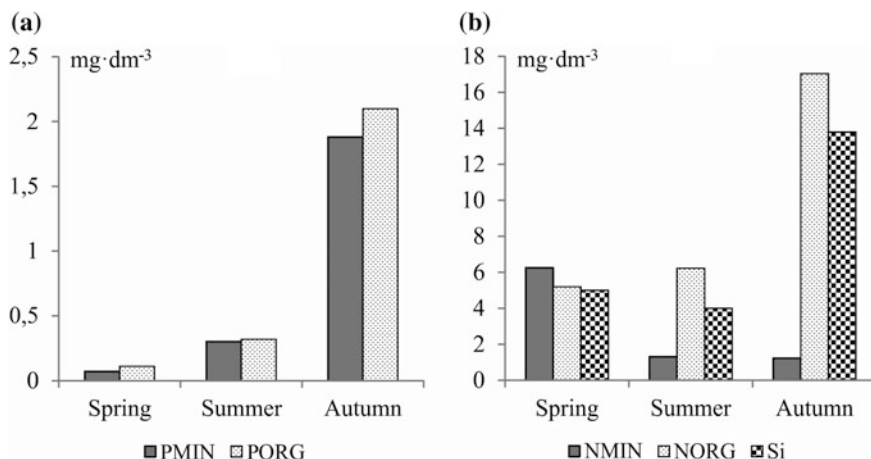


Fig. 2.22 Seasonal variability of nitrogen, phosphorus and silicon compounds in pore waters of the bottom sediments of Yuzhny MP (Grigorievsky Liman) in 2003

Long-term studies in Grigorievsky Liman determined that the BM concentrations are one order of magnitude (or more) higher in sediment interstitial waters than in the water column [196]. In MPs bottom sediments, the seasonal variations in the concentrations of nitrogen and phosphorus compounds are characterized by an increase from spring to autumn, especially for organic forms, which is connected with accumulation and destruction of OM (Fig. 2.22).

In MPs, concentrations of mineral and organic compounds are dozen times higher in the pore waters of bottom sediments than in the water column, so that pore waters serve as a source of additional inputs of BM into pelagial. BM release from pore waters can intensify the eutrophication of aquatories.

An increased content of BM is the main peculiarity of the north-western part of Novorossiysk port, into which flows the river Tsemes. In this aquatory, the amount of phosphates, nitrates and nitrites reach 44, 900 and 40–70 $\mu\text{g dm}^{-3}$, respectively. The highest concentrations of BM coincide with the period of rains and floods, in February–March, which favour mass development of phytoplankton. Oxygen content varies in the range 5.7–6.9 mg dm^{-3} , oxidability between 0.9 and 2.4 mgO dm^{-3} and BOD₅ between 1.37 and 2.20 $\text{mgO}_2 \text{dm}^{-3}$ [50, 182].

BM content in the aquatories of Novorossiysk, Tuapse and Sochi MPs considerably exceeds that of the adjacent regions of the Black Sea. Chemical oxygen demand in the aquatories of Novorossiysk, Tuapse and Sochi MPs is usually two- to threefold higher than in the adjacent regions. The content of phosphates in water is two to fourfold and that of nitrates 4–10-fold higher than in the open water areas [52].

In studies carried out in Odessa MP in 1998–2001, an increasing trend was observed for phosphates, total phosphorus, ammonium, nitrates, and total nitrogen, while dissolved oxygen content and pH showed a decreasing trend. Each year,

prehypoxia and hypoxia phenomena were recorded in the near-bottom layer during the summer period (July–August) [127].

In Sukhoy Liman, which is the aquatory of Ilyichevsk MP, a constant presence of BM was recorded in water, thus allowing a high level of OM production. Dominance of oxidized forms of nitrogen, i.e. nitrates (NO_3^-), over reduced ones, i.e. ammonium (NH_4^+), was observed only in early spring. In summer, the content of OM reduced, but the content of reduced nitrogen forms sharply increased in connection with increased intensity of the decomposition processes (increase of BOD_5) [129].

In Grigorievsky Liman, which is the aquatory of Yuzhny MP, typical natural cycles of phytoplankton development (spring and autumn maxima) are only weakly marked. This situation reflects the lack of nitrogen and phosphorus limitation for phytoplankton development, because excessive amounts of mineral N and P are present in the liman waters all year round [148].

The variation range of BM in Grigorievsky Liman is markedly higher than in the adjacent region of the Black Sea, despite similar values of hydrological parameters (but hydrodynamics is lowered in the liman). Production–destruction processes are active in the liman and they are more marked than in the adjacent regions of the sea. In Grigorievsky Liman, the value of BOD_5 —an index of the potential bacterial oxidation of DOM over five days—changes from less than 1.0 to 6.0–7.0 $\text{mgO}_2 \text{ dm}^{-3}$ in various seasons depending on water temperature, initial concentration of dissolved oxygen and OM content. It is commonly accepted that the admissible limit values of $\text{BOD}_{\text{total}}$ for marine waters should not exceed 3.0 $\text{mgO}_2 \text{ dm}^{-3}$. In 2004–2006, the COD in Grigorievsky Liman waters ranged from 0.5 to 6.0 $\text{mgO}_2 \text{ dm}^{-3}$ and was, on average, 3.0 $\text{mgO}_2 \text{ dm}^{-3}$. In 2007, it was 2.0–6.4 $\text{mgO}_2 \text{ dm}^{-3}$ for an average of 3.8 $\text{mgO}_2 \text{ dm}^{-3}$ [196]. These indices testify a high content of OM in the liman waters. In spring and summer, the content of labile OM in the surface layer of Grigorievsky Liman is twice than in the near-bottom, while OM accumulation in the near-bottom horizon is mainly observed in autumn [196].

The average phosphate content in Grigorievsky Liman is rather stable. The permanent summer enrichment of the surface horizon by phosphates and their accumulation in the near-bottom layer are connected with intensification of OM destruction and with phosphates desorption from bottom sediments. The latter phenomenon is characteristic for reducing conditions occurring during hypoxia and anoxia in the near-bottom horizon. In autumn, the content of organic phosphorus (P_{org}) decreases and becomes vertically homogeneous following the reduction of the vital activity of many aquatic organisms, OM mineralization and active water mixing [196].

In Varna Lake, the average BOD_5 was 5.02 $\text{mgO}_2 \text{ dm}^{-3}$ in the period 1976–1985. During the same period, in the central part of Varna Lake, the COD changed from 0.41 to 8.14 $\text{mgO}_2 \text{ dm}^{-3}$ (average 3.0 $\text{mgO}_2 \text{ dm}^{-3}$) in the upper layer and from 1.25 to 7.40 $\text{mgO}_2 \text{ dm}^{-3}$ (average 2.36 $\text{mgO}_2 \text{ dm}^{-3}$) near the bottom [144]. In Varna-West aquatory, the COD near the berths had an average value of 2.80 $\text{mgO}_2 \text{ dm}^{-3}$ in the autumn period of 1990–1998 [194, 195].

In Sevastopol Bay, the waters of river Chernaya, receiving wastewaters and sewages from various discharges, are an important source of BM. During the period 1960–1990, significant changes in BM concentrations and in the structure and quantitative indices of phytoplankton took place in the bay, witnessing the evolution of its ecosystems from an eutrophic phase to a hypertrophic one [3]. In Sevastopol Bay, the level of BM concentrations is 10–100-fold higher than in relatively clean coastal waters and in the photosynthetic layer of the open sea [123]. In the bay, the peak of BM accumulation is recorded in winter and is followed by a significant reduction of BM at the beginning of spring [59]. In summer months, the phosphates concentrations in the surface waters are higher than in the near-bottom, while the opposite situation occurs in late autumn. The water enrichment in phosphorus is connected with the intensification of OM destruction processes leading to the formation of mineral phosphorus [59].

In MPs, part of the DOM can be directly removed from the water column together with biogenic elements and assimilated by plants, as well as by other hydrobionts from different systematic groups, without undergoing total degradation [1, 2, 40, 156].

In MPs, water temperature is an important factor controlling the formation and destruction of OM primary production and the concentrations of BM in various horizons of the water column. Indeed, each algal species reaches its maximal photosynthetic rate within a defined temperature range [145, 180, 181]. Fluctuations of temperature outside this optimal range in semiclosed MP ecosystems lead to a reduction of photosynthetic production. Thus, BM concentration is indirectly connected with temperature. Mass development of planktonic algae leads to an increase of their metabolites and DOM in water and, on the other hand, to the possibility of DOM consumption by algae themselves.

In the coastal marine ecosystems, the foam forming in the surface water layer contains increased DOM and BM concentrations [71, 190]. The carry out of foam on flat shores provides support to organisms inhabiting the sea psammocontour on the one hand and is a mechanism for eliminating excessive amounts of dead OM and BM from the water column on the other hand. This mechanism is reduced to a minimum in the conditions typical of many MPs.

MPs aquatories become sedimentation traps owing to the artificial reduction of hydrodynamics, weakening of water exchange and presence of natural or artificial protection. At the same time, they trap dissolved BM, entering from the adjacent sea zones, which is used for cell construction by phytoplankton. At phytoplankton death, the remaining suspended OM is only partly removed outside the boundaries of MPs aquatories and its main mass settles to the MP bottom because of gravity and following the activity of various filter-feeding organisms (biological sedimentation). Sediments rich in OM are a food source not only for bacteria and fungi, but also for many protozoans and multicellular animals. While moving along the food chain, sediments turn into faecal pellets of different sizes which, in turn, become a food supply for other hydrobionts. Bacteria and fungi conclude the final destruction of OM. Because of the relatively small depths and weakened hydrodynamics, organic suspended matter settles to MPs bottom relatively quickly (hours, dozens of hours) as a component of detritus. MPs bottom sediments are a reservoir of BM.

2.2 Main Biotic Peculiarities

The MPs aquatories ecosystems are formed by natural and artificial components and differ in many respects from those of the adjacent sea zones. Along with the reduction of hydrodynamics, conditions for the increase of various carbon containing compounds and decrease in dissolved oxygen content are artificially created in MPs. In MPs, situations typical of ancient and modern ecosystems with saprobiotic (or similar) conditions often originate owing to anthropogenic impact.

It is well known that CO_2 , O_2 and OM play an important role for the maintenance of modern life in seawater, while a harsh solar radiation is destructive for all living organisms on the planet. However, on the first stages of hydrosphere and atmosphere formation, solar radiation favoured the formation of complex organic (carbon containing) compounds, foregoing the origin of life, by abiotic reactions. At the same time, harsh solar radiation also contributed to the formation of free oxygen in the atmosphere. Free oxygen, although slowly, was formed chemically by water photodissociation under the influence of light. In the primitive atmosphere, a thin layer of O_3 already formed at relatively low oxygen concentration (about 0.001% of its modern level) and has since played a role of protective screen from harsh solar radiation until our time. In the same period, carbon dioxide (CO_2) was present in the reducing atmosphere and hydrosphere. Because of the processes described above, preconditions for the origin and development of life and for the synthesis of OM by heterotrophic living organisms appeared first in the aquatic environment and later on land.

Carbon is the main component of chemical organic compounds. Carbon has not only played a key role in the origin of life on Earth, but also in its sustention. Carbon content characterizes the state of aquatic ecosystems. In coastal seawaters, organic carbon enters in the composition of DOM, detritus and live OM approximately in the ratio 90:9:1 [32].

The major characteristic of carbon is its ability to form an immense amount of compounds, comprising a practically unlimited number of atoms. Carbon enters into the OM of all plants and animals in the form of various compounds and its average content in living matter is about 18%. In water, modern algae and aquatic plants obtain carbon by assimilation of CO_2 that diffuse into water from air or is released in water as a result of hydrobionts respiration or bacterial activity. Animals fulfil their carbon needs via feeding on live or dead OM. The total decomposition of OM ends with the formation of CO_2 and H_2O , i.e. carbon returns into the environment surrounding hydrobionts in a form available for autotrophs. Life in the aquatic environment in general, and in MPs aquatories in particular, can be viewed as a continuous transformation of carbon compounds.

The carbon dioxide present in the atmosphere plays a key role in the carbon cycle in the hydrosphere. Carbon dioxide not only dissolves in water like other gases, but also reacts with water forming carbonic acid and its dissociation products which, on the whole, constitute the so-called carbonate system of seawaters [27, 28, 34, 138]. The carbonate system has a dynamic character and anthropogenic perturbations of this system significantly disturb the life conditions of hydrobionts.

In seas, primitive aquatic ecosystems already originated with the appearance of the first life forms. These primitive ecosystems functioned as systems of reciprocally connected and regulating populations performing various functions (primary production, reduction, OM mineralization), organisms and components of environment, including carbon, oxygen, nitrogen, phosphorus and other elements.

The process of primary OM formation by photosynthesis did not appear immediately because it is a quite complex one. Many scientists consider that the primary marine ecosystems consisted of anaerobic heterotrophic organisms, mainly receiving energy from abiotically generated OM (i.e. the analogue of modern allochthonous OM at that time) which, gradually, was completely included into the biotic turnover [56, 124, 139]. With the origin and distribution of photosynthetic organisms, a source of oxygen became available for aerobic hydrobionts.

With the gradual increase of oxygen amount thanks to the activity of plants (autotrophs), various aerobic organisms (from protozoans up to mammals) appeared and spread into the seas. However, at the same time, some ancient anaerobic life forms have survived until modern times in certain niches. In general, the efficiency of aerobic metabolism is 30–40% higher than that of anaerobic one [139]. Disintegration of one molecule of glucose via fermentative processes (anaerobes) yields 2 calories compared with the 38 calories obtained during aerobic respiration [32]. This fact played, and still plays, a significant role in competition among various life forms and in their evolution into separate taxonomic groups of hydrobionts. In marine ecosystems, it is important that the functions of big biotic groups accomplishing matter turnover remain at equilibrium [32, 227].

During the evolution of the World Ocean and marine ecosystems, anaerobes were preserved, and continue to be preserved, in specific ecosystems reservoirs to ensure the continuity and circularity of biotic processes in the case of onset of reducing (anaerobic) conditions. For these reasons, energy (external sources, food) and matter (organic as well as mineral) are required by all hydrobionts, aerobes as well as anaerobes. In MPs aquatories ecosystems, unicellular (protozoans), as well as multicellular organisms, play various roles. The protozoans' cell is a whole organism and independently fulfils its vital functions: nervous, secretory, excretory and muscular. In contrast, multicellular organisms have specialized cells organized into tissues, organs and systems. According to classical concepts of life evolution, multicellular organisms originated in seas on the basis of various unicellular structures. Amplification of the organization created new possibilities in the competition for food and other resources.

The presence of regulation mechanisms of metabolic processes intensity permits to free-living and attached protozoans to switch into anabiosis at unfavourable environmental conditions. By accumulating in stagnant waters, the metabolites of protozoans act as a control mechanisms, hampering or suspending their reproduction when their population increases excessively [145]. Food availability is another important limiting factor regulating protozoans' quantity. Protozoans usually have a wide food spectrum which permits them to easily switch from one food item to another, thus avoiding trophic competition [218, 224].

In modern aquatic ecosystems, there is a great variety of hydrobionts differing on size, reproductive and locomotive strategies, feeding methods and food preferences. However, the mechanisms for digesting food and extracting energy from it are much less diversified.

Autotrophic and chemotrophic organisms extract from solution ions and other compounds they need via the process of mineral nutrition and formation of the primary OM. Food digestion by animals also requires the ingested food to stay in a liquid condition.

Nutritional strategies of heterotrophic organisms reflect their progressive adaptation to an increasingly more complete use of the possible food sources. It is believed that evolution of nutritional strategies went from a primary osmotic feeding towards a holozoic one. At the same time, marine invertebrates belonging to 11 taxa were shown to consume DOM (aminoacids) with 10 of them showing osmotrophy. Osmotrophy partly satisfies their food requirements, but nevertheless the main feeding strategy of heterotrophic hydrobionts is the holozoic one and food digestion takes place inside the organism. Some exceptions exist and food can be also digested outside the body, as in the case of *Rhizostoma pulmo*, commonly known as the barrel jellyfish [89].

For heterotrophs with holozoic feeding, food processing consists in mechanical fragmentation followed by chemical dissolution. The first stages of fermentation and absorption take place in an acidic environment, which was the common situation in the primary ocean.

Because dead and live OM consist of a limited number of main chemical compounds (proteins, fats and carbohydrates), the corresponding enzymes realizing the actual chemical reactions for their decomposition were also necessary. Such enzymes are necessary for all nutritional strategies (endocellular, extracellular, cavity, membranous) and at all levels of living OM organization.

Aminoacids and small peptides, fats (glycerine and fatty acids) and monosaccharides, which are subject to absorption, are the principal final breakdown products of proteins, fats and complex carbohydrates. Cells, tissues and organs specific compounds are synthesized in organisms starting from these fundamental building blocks.

During extracellular nutrition, which is widespread among invertebrates, the enzymes synthesized in cells are excreted into the environment where they hydrolyze nutrient substances. In multicellular organisms, the extracellular digestion takes place in specialized body cavities and intestines.

The majority of highly organized animals have membranous or parietal digestion realized by enzymes, localized on membranes of the intestine cells. These systems accomplish the initial and final stages of food fermentation and the initial phases of its absorption.

Some symbiotic groups of bacteria and protozoans participate in the digestion process of both invertebrate and vertebrate animals. Their role consists in the secretion of digestive hydrolytic enzymes and a series of other substances. The symbiont's enzymes assist molecule cleavage by enzymes secreted by the cells of

the host organisms itself during the digestion of food in digestive tracts. Food preferences (i.e. specificity of ingested objects or prey items) determine the set of digestive enzymes. The mechanisms of disintegration and digestion already found in the first stages of life evolution in seas are presently preserved by modern hydrobionts in various forms.

As food advances along the intestinal tract and nutrients are adsorbed, the gut contents are compacted into faecal pellets and thread-like faeces of various sizes and forms that are excreted outside. They serve as substratum for bacteria and food supply for other hydrobionts in the water column or on bottom and lateral surfaces of artificial HS in MPs.

Studies performed over the last decades testify about the extremely important and previously undervalued role of picoplankton, which is not caught by planktonic nets, in the trophodynamic processes of marine ecosystems [29, 55, 92, 159]. In the photic layer, picoplanktonic organisms (0.4–1.0 μm) can reach densities of 10^4 – 10^5 cells (or more) per mL of water. They account for up to 60% of all phytoplankton primary production, including that of the net phytoplankton. Picoplanktonic organisms perform photosynthesis at even lower levels of illumination than net phytoplankton. In MPs aquatories, this capability confers them a certain advantage. Picoplanktonic organisms, along with bacteria, represent the smallest food objects available for feeding to microheterotrophes and are thus part of the first links in the trophic chains of MPs ecosystems.

Studies of algal functioning showed that, whatever mineral carbon forms are used, pure autotrophy is quite rare among algae. Usually, the photic assimilation of carbonates (photosynthesis) is somehow accompanied by the use of organic metabolites dissolved in water. It was also determined that heterotrophy is accompanied by dark fixation of CO_2 . Among marine animals, there are practically no “clear-cut” types of nutrition, with each species having a more or less mixed food spectrum. OM dissolved in the water serves not only as a food for animals, but some dissolved metabolites are specific regulators of growth and morphogenesis. The most primitive life forms are able to use the carbon dissolved in water as carbonates for their metabolism which uses an external source of energy. In seas, animals are connected with all the carbon forms of ecosystems, but the role of each carbon form in biological production is extremely different. In the marine environment, animals actively participate in OM destruction (carbon compounds), along with bacteria and fungi [21].

The DOM share in the ration of various plankton and benthic invertebrates varies from 1–2 to 90%. DOM plays the greatest role in the feeding of organisms inhabiting the interstitial waters and the near-substratum water layers of fouling communities. Quite often, CO_2 , DOM, detritus and biomass of other species are simultaneously used in the formation of the biomass of various hydrobionts. The ratio of the various forms of carbon used by organisms differs on each trophic level. On lower levels, dissolved forms of carbon constitute the basis of the ration, while slime and particulate carbon suspended in water are the main ration for the higher trophic levels. In ecosystems, both depletion and renewal of the “stock” of each form of carbon are linked to all other forms and their transformation into each other.

The trophic value of dead organisms' remainants reduces according to their degree of decomposition. At the same time, chemical transformation of organic metabolites takes place. "Old" detritus and DOM are usually distinguished from "young" ones formed by recently dead and scarcely decomposed organisms and metabolites, which have not yet undergone significant chemical changes [21, 165, 181].

In aquatic ecosystems, about 10 groups of bacteria can be distinguished on the basis of their main functions. The following are particularly important: nitrogen-fixing, denitrifying, hydrogen oxidizing, methane-oxidizing, methanogenic, thion bacteria and iron bacteria [68, 69, 139, 145]. The various bacteria use photosynthesis or oxidize hydrogen, methane, ammonium, nitrites, sulphur compounds and iron to obtain energy. Apparently, these are one of the most ancient mechanisms of energy generation, used in the processes of chemosynthesis and photosynthesis of OM and also destruction of OM of abiogenic, as well as biogenic origin. In the World Ocean, bacteria and fungi have a main role in the mineralization of dead and, sometimes, alive OM. In fact, microorganisms control the biogeochemical cycles of nitrogen, phosphorus, sulphur, iron and other important biogenic elements. In MPs aquatories, various groups of bacteria and fungi are present in higher numbers than in the open sea waters, both in the water column and on the sediments' and HTS surfaces [32, 40, 140].

Situations, connected with mass mortality of the bottom fauna and many organisms living in the water column periodically arise in the ecosystems of many MPs aquatories. This phenomenon leads to mass mortality of aquatic organisms and is caused, first of all, by a reduction of oxygen content in water to less than $3\text{--}4\text{ mg dm}^{-3}$ because of worsened aquatory aeration, anthropogenic pollution by OM or accumulation of decaying vegetation [57, 141]. Mass mortality is indicative of a breach in the balance between the amount of live and dead OM and oxygen content in the ecosystems of MPs aquatories; i.e. a breach in the balance of important factors in the origin and evolution of aquatic ecosystems [6, 72].

In fact, in ecosystems of MPs aquatories, mass mortality is a mechanism of autoregulation that adjusts the quantity and quality of live OM to critical abiotic conditions represented by hypoxia, anoxia and appearance of hydrogen sulphide. At a later stage, following an increase in oxygen concentration, the functional structure of MPs aquatories ecosystems recovers owing to preservation of viable biotic components in the form of resting stages in different microniches and to colonization by different hydrobionts coming from neighbouring ecosystems.

Studies over the last decades clearly demonstrate that many important trophic-dynamic processes in aquatic ecosystems are carried out and regulated by microorganisms, including viruses, unicellular prokaryotes and eukaryotes and small multicellular organisms. Along with bacteria, fungi, which are heterotrophic eukaryotic organisms, have an enormous role in the destruction of OM in the water column and on the surfaces of sediments and HTS. Some fungi are unicellular, reproduce by spores and have a branched mycelium. Fungi without mycelium are observed in water. The maximum number of fungal species is registered in aquatories under strong anthropogenic impact [134]. For example, 56 species of higher fungi were found in the aquatory of Grigorievsky Liman [196].

The wide distribution and extremely rich enzymatic abilities of fungi (including the ability to saprotrophism and parasitism) determine their huge and not yet fully understood role in marine ecosystems [15]. In ecosystems with increased productivity, limited water exchange and lowered hydrodynamics such as MPs, the role of fungi in the ecosystem's functioning is much higher than in open sea regions. Fungi are the most important transformers of dead OM.

Polychimism is a peculiar characteristic of fungi. It consists in the ability to synthesize a high number of organic substances of different classes (sugars, organic acids, alcohols, aminoacids and others) and also biologically active substances such as vitamins, antibiotics and toxins. Some fungi use petroleum hydrocarbons and oil products, frequently detected in MPs aquatories, as the only source of carbon [15]. This ability has an extremely significant importance in the ecosystems of various MPs polluted by oil products. Representatives of marine fungi from the genus *Penicillium*, *Verticillium*, *Trichoderma* and *Cladosporium* are able to grow on all oils and oil products and representatives of the genus *Aspergillus* and *Mucor* on most of them [15].

Marine fungi are able to decompose very resistant substances such as cellulose and chitin.

By destroying oil hydrocarbons, cellulose and chitin, otherwise resistant in the marine environment, fungi transfer the organic carbon of these compounds into the protein of their body which are available to bacteria and various heterotrophs. Fungi thus return carbon incorporated in refractory compounds into the general carbon circulation of marine ecosystems [15].

In marine ecosystems, fungi belong to various trophic levels, first of all to decomposers of dead OM of vegetal and animal origin. They can themselves serve as a food chain link when different animals belonging to plankton, nekton and benthos consume their cells, spores and mycelium. In many cases, fungi act as parasites and affect different marine plants and animals, thus controlling their quantity and biomass and causing further reorganizations in other trophic levels.

In terms of size, fragments of mycelium and spores of fungi are comparable with nanoplanktonic algae and some protozoans, thus being a valuable food supply. Mycelium and spores of fungi from the genus *Penicillium* contain 36.31–37.81% of protein, 0.46–0.85% of sugar, 4.18% of fat and 10.80–12.05% of mineral matter [15].

Fungi play a noticeable role in the formation of the slimy biological film on fouling of HTS. Marine fungi, belonging to various groups, settle and develop on bacterial–detritus and bacterial–algal films.

Artenchuk [15] gave a general overview on the role of fungi in the Black Sea trophodynamic processes during the spring-summer period. The mass hatching of larvae belonging to important species of MPs benthos and periphyton starts in March (e.g. *Mytilus galloprovincialis*, *Mytilaster lineatus*) or April (e.g. *Balanus improvisus* and *B. eburneus*). Their free-swimming stage lasts 3–4 weeks. In April, a great number of invertebrates' larvae consume fungi in water, thus reducing their amount by fourfold, which likely causes the spring minimum of fungi in aquatic environments. In May, the larvae settle down and start to consume fungi on bottom

sediments and from the macrophytes' surface together with other components of their ration. This situation may explain the corresponding maximum of fungi in water and their minimum in bottom sediments and on macrophytes in the same period. A second peak in the reproduction of *M. galloprovincialis*, *M. lineatus* and *Balanus* is usually observed in June–July. In this period, the quantity of larvae is usually much higher than in spring and the reduction of fungal quantities in water (by almost fourfold compared with May) is likely connected with the associated summer grazing.

It is necessary to stress that MPs aquatories offer extremely favourable conditions for the life and reproduction of *Mytilus*, *Mytilaster* and *Balanus* as well as for fungal development. The mechanisms observed by Artemchuk [15] are characteristic for these ecosystems.

In MPs, marine fungi actively participate in the processes of ecto-metabolism, especially in benthal and periphytal communities.

During mass mortality and sedimentation of dead phytoplankton cells, compact fungi settlements with an area from a few to a couple of dozens square metres sometimes form on the sediment surface. Such zones are characterized by whitish, yellowish and pinkish colours.

A high diversity of ecomorphs and life forms is characteristic for the inhabitants of the water column (including MPs) and linked, first of all, to two features determining the general organisms' architecture: the character and type of movement and the feeding strategy [139]. All constant or temporary plankton representatives have various adaptations for prolonging their residence time in the pelagial. In MPs, interaction between plankton and benthos takes place in the near-bottom water layer, while interactions between plankton and periphyton occur in the near-wall or the near-substratum water layer of the periphytal zone. Peculiar features concerning the movement and feeding strategies of the various representatives of pelagic populations in MPs are discussed in the respective sections. In plankton composition, several groups are distinguished depending on the organisms's size.

As already mentioned, picoplanktonic organisms (0.4–1.0 μm) are able to carry out photosynthesis at much lower light intensities than larger representatives of the phytoplankton [141]. This ability gives them an advantage to produce OM in the water layer under the pycnocline and in the shadowed zones of MPs aquatories.

Ultra-nanoplankton (including picoplankton) is represented by organisms smaller than 2 μm (viruses, bacteria, algae). Nanoplankton, microplankton and mesoplankton are formed by organisms having sizes between 2 and 20 μm (algae and flagellates), 20–200 μm (protozoa, rotifers and algae) and 200–1000 μm (protozoa, algae, larvae of benthic organisms, crustaceans and others), respectively. Macroplankton is formed by organisms with size from 1 cm to a couple of centimetres, while organisms larger than 10 cm belong to megaplankton. In MPs aquatories, some comb-jellies and jelly fishes can be ascribed to megaplankton.

Given the small sizes and relatively small velocity of displacement of planktonic organisms, the water flow regime around their bodies has a laminar character in the majority of cases. This circumstance has an impact on all their locomotive apparatus and feeding strategies.

Plankton organisms have relatively short life cycles and, once dead, form SOM particles, dissolved OM and slime blobs. Faeces and different metabolites of planktonic organisms play an important role in trophodynamic processes. Their survival in MPs ecosystems is favoured by the presence of resting stages, frequently able to preserve their viability for a couple of months and up to couple of years.

The body density of various nano-, micro- and mesoplankton organisms (given the composition of their capsules, valves and shells) is practically equal to or slightly higher than the density of seawater in which they live. After death and destruction of cellular membranes and external solid body parts, the protoplasm is released into the environment where it forms fine drops of slime less dense than the formerly living whole organisms. These drops, clods and slime clots occupy an intermediate position between DOM and SOM, concentrate in the near-surface water layer and become a food supply [181].

Because food is present in different states in the water column, plankton organisms have developed different methods to use dead OM. Some of them osmotically use dissolved OM, others swallow OM in the form of slime, and others use phagotrophic feeding, based on filtration and selective sizing of separate hard food particles and whole organisms.

Plankton communities are spatially and temporally dynamic. Such dynamics manifest in quick changes of their taxonomic composition, abundance and biomass. Many planktonic organisms perform horizontal and vertical nocturnal migrations. The significant expenses of energy necessary for vertical migrations are compensated by the fact that the upper water layer is richer in food with a high caloric content [139]. In the surface water layer, migrating planktonic organisms are less subject to grazing risk at night than in daylight hours.

Planktonic communities have specific spatiotemporal structures. Under the influence of various factors, plankton forms certain aggregations and condensations, which can also be observed on a small scale [135, 136, 139].

In aquatic ecosystems, groups of mass parasitic organisms are present and participate in controlling quantity and biomass of many plankton, nekton and benthos forms by leading to their more or less their simultaneous death and substitution with other forms.

In aquatic ecosystems, phages and viruses regulate the processes of production and dying of primary OM, determining the end of microalgae water “blooms” [69]. Viruses are present in all aquatic ecosystems and there are no hydrobionts, starting from smallest picoplanktonic forms up to fish, dolphins and birds, which are not subject to contamination by them. The viruses’ size varies from 0.20 to 200–300 nm. Viruses are usually many times smaller than the majority of bacteria and their quantity in water and at the sediment surface can exceed that of bacteria by many folds. Viruses also regulate bacterioplankton development [94].

Molecular particles similar to viruses and infecting cells of living organisms are also known under the name of viroids. Viroids distinctly differ from viruses with regard to size, are depleted of the protein coat and consist only of circular RNA. Viroids are significantly smaller than the smallest viral particles. Even much smaller protein prions particles do not contain molecules of genetic substance. Subviral

particles, the so-called virus satellites, consisting of nucleic acid molecules were also found. All listed particles reproduce themselves inside the cell of a living host and can cause infectious diseases leading to the death of host organisms. It is commonly believed that viruses are carriers of interspecific genetic information, genetically connecting all live beings into a single global ecosystem—the Earth biosphere—in spite of their diversity. Viruses are important participants in the evolutionary process on the planet [42].

In marine ecosystems, the richest communities in terms of viruses' genotypes are found close to upwelling zones, while those with the highest density occur in surface waters with hundreds of millions of virus particles per litre of water. Such conditions are typical in MPs. Viruses can significantly influence the state and quantity of bacteria and phytoplankton communities. All cellular forms of life are sensitive to viral contamination and any marine organism is a host of at least one type of virus. All the World Ocean could contain about 10^{30} viral particles. Viruses are frequently a starter for bacterial and fungal infections [42, 216, 230].

In last years, numerous viruses' genotypes were discovered. They affect different species of commercial and non-commercial organisms belonging to different systematic groups. In particular, bivalves, which are widespread in MPs, are not only infected by viruses, but also act as their reservoir transferring them further along trophic chain or diffusing them in the ecosystem via faeces and pseudofaeces [42].

Among bacteria, there are photosynthetic ones using bacteriochlorophyll and bacteriorhodopsin pigments. Some bacteria are able to fix atmospheric nitrogen. Some of them can consume not only dead OM, but also live bacteria. Many bacteria are pathogenic for hydrobionts.

In MPs, parasitic flagellates, protozoans, worms and line of other groups of animals and fungi actively participate in the regulation of the abundances of many hydrobionts.

The composition of microalgae, protozoans and some fine-sized multicellular organisms includes autotrophs, heterotrophs and mixotrophs which are able to use both ways of feeding and energy production. Many macrophytes and multicellular invertebrates also utilize dissolved OM. Some protozoans feed and produce energy with the help of microalgal-symbionts, which is called algae-trophism. In MPs, such organisms exhibit certain universality in trophodynamic processes.

In both natural and anthropogenically modified ecosystems such as MPs aquatories, the transfer of energy has the form of a pyramid, as a result of the energy loss during each transition from one trophic level to the next one according to the laws of thermodynamics. The productivity of coastal waters, in which are located MPs aquatories of the Black–Azov Sea basin, usually varies between 0.5 and 5.0 g of carbon per 1 m^2 per day, although significant deviations on both sides can sometimes be observed. In ecosystems of MPs aquatories, the primary production is controlled by limiting factors such as presence, concentrations and ratios of biogenic elements, the intensity of solar radiation, hydrodynamics and the presence and distribution of various viruses. In MPs aquatories, the quantity and distribution of separate biotic components depend on primary productivity, inputs of allochthonous matter, predation, growth and migrations beyond the ecosystem borders.

Spatial-temporal changes and heterogeneity are characteristic for the ecosystems of MPs aquatories. The causes of such heterogeneity can be natural factors and processes as well as anthropogenic activity, which complicates the study, modelling and control of these ecosystems [173].

Each theory concerning the functioning of natural ecosystems and understanding of natural phenomena is inevitably based on some simplifications and therefore it is, in some way, approximated [103]. This caveat fully applies to the conception of biotic and ecological structures, organization and functioning of MPs aquatories ecosystems in general and to the corresponding subsystems in particular.

In MPs, the water column population is subject to diurnal, seasonal and inter-annual changes. It is connected with temperature, salinity, content of oxygen and biogenic matter, pH, hydrodynamics and vertical stratification to the fullest extent.

Organisms belonging to hyponeuston, plankton and nekton communities inhabit the MPs water column. The planktonic community is represented by bacterio-, phyto-, zoo- and ichthyoplankton. In MPs the planktonic complexes, as the similar complexes in the ecosystems of the Black Sea adjacent to them, have a relatively simple large-scale spatial structure. The relatively high homogeneity of their biota is connected, first of all, with mixing of water masses. Nevertheless, the vertical stratification of water masses, favoured by artificially created conditions, has a certain influence on the small-scale distribution of plankton in MPs along with many other abiotic and biotic factors.

In MPs, the thermocline is usually located closer to surface and more sharply marked in summer. In the aquatories of ports receiving inputs of river waters such as Sukhoy and Grigorievsky Limans and Novorossiysk and Sevastopol Bays, a horizontal heterogeneity in the distribution of planktonic communities is often present in connection with local processes.

In most cases, the hydrological regime is the main geographic factor in the formation of marine ecosystems structure [18, 22, 60]. In the MPs pelagial zone, as well as in the Black Sea water column, a two-layer distribution of organisms' complexes is evident below the hyponeuston micro-horizon (0–30 cm). In the Black Sea coastal waters, the first epiplanktonic complex inhabits the upper 5–20 m layer above the thermocline. This layer is well illuminated, relatively warm and has high rates of phytoplankton production during most of the year. It is inhabited by organisms which, as a rule, do not migrate and never leave this layer. The second complex is the bathyplanktonic one which inhabits the depths of more than 5–20 m below the thermocline and comprises mainly migratory organisms [131, 132].

At temperature gradients of 3–4 °C m⁻¹, the thermocline layer already becomes an almost insurmountable barrier for the majority of epiplanktonic and bathyplanktonic zooplankton organisms. At temperature gradients lower than 0.6 °C m⁻¹ in the thermocline layer, the border between the two complexes is lost and is registered in the thermocline zone which becomes an ecotone [161]. Primary and secondary production of OM above the thermocline occurs at higher rates than under the thermocline [53].

In MPs, a “liquid bottom” phenomenon can originate during density-related vertical stratification of the water masses. The phenomenon consists in the

accumulation of dead SOM particles and small-sized planktonic organisms at the border between the surface and deepwater masses [161]. It is favoured by the reduced MPs hydrodynamics.

During the hottest months, the redoxcline plays an important role in the hydrobionts' distribution in the deepwater zones of MPs aquatories. Because of the confined nature of aquatories, the raise of the redoxcline from the bottom into the water column reduces the aquatories volume suitable for the normal life of oxyphile species.

Planktonic organisms distribute in MPs pelagial zone in tight connection with SOM and DOM. Many pelagic planktonic animals feed on SOM, DOM and protoplasmic slime, formed during phytoplankton decomposition, i.e. detritus and aggregated DOM. However, in MPs aquatories, benthic animals inhabiting benthal and periphytal zones are the main consumers of the detritus and faecal pellets of planktonic organisms [76]. The faecal pellets are also colonized and used by nanoplanktonic organisms [233].

It was already mentioned that the majority of organic products of hydrobionts metabolism are present in the dissolved form in seawater along with seston and detritus, especially in coastal regions. These products include various carbohydrates, organic acids, proteinaceous compounds, amino acids, vitamins, hormones and other substances [33].

In seawater, the most substantial contribution to the total DOM content comes from macrophytes, first of all from the species dominating their biomass. The total quantity of OM excreted by a macrophytes' community during its vital activity reaches 2.6 kg per annum per 1 m² of substratum surface. The secretion speed of organic metabolites among actively growing bacteria could be 2.5–3-fold higher than that of bacteria with inhibited growth [33], and thus manifests certain seasonality.

Many algae inhabiting MPs aquatories have pelagic stages during their life cycle. Even if macrophytes are attached to HS, their thalli develop in the water column, either in the near-bottom layer or in the near-surface one if they form settlements on piers, berths and breakwaters. In MPs, the macrophytes belt growing on lateral surfaces of HTS usually forms at the depths between 0.2–0.5 and 1.0–1.5 m.

In the Black Sea coastal waters, the highest quantity of fungi spores and mycelia is observed in the near-surface water layer. In the water surface foam, the quantity of fungi is often two times higher than in the subsurface horizon. This phenomenon could be connected with the accumulation of SOM and DOM under the film of surface tension owing to hydrodynamics peculiarities [154]. The spores and fungi mycelia present in the hyponeuston constitute the miconuston.

In MPs aquatories ecosystems, fungi play an important role by actively participating in OM destruction during conditions of high production and high concentrations of SOM and DOM. In MPs aquatories, the inhabitants of benthal and periphytal zones from various taxonomic groups anyhow participate in the formation and utilization of DOM.

In seawater, the distinction between SOM and DOM is operationally defined, but DOM plays an extremely important role in trophic chains owing to its lability and

biological activity. According to some estimations, the level of DOM in seawater could exceed by more than 100-fold the amount of OM contained in all living marine organisms as a whole [48]. Average DOM concentration is 3.0 mg dm^{-3} in the NWBS open waters and $10\text{--}25 \text{ mg dm}^{-3}$ in the NWBS coastal zone [181].

In MPs, DOM concentration increases at the sediment–water interface, in zones adjacent to the underwater surfaces of HTS and in the hyponeuston layer of the water mass. In protected MPs aquatories, owing to hydrodynamical processes, DOM is a cumulative, more or less averaged metabolite. An important role in DOM formation belongs to bacteria and diatoms, as well as to various zoo- and phyto-organisms [48].

Although the majority of planktonic organisms do not have a strong ability to move actively, many of them can perform significant migrations in the water column, especially vertically. Such displacements usually take place due to the work of locomotor organs or via changes in specific body gravity. The absolute majority of sea hydrobionts is heavier than water. However, many planktonic species from various systematic groups are able to create neutral and positive buoyancy with the help of gaseous inclusions or prolong their presence in the water column owing to various body appendices and active movement. The hydrobionts' feeding is also connected with displacement. In MPs aquatories, planktonic and benthic organisms (and their larvae) with morphofunctional adaptations for the creation of water flows (flagella, cilia and sifonal channel through which water is being pumped) have a competitive advantage [79, 89, 145].

Planktonic organisms are able to submerge at increased roughness, thus protecting themselves from mechanical damage. Gravity facilitates immersion, but planktonic organisms must then spend energy to overcome it when rising up again. However, upwards vertical migrations can be favourable because of better living conditions.

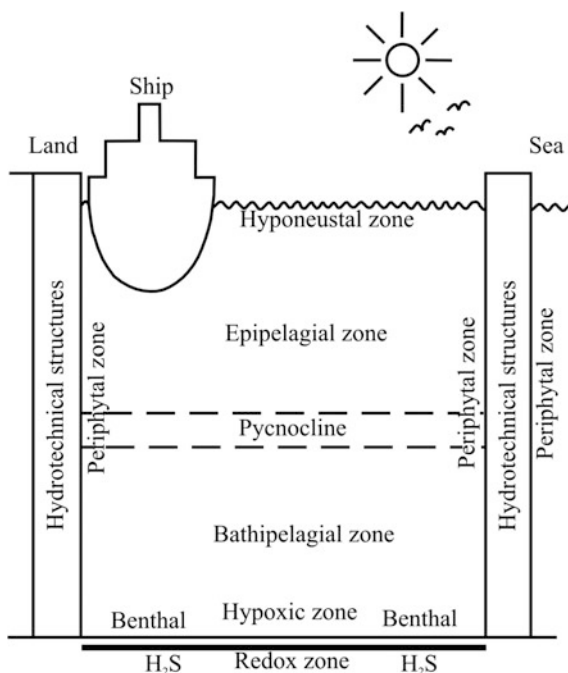
Figure 2.23 schematically shows the main pelagial biotopes in MPs.

For planktonic organisms, micro- and small-scale water motions play an important role, while large-scale ones could have catastrophic consequences. The frequency of interaction between planktonic predators and preys notably differs in “non-turbulent” and turbulent environments, being significantly higher in the latter. The microscale turbulence also influences the production rate of eggs and metabolism intensity, in particular among copepods. Heterogeneity and scale of turbulent processes in the water column (from the surface until the near-bottom layer) influence organisms' behaviour during vertical diurnal migrations as well as their distribution [135, 136].

Numerous studies showed that spatial and temporal distribution of planktonic organisms is not random, but depends on the combination of hydrodynamic conditions, specific physical and chemical factors and absence or presence of other organisms with which plankton interacts directly or indirectly. For planktonic animals, a patchy and layered distribution in the water column is most often typical and is also connected with isopycnal layers [36, 135, 136].

The formation of specifically organized accumulations of plankton led Wiebe [235] to conclude that their formation is tightly connected with physical processes,

Fig. 2.23 General scheme of a marine port ecosystem of the classical type



in particular Langmuir circulation, occurring between the surface horizon until and the pycnocline.

It was already mentioned that wind, friction and the Coriolis force are the main factors causing movement and water rotation, i.e. the formation of vertical and horizontal circulations on various scales, including those of MPs. The smaller is the area of a MP harbour aquatory and the shallower its depth, the bigger is the role of frictional forces. The speeds of water circulations most distinctly reduce at shores, near the internal surfaces of MPs HTS and also near the bottom, while they are preserved over longer time spans in the central parts of aquatories. This pattern influences the distribution of both planktonic and benthic organisms.

In MPs aquatories, the dynamics of various frontal formations and circulations, including Langmuir vortices, generates parasitic water circulations with different scale in the epipelagial zone. These parasitic circulations collect live and dead organisms from phyto-, zoo- and ichthyoneuston, and phyto-, zoo- and ichthyoplankton. Mono- and polyspecies plankton accumulations of various densities are registered in MPs harbours.

Langmuir [212] determined that a significant part of dissolved OM produced by vegetal cells concentrates in the thin near-surface film at the air–water interface. Later on, it was shown that Langmuir vortices concentrate OM present in the subsurface film along convergence lines on the water surface [229].

During the process of lateral compression in convergence zones, OM forms small organic conglomerates which, owing to surface microconvections and

Langmuir vortices, sink to various depths and accumulate at isopycnic surfaces. The aggregates formed from the dissolved OM, along with the bacteria adsorbed on them, serve as food for zooplankton [36].

Zooplanktonic organisms of various sizes are influenced by Langmuir circulation and their spatial distribution is eventually determined by the ratio between the speeds of water circulations and the speeds and direction of the movement of individuals. Organisms concentrate in zones of waters' divergence and raising at high flow speeds and in zones of convergence and sinking at low flow speeds [209, 228].

In Langmuir cells, the water sinking speeds usually range from 4 to 8 cm s⁻¹, but can sometimes reach 27 cm s⁻¹. These speeds already notably exceed the average movement speeds of copepods [136] and of most of the other zooplankton organisms.

Langmuir vortices not only form streaks with increased concentrations of OM and planktonic organisms on the water surfaces, but also determine plankton distribution in the MPs epipelagial zone and form plankton accumulations, with a more or less spherical shape, resembling cloud structures.

In MPs pelagial, accumulation of zooplankton in forms resembling cloud structures is connected with physical processes. The most important processes are water movement (first of all, small (metres) and average (dozens of metres) scale circulations at small or average Reynolds numbers of 1–10) and the regular active behaviour of zooplanktonic organisms. Mono- and multispecies aggregations form, first of all, during the feeding, reproduction and development processes at low Reynolds numbers.

Besides Langmuir circulation, gravitational internal waves [136] and ships' waves can influence the distribution of zooplankton in MPs over defined spatiotemporal scales. Plankton concentration in slick zones formed, for example, by internal waves could be very significant. In particular, concentration of fish larvae in the slicks can exceed the concentration outside them by 13–36-fold [221].

In MPs pelagial zone, all zooplankton aggregations have their own lifetime. They form over a period of time, preserve their main characteristics for a defined period and then disappear under the influence of various abiotic and biotic factors. Formation and destruction of variously sized accumulations of zooplankton in the water column is one of the main mechanisms for the normal functioning of pelagial subsystem in MPs. The constant process of redistribution of the alive and dead OM and energy in this subsystem takes place thanks to the cyclic nature of such accumulation. For zooplankton organisms, the presence in accumulations is an absolute requirement during their whole life cycle or at some of its stages [32, 198, 211, 220].

According to some hypotheses, Langmuir circulation could have had a significant role in the sustention and evolution of marine life already in the Precambrian time. At that time, the atmosphere was reducing, while seas were warm, shallow-watered, salty, and inhabited by cyanobacteria. In the Precambrian seas, oxygen was completely consumed by biotic components of ecosystems in the epipelagial zone and was entirely spent on the oxidation of minerals near the

bottom, i.e. reducing conditions occurred both near the surface and at the bottom. The oxygen produced by cyanobacteria, even in small amounts, could concentrate, and not completely exhausted, only in the pycnocline layer because of the low speed of diffusion via isopycnic surfaces. Thus, the pycnocline was an ecological niche in which organisms requiring oxygen could survive and develop. Owing to Langmuir circulation, the pycnocline zone was also enriched in dead OM from the near-surface water layer. The first representatives of many hydrobionts types could have appeared in the pycnocline and later on quickly diffuse in the oxidizing conditions of the Cambrian period [36].

Thus, the pycnocline has played an important positive role at a certain stage of life evolution in the World Ocean. At present, in conditions of excessive eutrophication, the pycnocline quite often hampers aeration of the near-bottom water layer and is one of the factors of fauna mass mortality and simplification of biota composition in MPs aquatories ecosystems.

In the modern Black Sea MPs, downwelling of surface waters causes only an insignificant input of oxygen into the water column below the pycnocline.

2.2.1 Phytoneuston and Phytoplankton

In the Black Sea, according to the classical scheme, the mass development of diatoms is observed in spring (February–March), while dinophytes become dominant in summer (June–September). A new bloom of diatoms occurs in autumn (October–November). In desalinated aquatories, cyanobacteria (Cyanophyta) play an important role in phytoplankton composition during some periods. Cyanobacteria are the most ancient organisms among the known prokaryotes and euglenoids (Euglenophyta).

Cyanobacteria show characteristics of both bacteria and plants (unicellular and colonial). They include autotrophs, heterotrophs and mixotrophs, although their functional role in aquatic ecosystems is usually close to that of autotrophic algae.

Planktonic microphytes often have organs of locomotion in water and many cyanobacteria move with the help of flagella. As a rule, euglenoids have a flagellar apparatus and include colourless forms, i.e. heterotrophs. The majority of the golden algae (Chrysophyta) have 1–4 flagella and include the ecologically important group of coccolithophora. The pelagic yellow-green algae (Xanthophyta) also have flagella and can be endocellular symbionts of protozoa. Algae from the phylum Raphidophyta swim with the help of a pair of flagella. Cryptophytes (Cryptophyta) and many dinoflagellates (Dinophyta), widespread in MPs aquatories ecosystems, have the same number of flagella.

In the Black–Azov Sea basin, dinoflagellates (Dinoflagellata), or dinoflagellate algae dominate the phytoplankton composition of MPs aquatories together with diatoms (Bacillariophyta).

Among botanists, the term “dinoflagellates” includes the monades (unicellular) forms of dinophytes. In zoology, it is the same as peridinean (Peridinea). They can have one to eight flagella.

Among dinophytes, there are species using phototrophic and heterotrophic (osmo- and phagotrophic) feeding. Phototrophic species have brown chloroplasts, containing chlorophyll “a” and “c”, and xanthophylls. Some tiny dinophytes are symbionts of protozoans, coelenterates and comb-jellies.

More than half of the Black Sea dinoflagellates can switch from the phototrophic to the mixotrophic (54.8%) feeding strategy and only about 12.1% of them can be considered obligate phototrophs [168].

In many MPs aquatories, water “blooms” phenomena are quite often observed and are usually caused by mass development of planktonic (from pico- to meso-planktonic) algae or protozoans. Water “blooms” are usually connected with different types of anthropogenic impact, but cases of phytoplankton mass development caused by a rare combination of completely natural causes are also known.

For example, a case of mass development of planktonic algae belonging to the genera *Gymnodinium* and *Gonyaulax* (resulting in a brown-red colour of seawater) was recorded on the southern coast of Ireland in the absence of wastewater discharges and after an extremely long period of summer calms (not even ripples). In this situation, a “red tide” phenomenon is tightly connected with lowered hydrodynamics [45].

Numerous literature data indicate that lowered water dynamics in water reservoirs along big rivers creates preconditions for the intensive development of some planktonic algae, that can then cover all the reservoir’s surface. In the Azov Sea, descriptions from the 1930s report situations in which great amounts of phytoplankton accumulated in the surface water horizon, completely covering it with an intensively coloured green layer during periods of water blooms [85]. In June 2011, wide areas covered with an algal mat of the species *Nodularia spumigena* were registered in the NWBS open waters.

In both freshwater and in marine ecosystems, the prolonged natural or artificial reduction of hydrodynamics quite often causes mass development of unicellular and colonial algae. Depending on the various hydrological situations, the intensive phytoplankton development can take place in the water surface layer, in the pycnocline zone and even under the pycnocline.

In MPs aquatories, the greatest phytoplankton species diversity is observed in zones with good water exchange [40, 156, 197].

In 1976, mortality of fish, crustaceans and molluscs was registered in the region of Lower New York Bay. On that occasion, oxygen concentration near the bottom had dropped below 2 mg dm^{-3} . Occasionally, a complete absence of oxygen and the appearance of hydrogen sulphide were observed in the near-bottom water layer at a depth of 35 m. Abnormally warm and windless spring and summer resulted in the development of a stronger than usual thermocline, which separated the much lighter and warmer surface water from the heavy and cold near-bottom water. Under the thermocline, extremely strong development of phytoplankton occurred. This rarely occurring combination of natural processes caused mass mortality [45]. Similar situation could form also in MPs aquatories.

Phytoplankton usually develops more intensively in sea zones experiencing a constant pollution by domestic wastewaters than in unpolluted ones. The content of phosphates in these zones can sometimes increase so much that the planktonic algae are not able to exhaust it during the spring-summer period and “blooms” phenomena occur during most of the year [214].

In the Black Sea, several conditions are necessary for the onset of the “red tide” phenomena: 1—water temperature above 20 °C; 2—salinity in the range 11–15‰; 3—abundance of biogenic matter; 4—absence of wave action (sea force no more than 3); 5—illumination not less than 600,000 lx [12].

In darkness, the density of microalgae cultures diminishes after a couple of hours. This phenomenon is connected with the dark respiration and is called “night biomass loss”. Losses during nighttime can reach 14% of initial density. Ad hoc studies showed that maximum dark loss of biomass takes place due to a decrease in carbohydrates’ content, sometimes almost by a factor of two. In such situations, the content of protein slightly increases and the lipids’ share reduces [170].

As it was already mentioned, many species of planktonic algae are able to shift from autotrophy to mixed feeding (mixotrophia) under certain conditions. In the Gulf of Burgas, the shift of a whole population of *Exuviella cordata* to heterotrophic nutrition was recorded during the decline period of water “blooms”. The use of dissolved OM became the main source of energy supply for the cells [12].

In coastal waters and, consequently, in MPs aquatories, the heterotrophic planktonic algae are present nearly all year round and sometimes comprise more than 50% of phytoplankton biomass. The role of heterotrophic algae in the trophic dynamics of coastal waters is comparable with the role of nano- and microzooplankton [12].

A sudden die-off of the “bloom-forming” planktonic algae is often observed after the period of mass development following damage caused by viruses, protozoans, fungi, etc. The death of *Exuviaella cordata* was connected with the activity of parasitic protozoans [12].

Some algal species, in particular cyanobacteria, excrete reducing substances into the environment both after their death and during their normal functioning. Such substances react with oxygen and deplete its resources [12].

Cyanobacteria that cause water “blooms” have diurnal rhythms of vertical migration and create regular flows of matter in the water column.

Cyanobacteria and euglenoids are considered as one index of water pollution. Thus, they comprise 11.5–17.0% of total organisms’ abundance in Novorossiysk and Tuapse MPs [157].

Following the death and decomposition of green algae, more or less hard detritus particles are formed along with pellets and protoplasm slimes clots populated by bacteria. The cells of various planktonic algae species have different nutritional value for their consumers. Diatoms, which quite often have hard shells with various outgrowths, are less valuable than the round-shaped cells of dinophytes with their soft membrane.

In Novorossiysk Bay, the maximal development of dinophytes takes place at the end of the period of diatoms’ intensive development (May–July). The role of

Dinophyta in using the “dying bloom” dead OM can be compared only to the role of planktonic infusoria [197]. The reproduction of many fish with pelagic stages of development is also confined to the same period.

In June and August 1998, after diatoms “blooms”, the dinoflagellates *Gyrodinium cornutum* and *Polykrikos schwartzii* accounted for up to 95.0% of phytoplankton biomass in Odessa MP. In September 2000, an outbreak the dinophyte *Akashiwo sanguinea* (678×10^3 cells dm^{-3} and 55.3 g m^{-3}) developed in Odessa MP aquatory and comprised 79.0% of phytoplankton quantity and 96.0% of its biomass. In August 2000, “blooms” in Odessa MP were caused by *Gymnodinium simplex* (250×10^3 cells dm^{-3}) [168]. Such mass development of these algae was closely connected with the prolonged calm weather and high water temperature.

The works of Nesterova [120–122] showed that constant accumulations of unicellular algae are often registered in the near-surface layer of the Black Sea, where they can exceed by up to threefold their quantity in the water column. Diatoms, peridinean and cyanobacteria were usually prevailing in phytoneuston composition.

In the coastal regions of the Black Sea, the foam forming on the water surface contains high numbers of bacteria, cells of planktonic algae and their cysts. In Odessa Gulf, the quantity of dinoflagellate cysts under the film of surface tension exceeds that in the subsurface water layer by twofold. Analysis of the vertical distribution of some mass species of phytoplankton showed their regular concentration at the surface of the pelagial zone [154].

In marine ecosystems, planktonic autotrophic algae, macrophytes and micro-phytobenthos transform inorganic components contained in marine water into organic compounds using solar light for photosynthesis. Phytoplankton is the main producer of OM in both seas and MPs aquatories. The life of organisms in the water column and in the benthal and periphytal zones frequently depends, directly or indirectly, on the OM of planktonic algae.

In MPs, the intensive development of phytoplankton changes not only the colour of water, but also sharply reduces water transparency and worsens the illumination of the deeper water layers.

In the surface sea layer, phytoplankton reaches its maximal diurnal development during daytime and evening hours. In this period, a growth of oxygen concentration is recorded because of the photosynthetic activity of planktonic algae. In the Black Sea surface water layer, the diurnal maximum and minimum values of oxygen concentration occur between 5–8 p.m. and 7–8 a.m., respectively [161].

In MPs, the hydrodynamical processes have a significant importance for the distribution and vital activity of phytoplankton and of the bacteria and protozoa trophically connected with it. Plankton diatoms with siliceous frustules develop better in conditions of active water mixing, which keep them in suspension. The diatoms most widely distributed in MPs ecosystems develop well at flow speeds of 0.7 m s^{-1} and above. For green algae, the limiting flow speed is within $0.5\text{--}0.8 \text{ m s}^{-1}$ and flow speeds of $0.2\text{--}0.3 \text{ m s}^{-1}$ are already unfavourable for the cyanobacteria responsible for water “blooms” [145]. In MPs aquatories, high flow

speeds are absent during most of the year, thus limiting phytoplankton development. Extremely low speeds (lower than 0.01 m s^{-1}) are quite often observed [196].

For example, the phytoplankton vertical distribution in Grigorievsky Liman is unstable and depends on the hydrological situation that changes in the various seasons. In spring and summer months, the cells' number in the surface layer is up to twofold higher than in the near-bottom, while the phytoplankton accumulation occurs in the near-bottom layer during the autumn and winter months [196].

The Black Sea water column hosts both heliophilous and sciophilous species of planktonic algae, which belong to the epi- or bathyplanktonic complexes, respectively. Some peridinean have a photosensible organ and can actively move towards the source of light. Unlike planktonic algae, most planktonic animals have positive or negative phototaxis. However, they distribute in the pelagial zone according to not only illumination, but also food availability and dissolved oxygen content.

In the majority of MPs aquatories, the presence of protective HTS and of only one passage reduces, to a various degree, the possibilities of transport and dispersion of live and dead phytoplankton.

As already mentioned, many pelagic microalgae can simultaneously have autotrophic and heterotrophic feeding. Forms with a prevailing autotrophic mode of feeding inhabit the euphotic layer of Black Sea regions with relatively low DOM concentration. The big MPs aquatories do not usually belong to these regions and offer conditions for heterotrophic nutrition. At light attenuation, many microalgae easily switch from autotrophy to the heterotrophic utilization of some dissolved organic compounds. Thus, the so-called umbraticolous microalgae, usually concentrating in and below the thermocline zone, can use the heterotrophic mode of nutrition in shadowed zones and above the thermocline in MPs.

Light frequently plays a role as signal factor for selecting the best environment according to positive or negative phototaxis. For many planktonic animals, light is also essential for gonads' development and formation of vitamin A from carotenoids assimilated from phytoplankton [161].

All main algal groups present in the Black Sea plankton and inhabiting MPs (diatoms, dinoflagellates, silicoflagellates, coccolithophores, green flagellates, cyanobacteria) are able to regulate their position in the water column to a various degree by changing their specific weight by fat accumulation (diatoms), formation of air bubbles (cyanobacteria), increasing floating ability (diatoms) or owing to active movements (flagellates).

Planktonic diatoms float in the water column; their buoyancy being provided by the presence of numerous inclusions of fat in their body as well as by light-weighted tests with numerous spines, projections and spikes that increase cell surface.

Migrations of planktonic algae and their mass development in the surface layer ensure them better illumination and higher hydrodynamics and causes shading of the underlying water layers suppressing the development of non-concurrent phytoplankton species for some time.

At the initial stage of their mass development, young diatom populations increase their buoyancy by forming fatty drops inside cells. In this period, their

populations remain close to the water surface under approximately optimal light conditions. The photosynthetic activity of populations reduces along with the depletion of the stocks of biogenic substances, the amount of fat in their cells decreases and the population “sinks” to a depth where their buoyancy becomes neutral. This depth is the upper limit of the thermocline.

A special flora of diatoms, adapted to low light intensities, inhabits the zone between the upper limit of the thermocline and the lower border of the photic zone. This flora is retained here owing to its ability to float and to the presence of various convective flows [161].

The “sedimentation” of microalgal populations to the depths of about 10 m, i.e. the upper border of the thermocline, is often observed in the NWBS in general and in MPs aquatories; in particular during the period of their mass development. In the thermocline zone, the concentration of microalgae can be up to twofold higher than at the surface. The mass “sedimentation” of algal populations and their die-off increase the transparency of the upper layer of the water column and favour BM turnover, thus creating conditions for the development of other phytoplankton representatives.

In MPs aquatories, a significant amount of the so-called accidentally planktonic or benthoplanktonic microalgal species, predominantly diatoms, is recorded in the water column. Thus, in the phytoplankton of Sevastopol Bay, 43 out of 110 species of diatoms belonged to benthoplanktonic species. These algae normally develop on the bottom and on periphyton and have no specific adaptations for floating. However, they can live and feed for quite a long time in the water column [161].

In MPs, diatoms provide a link between the pelagial, benthic and periphytic zones. After intensive vegetation and mass development, as well as at the onset of stress situations in water column, many diatom species sink to the surface of bottom sediments in the form of resting spores, separate vegetative cells and filamentary colonies. Spores and vegetative cells are able to return into the pelagial zone when abiotic conditions improve. Benthic diatoms can pass from benthos into plankton and vice versa in any season [99]. Such mechanism preserves the diatom populations in MPs aquatories during periods of unfavourable environmental conditions and contributes to a higher stability of MPs ecosystems. The resting stages of diatoms and other planktonic microalgae allow them to return into the cycle of matter in MP ecosystems, without passing through the stage of mineralization.

In MPs aquatories, dinoflagellates and other flagellates are able to perform active migration across the thermocline and accumulate in layers with optimal illumination and sufficient biogenic nutrition [161]. The lowered hydrodynamics of MPs facilitate flagellates in selecting the best conditions.

Some phytoplankton species in the surface layer can be grazed by the zooplankton migrating towards the surface during night hours or constantly inhabiting there. At night and during the afternoon, the growth rates of planktonic algae frequently drop [145, 161].

Diatoms (Bacillariophyta) of various species often dominate the phytoplankton composition of MPs aquatories in terms of both density and species abundance. They are an important primary source of live OM and detritus, can contribute to the

aquatories' oxygen regime and serve as food for many animals of pelagial, periphytal and benthal zones. Processes of matter and energy turnover in marine ecosystems, particularly in MPs aquatories, involve their active or passive participation.

In Sevastopol Bay, diatom algae form the basis of phytoplankton. In the summer–autumn period, the contribution of pyrophyta to the total phytoplankton quantity increases. Algae of the class chrysophyceae are registered all year round. Representatives of Cyanophyta, Euglenophyta, Cryptophyta, Flagellata, etc. are found in Sevastopol Bay at different locations. Small-sized algae dominate in terms of quantity, while big-sized ones represent most of the biomass [3].

Development of large-sized species of planktonic algae was observed in Tuapse MP during summer. Diatoms of the species *Proboscia clavata* comprised 90% of the quantity. *Gymnodinium simplex*, *Oblea rotunda* and species of the genera *Gymnodinium* and *Prorocentrum* were found among dinophytes ($\leq 5\text{--}6\%$ of the total). The euglenophytes *Eutreptia lanovii* and *Euglena* sp., and cyanobacteria of the genus *Oscillatoria* (in total 0.5×10^6 cells m^{-3}), which are indicators of water saprobity, reached noticeable abundances. The total quantity of planktonic algae reached 84×10^6 cells m^{-3} and its biomass 453.0 mg m^{-3} [155].

In Varna Lake, oxybiont phytoplankton is observed only in the upper water layer enriched by oxygen. From the depth of 10 m down to the bottom, *Exuviella cordata* and *Prorocentrum micans* are observed in small amounts. In Varna and Beloslav Lakes, diatoms cause water “blooms” even in winter–spring months. The number of planktonic algae varies from 142×10^6 up to 838×10^6 cells m^{-3} [189].

Water “blooms” often are an ecosystem phenomenon, which testifies a surplus of BM in a marine ecosystem.

The biggest Ukrainian MPs (Yuzhny, Odessa and Ilyichevsk) are located in the desalinated NWBS and their ecosystems are variously influenced by large rivers; most importantly Dnieper and Yuzhny Bug. The waters of these rivers mix between themselves, and with seawater, in the Dnieper-Bug Liman and then spread over the saltier near-bottom mass of seawaters forming a layer up to a couple of metres thick. In MPs pelagial, an increase in the share of marine phytoplankton forms is observed from Grigorievsky Liman to the Odessa Gulf and farther towards Sukhoy Liman. Furthermore, the amount of unicellular algae, usually belonging to micro-phytobenthos, appears higher than in regions adjacent to these ports.

The modern structure of phytoplankton in the main Ukrainian MPs (Yuzhny, Odessa and Ilyichevsk) genetically consists in representatives of three complexes: freshwater, brackish and marine.

There are 265 species included in the general list of species and varieties of planktonic algae of Grigorievsky Liman [196]. They belong to seven systematic divisions of phytoplankton, namely: diatom (Bacillariophyta), dinophytes (Dinophyta), cryptophytes (Cryptophyceae), green algae (Chlorophyta), cyanobacteria (Cyanophyta), golden algae (Chryzophyta) and euglenophytes (Euglenophyta). More than 52% of the species are marine, brackishwater–marine and brackish water [196]. Diatoms are represented by 97 species. Phytoplankton representatives usually recorded in the NWBS are constantly observed in the liman:

the diatoms *Skeletonema costatum*, *Nitzschia closterium*, *Cyclotella caspia*, the dinophytes *Heterocarpus triquetra*, *Scrippsiella trochoidea*, *Hillea fusiformis*, *Diplosalis lenticula*, the cyanobacteria *Oscillatoria kisseleva* and the green alga *Scenedesmus quadricauda*. Algal species new for the NWBS were first found in the phytoplankton composition of Grigorievsky Liman: the yellow-green algae *Amphiri epizootica*, the green algae *Pyramimonas longicauda* and the choanoflagellate *Bicosta spinifera*.

In Grigorievsky Liman, phytoplankton usually has an even vertical distribution in autumn and winter. In spring, its quantity is higher at the surface, but the biomass is evenly distributed. On the contrary, phytoplankton biomass concentrates near the surface and its quantity is evenly distributed in summer months. In Grigorievsky Liman, both quantity ($741\text{--}3903 \times 10^6 \text{ cells m}^{-3}$) and biomass ($2500\text{--}34,600 \text{ mg m}^{-3}$) of phytoplankton exhibited considerable interseasonal and interannual fluctuations. Thus, phytoplankton vertical distribution in the liman is variable and depends on the hydrological situation and on season. In spring and summer, the quantity of phytoplankton in the near-surface water layer is up to twofold higher than near the bottom.

During the year, diatoms comprise 10.3–83.9% of the quantity and 22–98.0% of the biomass of phytoplankton of Grigorievsky Liman. Dinophytes algae contribute 0.1–23.3% to phytoplankton quantity and 1.6–55.5% to its biomass. In 2004–2006, a tendency in the growth of phytoplankton was observed in Grigorievsky Liman; with a continue decrease of diatoms quantity (61.3%) and biomass (34.6%) accompanied by corresponding increases (21.3 and 64.1%, respectively) of dinophytes.

Out of 29 species of microalgae that were causing “blooms” in Grigorievsky Liman, 11 were diatom representatives, 7 dinophytes, 5 cyanobacteria, 2 green algae, 1 coccolithophora, 2 euglena algae, 1 picoplankton alga (*Prochlorococcus marinus*) and a combined group of small-sized flagellate alga [196].

In Odessa MP, dinoflagellates and diatoms are the main component of plankton. In its pelagial zone, 156 species and intraspecific taxa of microalgae were registered in the 2000s: diatoms—67, dinophytes—50, green algae—22, cyanobacteria—7. Golden algae and euglenoids were represented by eight species. Among diatoms, the genus *Chaetoceros* was the most diversified with 27 species and intraspecific taxa. In 2004–2005, 82 species of dinoflagellates were found in Odessa MP, compared with 31 species recorded in Sukhoy Liman [168].

In Odessa MP, dinoflagellates quite often cause water “blooms” in autumn. During mass development in June–July 1998, the quantity and biomass of *Prorocentrum cordatum* reached $5.6 \times 10^6 \text{ cells dm}^{-3}$ and 10.6 g m^{-3} , respectively. The corresponding figures were $1.3 \times 10^6 \text{ cells dm}^{-3}$ and 13.5 g m^{-3} for *Heterocarpus triquetra* (April 1999) and $780 \times 10^3 \text{ cells dm}^{-3}$ and 70.0 g m^{-3} for *Gymnodinium sanguineum* (October–November 2000). In 2001, the highest quantities and biomasses were registered for *H. triquetra* ($34.3 \times 10^3 \text{ cells dm}^{-3}$, 362.6 mg m^{-3}), *Scrippsiella trochoidea* ($10.7 \times 10^3 \text{ cells dm}^{-3}$, 124.6 mg m^{-3}), *Prorocentrum micans* ($8.0 \times 10^3 \text{ cells dm}^{-3}$, 142.1 mg m^{-3}) and *Oblea rotunda* ($5.9 \times 10^3 \text{ cells dm}^{-3}$, 23.7 mg m^{-3}) [16].

Water renewal in Odessa MP can happen quicker than in most big ports of the Black–Azov Sea basin owing to the presence of three wide and deep passages into its aquatory. In MPs, changes in phytoplankton composition are observed along with the changes of water masses. In Odessa MP, the processes of phytoplankton development are synchronized with those in the NWBS to a greater extent than in Grigorievsky and Sukhoy Limans.

In Grigorievsky Liman, the share of marine and brackishwater–marine species exceeds 52.0% of the taxa number. In Sukhoy Liman, which is much less influenced by the Dnieper–Bug Liman waters, the share of marine and brackishwater–marine species comprised 81.5% and that of freshwater and freshwater–brackish water species only 18.5% [196].

Out of the 123 species and intraspecific taxa of planktonic microalgae found in Sukhoy Liman, 43 were dinophytes, 41 diatoms, 14 cyanobacteria, 10 green algae, 9 golden algae, 4 euglena algae and 2 cryptophytes. Phytoplankton quantity varies from 0.1 to 4.6×10^6 cells dm^{-3} with an average of 1.9×10^6 cells dm^{-3} . Biomass ranges from 0.6 to 20.1 g m^{-3} with an average of 8.0 g m^{-3} . Sukhoy Liman is characterized by water “blooms” in the summer–autumn period. In June 2001, the density of *Prorocentrum cordatum* was 3.3×10^6 cells dm^{-3} with a biomass of 16.7 g m^{-3} , corresponding to 93.0% of the whole dinophytes’ biomass.

In the NWBS, the phytoplankton concentration is always higher than near Crimean and Caucasian shores and everywhere is higher nearshore than offshore. In the NWBS, the highest productivity of phytoplankton is registered in limans, gulfs, bays and port aquatories. Considering a water layer 25 m deep and with a surface of 1 m^2 , the daily carbon production is 0.15–0.25 g in offshore Black Sea regions and 0.2–1.0 g in the coastal zone. The diurnal carbon production reaches 1.0–2.0 g m^{-2} in Sevastopol Bay [161, 179] and it can often exceed 2 g m^{-2} in aquatories of the big MPs of the Black–Azov Sea basin during the summer–autumn period. In many cases, such high diurnal carbon production values are favoured by the entrance of river waters and various wastewaters into ports aquatories.

In MPs, the mass development of permanent planktonic algae causes self eutrophication of their ecosystems.

The total phytoplankton biomass reaches 100–150 mg m^{-3} in the open parts of the NWBS and 3–4 g m^{-3} in deeply cutting inland bays and MPs. During diatoms “blooms”, especially during those caused by peridinin algae (red tides), phytoplankton biomass reaches 1 kg m^{-3} and primary production—20.0 g C m^{-3} [12].

One of the highest values of dinoflagellates density in the NWBS was registered in Odessa MP with an average of 71.8×10^3 cells dm^{-3} per year. The highest values of density and biomass of the exclusively heterotrophic dinoflagellates species *P. schwartzii* and of the mixotroph *Ceratium furca* are also connected with Odessa MP aquatory. Both species are considered indicators of high organic pollution.

During unfavourable conditions, dinoflagellates form resting cysts on the bottom. Indeed, cysts of 31 dinoflagellates species were found in Odessa MP [168].

According to Selifonova [156], the phytoplankton composition of Novorossiysk and Tuapse ports aquatories included 145 taxa: Bacillariophyceae—66,

Dinophyceae—59, Prymnesiophyceae—2, Cryptophyceae—2, Chrysophyceae—1, Dictyochophyceae—2, Euglenophyceae—4, Chlorophyceae—5, Prasinophyceae—1 and Cyanophyceae—3. The number of taxa was 131 and 104 in Novorossiysk and Tuapse port, respectively. Diatoms and dinophytes dominated in Novorossiysk Bay during summer, their total number varying between 48 and 54 taxa. In spring and autumn, the number of taxa for these algae was in the range 28–39. In Tuapse MP, the amount of diatoms increased in autumn (28) and that of dinophytes in spring and summer (23–30); while number of both groups reduced to 13–20 in winter and autumn [156, 157].

In Novorossiysk MP aquatory, the greatest contribution belonged to diatoms both in quantity (78%) and biomass (81%). In general, their total quantity was lower than in open part of the bay where the share of peridinin algae, in particular coccolithophores and dinophytes, increased. Euglenoids were registered predominantly in the port aquatory [156].

Diatoms and dinophytes made up most of the total biomass of Novorossiysk MP phytoplankton.

In the aquatory of Novorossiysk port, peaks of algal biomass and density are sometimes mismatched owing to the predominant development of small-sized phytoplankton forms. Maximal biomass of phytoplankton in Novorossiysk MP aquatory was registered in May 2006, when it reached 5.4 g m^{-3} . In the open part of Novorossiysk Bay, the same species of diatom algae as in the MP usually dominate in terms of total quantity, but among them the share of the big-sized species and also of dinophytes, silicoflagellates and golden algae (Chrysophyta) naturally increases.

In Tuapse MP, diatoms are the main contributors to both quantity (46–48%) and biomass (63–69%) of phytoplankton. Dinophytes algae significantly contribute (24–34%) only to total phytoplankton biomass. Cyanobacteria and euglenoids, which can be an index of highly eutrophic waters, are a significant component of plankton in the port (about 17% of total quantity) [156].

In Novorossiysk and in Tuapse MPs, the quantity and biomass of phytoplankton are usually 1.2–2.0-fold lower than in the adjacent open waters [156, 157].

As a rule, the share of dinophytes does not exceed 7–12% of the total phytoplankton quantity and 24–34% of its total biomass in the aquatories of Novorossiysk and Tuapse ports. Many dinophytes from the genera *Protoperdinium*, *Prorocentrum*, *Gymnodinium* and *Gyrodinium* develop in ports as subdominant species and are able to switch to heterotrophic or mixotrophic nutrition. As previously mentioned, it is commonly believed that an increase of heterotrophic phytoplankton is first of all connected with a corresponding increase in the content of dissolved and suspended dead OM in water.

In the last years, a two to fivefold decrease of phytoplankton quantity and a three to fourfold decrease of its biomass were registered in Tuapse and Novorossiysk MPs aquatories. Such tendency can be explained by the cumulative influence of various negative factors. In general, the more polluted Tuapse port is characterized by lower level of phytoplankton development [17, 157].

In Novorossiysk MP aquatory, the long-term average annual values of phytoplankton were 0.35×10^6 cells dm^{-3} for density and 1.27 g m^{-3} for biomass. The corresponding values in Tuapse MP were 0.11×10^6 cells dm^{-3} and 0.37 g m^{-3} [157].

It is important to remind that MPs eutrophicated waters typically exhibit the so-called “microplankton paradox”. This phenomenon highlights that the major role in photosynthesis and OM production in MPs is often played by small planktonic algae belonging to mesoplankton net plankton and nanoplanktonic forms, especially green flagellates ranging from 2 to 20 μm in size. There is a direct relationship between the size of planktonic algal cells and the water eutrophication level [161].

According to contemporary notions, the phytoplankton in MPs aquatories not only realizes primary OM production via photosynthesis, but also uses and transforms the dead OM by mixotrophia and heterotrophia. In particular, mixotrophy is observed among many cyanobacteria and diatoms. In MPs ecosystems, the mixotrophes occupy an intermediate functional position between plants and animals and become less dependent on changing environmental conditions. Owing to their peculiarities, mixotrophes are able to maintain biotic turnover in aquatic ecosystems during critical periods.

About one-third of the Black Sea dinoflagellates are exclusively heterotrophic athecate and thecate species. In the coastal zone of NWBS (including MPs aquatories), the heterotrophic dinoflagellates comprise on average 36.36% of quantity and 48.33% of biomass [167].

2.2.2 *Bacterioneuston and Bacterioplankton*

Bacteria inhabit all biotopes of MPs aquatories and are present on the film of surface tension, in the hyponeuston layer, in the water column, at the surface of and inside bottom sediments, on HTS surfaces and on wetted surfaces of ships hulls. As it is well known, bacteria are one of the first links of trophic chains in marine ecosystems and, at the same time, they realize the mineralization of OM. They form the main food resource for mesozooplankton along with microalgae and protozoans (infusoria and zooflagellates). However, bacteria are not only food for hydrobionts, but also producers of various biologically active substances, such as vitamin B₁₂ (cobalamin), in the same way as microalgae [1, 2, 145]. In seas, bacteria play a key role in primary production and metabolism of OM. They decompose dead OM, transforming the products of its decay into suitable substances for phytoplankton and phytobenthos, and are a food item for many zooplankton and zoobenthos organisms. The presence of bacteria and their activity form the basis for biological production in marine ecosystems [204, 205].

The total quantity and biomass of bacteria in the water of a basin can serve as important indices of the level of trophicity and productivity. Bacteria form the

microheterotrophs group together with protozoans and, together with microalgae, can form primitive ecosystems with a close cycle of matter and energy. In marine pelagial ecosystems, bacterioplankton accounts for 60–90% of total energy flow formed by the heterotrophic part of planktonic community [161].

A significant amount of dead SOM and DOM returns into the biotic turnover owing to processes performed by heterotrophic microorganisms in the near-surface water layer. This material does not undergo total mineralization and does not sink to the bottom. This mechanism is often called the “microbial loop” [29, 55, 203].

Chemosynthesis is also observed in marine ecosystems, including MPs aquatories, but its intensity in the water column is dozens to hundred times lower than in sediments. Furthermore, chemosynthesis is considerably higher in silty than in sandy and shell-containing sediments because silts always have a higher content of dead OM and a lower oxygen content.

Several circumstances indicate the presence of bacteria throughout the marine environment. All objects immersed in seawater, in any region of the World Ocean, get covered by a slime film within a couple of days. This film is formed by various marine microorganisms, but predominantly by bacteria and diatoms. Slime film is a product of both organisms’ vital activity and their habitat. However, for film-forming microorganisms, the character of the substratum plays a secondary role. The film is present on the surface of all artificial constructions and also on ships regardless of their draft. A slimy film appears even on ships’ hulls treated with antifouling paints irrespective of their ability to prevent the settlement of phyto- and zoo-organisms [48]. Suspension particles, always occurring in seawater in various amounts and having different origin, are also covered by a slime film.

In MPs, besides substrata for microbial population typical of the adjacent sea zones, large areas of HTS surfaces of various form and quantity are artificially introduced into the water column. Wetted surfaces of ships hulls, performing short- and long-distance transfer, also favour the exchange of microflora between harbours of different seas.

A linear proportional dependence was established between the amount of detritus in water, bacteria and water productivity [49].

In open sea zones, bacterioplankton is responsible for up to half of the total respiration of planktonic communities. In coastal regions and bays, where MPs are located, the contribution of bacterioplankton to total respiration reaches 80–90%. The density of bacterioplankton in various water basins ranges between 10^5 and 10^7 cells cm^{-3} [94, 156].

Planktonic bacteria belong to the dimensional groups of picoplankton (0.2–0.6 μm) and nanoplankton. In water, they occur as individual free-floating cells and in aggregates. They can form microcolonies or adsorb onto organic and mineral particles suspended in water. Protozoans (representatives of nano- and microplankton) feed mainly on individual bacteria, while multicellular zooplanktonic forms, prelarvae and fish larvae feed on bacterial colonies, including those adsorbed on detritus.

Yeasts, actinomycetes and mold fungi are also included in bacterioplankton composition. In the coastal zone and in MPs aquatories, stalked and filiform

bacteria attaching to dying cells of planktonic algae and detritus particles, play an important role in bacterioplankton along with bacteria that form microcolonies in the water column. In conditions of lowered hydrodynamics inside MPs aquatories, such aggregates resemble snowflakes, floating or slowly sinking to the bottom where they form a loose sediment that is easily stirred up.

Marine bacteria freely floating in water, i.e. not attached to the surface of some particles, have low metabolic speeds that sharply increase as they attach to detritus particles. With the increase in the amount of detritus, bacteria then ensure higher speeds of mineralization of dissolved and suspended OM. In the end, their activity leads to a better supply of biogenic matters for planktonic algae and microphytes [2].

The cells of unicellular bacteria are usually bigger on detritus. The average volume of bacterial cells decreases by 1.5–2.0-fold from the surface to the bottom of the water column. Maximal individual volume of bacteria is registered in periods of most intensive die-off of planktonic algae [12]. In the semiclosed aquatory of Burgas Bay, the mass development and following die-off of planktonic algae is accompanied by the appearance of filamentous bacteria in the surface water layer (0–5 m). These bacteria represent up to 50–70% of the total bacterial quantity ($1-2 \times 10^6$ cells cm^{-3} or 150–300 mg m^{-3}) [12].

In open waters, the highest concentration of bacteria in the water column is usually found within a couple of metres below the surface. Bacterioplankton abundance gradually decreases with increasing depth.

In bays and in MPs aquatories, bacterial biomass in the upper mixed layer is equivalent, on average, to 20–40% of the phytoplankton biomass. In periods of seasonal maximums of phytoplankton development, the two biomasses are commensurable [156]. As a rule, abundance of bacterioplankton is considerably higher in spring and summer than in autumn, when the average size of bacteria also decreases.

At depths up to 20 m in intensive navigation zones within Burgas Bay, where constant water mixing occurs, the average quantity of unicellular bacteria in the water column comprises 1008×10^3 cells cm^{-3} and the average biomass 282 mg m^{-3} [12]. The highest bacteria concentrations are usually registered during relatively short periods of intensive phytoplankton die-off. The average size of bacterial cells and the number of bacteria aggregated on the detritus formed by decomposing algae increase at the same time.

In the open regions of the Black Sea, the total number of bacteria in the upper water layer varies from 50 up to 200,000 cells per cm^3 . In coastal regions under the influence of river run-off and eutrophication (where MPs are located) the total number of bacteria increases to 300–500,000 and sometimes up to 2 million cells, and more, per 1 cm^3 . In bays and gulfs in the coastal zone of the NWBS, the average bacterial biomass is in the range 100–500 mg m^{-3} [161].

The number of bacteria in various horizons of the water column is directly connected with concentrations of suspended and dissolved OM. Intensive development of bacterioneuston and bacterioplankton occurs in the presence of a high number of detritus particles. However, in the marine environment, formation of

material containing organic P from dissolved OM also takes place via physico-chemical adsorption to the surface of gaseous bubbles rising up through the water column. Aggregates of OM are the best substratum for marine bacteria [173] which are the main consumers of the organic metabolites dissolved in water. The turnover speed of low molecular and directly assimilable metabolites is about 1–10 days [180]. Many planktonic algae and planktonic animals also utilize DOM to a various extent [64, 65, 145, 180].

After dying, the cells of planktonic algae become detritus and gradually sink to the bottom. Detritus is not just a form of dead SOM, but also a food supply for various bacteria and other hydrobionts. Fragments of decomposing macrophytes, fungi and animals also contribute to detritus composition. Detritus particles are quickly covered by a bacterial film. In MPs aquatories, the well-known phenomenon of mass growth of “maturing” detritus is a result of bacterial biosynthesis [161]. In marine ecosystems, including those of MPs aquatories, processes such as “rain” and “anti-rain” of dead bodies of small-sized planktonic organisms are observed [71]. These phenomena are referred to as “marine snow” [74].

Diatom algae (dead and alive), heterotrophic bacteria and protozoans (vagile and sessile) are found on detritus as well as on periphyton. These organisms are interconnected among themselves and with the marine environment. They excrete metabolites, form DOM, influence the pH of suspension and precipitate carbonates at the surface of suspended matter. Correlations between microorganisms on suspended matter and microorganisms' metabolites, DOM and pH of suspension were observed. Diatoms, bacteria and protozoans, as well as their metabolites, interact among them and with environmental factors such as pH, DOM of suspension and carbonates. In this sense, they share a common biotope represented by detritus particles. Furthermore, they respond collectively to environmental impacts. The complex of microorganisms of suspension can therefore be considered as a community [49].

In marine ecosystems, owing to plankton filtering activity, the transport of faecal pellets represents about 80–90% of the detritus flow from the water surface to the bottom. The remaining 10–20% consists of dead bodies, hard parts of planktonic organisms and mineral suspension [32]. At shallow depths, the biofiltering systems of plankton and benthos are tightly interconnected because 70–80% of benthic species have a pelagic larval stage. In fact, benthic invertebrates themselves ensure a significant part of the filtration process in the water column.

At present, a large number of studies indicates that protozoa have an important role in the functioning of aquatic ecosystems of the pelagial, periphytal and benthic zones by participating in the transformation, production and destruction of OM [31, 86, 90, 91, 93, 112, 113, 176, 177, 183, 206, 207].

There are numerous data about the selective feeding ability of infusoria. In marine ecosystems, algophagous infusoria can consume up to 38% of the phytoplankton primary production (7% directly in the near-surface layer) [93]. In the Dnieper-Bug Liman, the proportion of gross phytoplankton production consumed by ciliates varies from 30% in spring to 0.12% in summer [86]. Protozoans react very quickly to the availability of new OM resources. Introduction of protozoa into

the “algae—bacteria” system stabilizes its functioning by providing a high speed of OM destruction [177].

In many coastal ecosystems, rotifers have an extremely important role [43] together with protozoans and other microzooplankton representatives [8, 32, 139, 145, 175, 201, 217].

For many heterotrophic saprophytic bacteria, detritus is the most favourable pelagial biotope and, at the same time, a source of food [187]. In marine ecosystems, there is practically no suspended and dissolved OM which cannot be used by some group or groups of bacteria. The microbial population of detritus cycles the DOM of marine water into trophic chains. Bacterioplankton (as a microflora of bottom sediments and periphytal) becomes a main source of food for filter feeders, sediment feeders and detritophages [145, 161, 181].

Bacteria are a major group of organisms, owing to which the share of primary production not directly incorporated into food chains (about two thirds of the total), is cycled back to trophic webs based on predator—prey relationships [181]. The destruction of microalgae by bacteria usually takes place within a dozen of hours [5, 145, 161, 181].

The destruction of one of the mass representatives of zooplankton copepods lasts from 4 up to 30 days depending on temperature. Regardless of their body-size, the process is completed in 5 days at a water temperature of 20 °C. The sinking speed of copepods is connected with their size and changes over time during the decomposition process [164].

In the water column, the decomposition of dead hydrobionts includes lysis, hydrolysis of high-molecular compounds to fragments of low-molecular weight and biooxidation of these compounds. Metabolites of living plants and animals also contribute to the composition of DOM. The microflora not only uses detritus and DOM, but also produces biologically active substances such as vitamins and antibiotics. Bacterioplankton, microflora of bottom sediments and periphytal, and diatoms also produce inorganic insoluble metabolites, which precipitate as carbonates. Thus, they participate in the formation of fine silt in MPs. Here, the slowed hydrodynamics and limited water exchange, the more stable hydrological and hydrochemical regimes and the high concentration of both DOM and SOM form conditions for a more intense activity of microorganisms compared with adjacent zones. These conditions also speed up the sedimentation of carbonates caused by the gravitational force. In MPs, part of carbonates precipitates because of the activity of micro- and macrophytes and animals having shells or skeletons consisting of carbonate [153, 161].

In MPs, bacteria are one of the main contributors to mineralization of SOM and DOM. In ports' aquatories, the dead OM necessary for bacterial development has autochthonous and allochthonous origin; the latter entering MPs via land run-off and discharges of different sewage waters. Conditions for OM dispersion in MP are limited and BM gradually accumulates in them.

In MPs, all the biotic components of the ecosystem participate in the formation of detritus. Plants (including micro- and macrophytes from phytobenthos and periphyton composition, phytoplankton and microphytobenthos) have an important

role in detritus formation. In the macrophyte belt forming on HTS in correspondence of the upper limit of the water level, the partial die-off of plants' biomass favours the development of bacteria.

In MPs, a vertical stratification is observed in the distribution of phytoplankton and in the quantity of heterotrophic bacteria. This distribution of living organisms reflects the stratification in the distribution of particles of different origin, i.e. detritus, caused by hydrological factors [102, 145, 161]. In MPs aquatories, conditions for detritus accumulation appear in the zones of the surface tension film, in thermo- and halocline layers, on the surface of bottom sediments and in the HTS fouling.

Accumulation of microflora in the hyponeuston layer is caused by physical and chemical factors characteristic for the air–water interface (flotation, surface tension) and by the intensive reproduction of bacteria because of the increased OM content [161, 186].

In spring, summer and autumn, the quantity of heterotrophic bacteria in the near-surface micro-horizon of 0–2 cm is one to threefold higher than in the remainder of the water column [186]. The concentration of heterotrophic bacteria in the 0–2 cm layer increases sharply in summer, slightly reduces in autumn and drops to its minimum in winter. The highest peak of microbial life in the zone of surface tension film is registered in summer; along with the intensification of all living processes in the NWBS and in the whole Black Sea during this period [161, 186]. Up to 75×10^6 cells cm^{-3} are registered in neuston [145].

The amount of ammonifying and denitrifying bacteria in the 0–2 cm layer is 10–100 times higher than in the water column, which testifies the high content of OM in the surface micro-horizon. Sulphate-reducing bacteria are also registered in this well-aerated layer, so that the concentrations of sulphate-reducing bacteria in the 0–2 cm layer are comparable to those in the near-bottom horizon. The number of thiobacteria in the 0–2 cm near-surface layer is also 10–100-fold higher than in the water column [186].

According to Tsyban [186], the concentrations of heterotrophic microflora in the upper half metre horizon in the Black Sea are equal to, or higher than, in the thermocline layer. At higher depths, the vertical distribution of heterotrophic bacteria in the water column shows a maximum in the thermocline layer during all seasons in all aquatories of the NWBS [186].

In stratified water masses such as MPs water column, bacterioplankton accumulates at the upper border of the thermocline, where phytoplankton and detritus also concentrate [161].

Five ecological niches are usually distinguished with regard to the distribution of bacteria and other small-sized hydrobionts in the water column. The first ecological niche is located under the surface water film, where the micro-convective mixing of the uppermost layer (0–30 cm) of the water column takes place and the levels of oxygen saturation and nutrients are high. Here, the total quantity of bacteria ranges from 0.3 up to 4.0 milliard cells per 1 cm^3 .

The second ecological niche starts at the depth of 20–50 cm and extends to the pycnocline. In this zone, phytoplankton undergoes mass development thanks to

optimal illumination (photic water layer). The intensity of bacterio-, phyto- and zooplankton activity in this layer is very high owing to wind and drift currents and Langmuir vortices that ensure a good mixing.

The third ecological niche coincides with the thermocline zone where detritus particles and sinking dead plankton accumulate because of the higher water density. The density of bacterial population sharply increases in the thermocline [145].

The fourth ecological niche is represented by the near-bottom water layer where the water exchange is limited and anaerobic stagnant zones occur. Under these conditions, the prevailing bacterial populations are iron reducing bacteria, thionic, methane-oxidizing and hydrogen-reducing bacteria. Sulphate-reducing bacteria and bacteria performing butyric fermentation dominate in the water zone directly in contact with the bottom.

The fifth ecological niche is connected with bottom sediments and pore waters, where bacterial density can reach dozens and even hundreds milliard of cells per 1 cm^3 of wet silt.

The lower part of the water column can be referred to as the microaerophilic zone, where dissolved oxygen is still present but reduced substances diffusing from the anaerobic zone of the near-bottom layer also appear. The anaerobic zone is located between the microaerophilic zone and bottom sediments [145].

In MPs pelagial zones, the bacterial population reflects the particular features of each ecological niche on the one hand and directly contributes to their formation on the other.

In MPs, besides the hyponeuston layer, organic matter accumulates in the highest quantity at the border of the pycnocline. This OM includes dead phytoplankton, organic remains of animals, faecal pellets of planktonic organisms and other detritus. Detritus, populated by bacteria, gradually settles from the pycnocline layer to the bottom sediments and is partly consumed. However, in MPs, part of the sediment returns again into the water column as a result of anthropogenic activity.

Fine-dispersed sediment fractions appear in the water column during dredging and navigation of deep-draft ships. This artificially re-suspended material could then accumulate again in the pycnocline layer. Besides reducing water transparency, stirring up of bottom sediments and associated microbial population can cause other negative consequences. During dredging, the microbial population, as well as resting cysts, spores and eggs of some hydrobionts are transferred from sediments into the water column where they can contribute to the development of unwanted phytoplankton species [169]. Studies in the estuary of the river Vilaine (France) showed that silt accumulation in the estuary began after construction of a dam. After some time, the thickness of the accumulated layer of silt reached 3–4 m and brought to mass development of the toxic microalgae *Dynophysis* and *Gymnodinium*. Deposition of fine port silts dredged in ports and dumped at submerged waste deposits had similar consequences [169].

The sheltered conditions of ports aquatories lead to a significant growth of bacterioplankton in terms of quantity and biomass. The number of heterotrophic bacteria in 1 cm^3 of ports' and harbours' water ranges from a couple of thousands up to hundred thousands and even millions. Their quantity quickly reduces in open

waters far from ports [48]. In Sevastopol Bay, the construction of protecting piers was one of the main causes of the sharp increase in bacterial density from 10^6 cells cm^{-3} in 1976 to 3×10^6 cells cm^{-3} in 1982 [3].

At the end of the 1990s, the total density of bacteria in the waters of Novorossiysk MP reached more than 1×10^7 cells cm^{-3} during the period of maximal water warming. In 2006–2007, the average bacterial biomass and density in the aquatory of Novorossiysk MP were $0.80\text{--}0.94$ g m^{-3} and $3.8\text{--}4.7 \times 10^6$ cells cm^{-3} , respectively. The corresponding figures were 2.0–2.5-fold lower outside the port. Bacterioplankton maximal biomass reached $1.9\text{--}2.5$ g m^{-3} in zones strongly polluted by coastal discharges [156].

In 2009–2010, the bacterial average biomass in Tuapse MP comprised $0.43\text{--}0.47$ g m^{-3} for a total density of $2.0\text{--}2.8 \times 10^6$ cells cm^{-3} [156].

In Tuapse port aquatory, the average number of heterotrophic bacteria during the summer of 2009 reached the upper limit of 3.6×10^6 cells cm^{-3} (776 mg m^{-3}) for eutrophic waters. An extremely high level of bacterioplankton development (density of 5.2×10^6 cells cm^{-3} and biomass of 1.1 g m^{-3}) is observed in harbour inner waters, near the berths that are most distant from the passage into the port and polluted by wastewaters [155]. In MPs waters, the high quantity of heterotrophic bacteria is directly connected with increased OM content and favourable hydrological conditions.

In 1993–1996, during the period from May to September, the amount of saprophytic bacteria in Sukhoy Liman varied between 2550 and 28,700 cells cm^{-3} in the near-surface layer and in the water column and was in the range 16,200–30,000 cells cm^{-3} in the near-bottom layer. On average, the abundance of saprophytic bacteria near the bottom was 1.7-fold higher than in the superficial layer above the thermocline [154]. In June 2003, the average number of saprophytic bacteria was 3625 cells cm^{-3} in the superficial layer of Sukhoy Liman waters and 8175 cells cm^{-3} in the near-bottom layer below them [154].

Besides seasonal reorganizations and local changes, bacterioplankton composition also undergoes large-scale changes connected with the general evolution of regional ecosystems. In the summer and autumn months of 1990–2000, the absolute maximum of bacterioplankton total quantity in the NWBS was registered in the near-bottom water layer. The content of bacteria in the near-bottom waters was usually 1.2–2.0-fold lower than in the surface 0.5 m horizon. Maximal bacterial quantity in the near-bottom layer was registered following a reduction of oxygen concentrations in the near-bottom water to values between 0 and 3.87 mg dm^{-3} , i.e. under hypoxic conditions. Such conditions stimulated the development of chemolithotrophic and chemoorganotrophic bacteria [154].

In Novorossiysk MP, the quantity of bacteria included in the composition of detritus particles and aggregates was less than half of the total, while it was more than a half of the total quantity in Tuapse MP [156].

The development of bacterial populations in port aquatories generally reaches levels typical of eutrophic-hypereutrophic waters. The lower level of bacterial biomass in Tuapse port, compared with Novorossiysk MP, may be connected with better water exchange with the adjacent sea zone in the former case [156].

2.2.3 *Hyponeuston and Zooplankton*

Small-sized planktonic animals temporarily or constantly inhabiting MPs water column form two main complexes: hyponeuston and zooplankton. Hyponeuston is mainly connected with the upper sea micro-horizon (depths from 0 to 30 cm), while zooplankton inhabits the water column from the surface to the bottom. In the Black Sea coastal zones where MPs aquatories are located, merohyponeustonic and benthohyponeustonic forms are a characteristic feature of the hyponeuston, especially in summer. Merohyponeustonic organisms include species that pass into the composition of plankton, nekton or benthos after the neustonic phase (usually as eggs, larvae and juvenile) of their life cycle. Benthohyponeuston refers to the part of hyponeuston consisting in organisms alternatively staying in a benthic (during the day) or a hyponeustonic (during the night) state. Many species of amphipods, cumaceans, shrimps and polychaetes belong to this group.

Mero- and benthic-hyponeuston are tightly connected with meroplankton [71]. Holoplankton invertebrates constitute the relatively constant fraction of pelagial population in MPs.

In various regions of the Black–Azov Sea basin, the number of animal species included into plankton and hyponeuston species lists is constantly changing and being updated. This situation is connected with disappearance, introduction and discovery of new species, as well as with revision and clarification of taxonomy. In the last years, 150 taxonomic forms of animals were recorded in plankton composition in NWBS, 125 in NEBS and 162 in the coastal regions of Crimea. More than a half of them consisted in larvae of bottom (periphyton) animals [156].

Because of low, frequently almost null, flows' speeds and of the stable stratification of water masses, the ability of haloplanktonic animals and pelagic larvae of zoobenthos and periphyton to perform vertical migrations often has a fundamental importance in determining their distribution in MPs.

The microzooplankton organisms with sizes between 50 μm and 1.0 mm, the nanoplanktonic forms smaller than 50 μm and even the smallest ones, such as ultrananoplanktonic organisms that are not caught by plankton nets, are an important component of plankton composition.

In MPs aquatories, the absence of strong currents and big waves creates the conditions for the accumulation of hydrobionts from various systematic groups in the subsurface water layer. Hydrobionts are attracted to the film of surface tension for a variety of reasons.

In spring, coldwater forms dominate the hyponeuston composition and the biocenoses is characterized by overall low quantitative indices. The maximum species diversity of hyponeuston is observed in summer owing to the development of the larval stages of numerous invertebrates. In autumn, the main part of mero-hyponeuston disappears and the hyponeuston of the Black Sea coastal regions is poor during winter.

A reduction of zooneuston quantity has been registered over the last decades, first of all owing to a decrease in their abundance by more than one order of

magnitude. The decrease mainly occurred in the previously abundant *Oithona minuta*, *Paracalanus parvus*, *Centropages ponticus* and more typical neustal copepods of the Pontellidae family. The quantity of polychaetes larvae in the neustal zone has increased because of their parental animals inhabiting on the silted bottom under the near-bottom water layer with reduced oxygen content [154].

Zooplankton is formed by many groups of small-sized animals which are not able to withstand strong currents. In marine ecosystems, zooplankton plays an important role in the formation of energy and in matter flows. On the one hand, it is a main consumer of phyto- and bacterioplankton production in the water column and, on the other one, a food item for many benthic invertebrates and commercial and non-commercial fish species at various stages of ontogenesis. In MPs aquatories, the zooplankton development directly reflects its development in the adjacent regions of the Black and Azov Seas and is controlled by the same processes. However, in MPs, there are some specific peculiarities connected with the relative isolation of aquatories, their lowered hydrodynamics and more intensive development of phyto- and bacterioplankton, and the presence of large areas of artificial HS. In MPs, the zooplankton composition depends on the geographical position and has a seasonal character.

Although zooplanktonic organisms are heterotrophic, many of them are able to accumulate and use macromolecular compounds dissolved in seawater in the same way as bacteria and microalgae. To various extents, heterotrophic feeding on DOM is common in representatives of zooplankton from various systematic groups. Concentrations of DOM nutritionally valuable components similar to natural ones can satisfy up to 30–50% of the respiratory energy requirements of some planktonic invertebrates [65, 185].

In Grigorievsky and Sukhoy Limans, a sharp reduction of zooplankton quantity is registered during years with increased continental run-off. The zooplankton quantity increases again in the following years. Zooplankton biomass can decrease sharply in years of rapid development of planktonic phytophagous animals that actively graze on phytoplankton [115]. The indices of phytoplankton can reach maximal values at low levels of zooplankton development.

In the Black Sea, the daily dynamics of phytoplankton biomass and quantity during the spring–summer period is usually described by an unimodal curve with maximum values in the evening and night hours [115]. In connection with this regular feature, zooplanktonic organisms feeding on phytoplankton also migrate to the near-surface layer during evening and night hours. Thus, in the near-surface layer, phytoplankton grazing by meroplankton occurs at nighttime.

In MPs aquatories (e.g. in Sevastopol Bay), zooplankton biomass could exceed by 5–10-fold the corresponding average biomass in open regions of the Black Sea [161]. In other MPs, zooplankton biomass is quite often a couple of times higher than in the adjacent regions [16, 154, 196].

The distribution of planktonic organisms in MPs water column is connected with the water physical characteristics and various movements, as well as with the behaviour of the planktonic organisms themselves and with their capability to move into the pelagial zone both vertically and horizontally. Hydrobionts can have

passive and active methods for vertical displacement. For example, flagellates actively swim using flagella.

Copepoda, which are relatively complexly organized organisms widespread in MPs, actively control their distribution along salinity gradients. Copepoda at various stages of development, as well as Decapoda larvae, select water layers with the most favourable salinity by regulating their locomotive activity. In MPs aquatories, sharp increases in salinity lead to active displacement of planktonic animals towards the surface layer. At the opposite, a decrease in salinity causes the immersion of planktonic animals by both passive and active mechanisms [136]. Many pelagic microplanktonic infusoria and rotifers respond by active displacement to sharp changes in salinity.

Ultramicro- and microplankton (especially colourless flagellates, zooflagellates, infusoria and rotifers) have a key role in the transformation of matter in the pelagial zone of coastal ecosystems both in the Black–Azov Sea basin and in other seas [161].

As mentioned above, microplankton usually indicates a complex of heterotrophic organisms with linear dimensions in the range 20–200 μm and including dinoflagellates, infusoria, naupliar stages of copepods and some copepodit stages as well as meroplankton larvae. As a rule, heterotrophic dinoflagellates constitute the bulk (on average 63–65% of the total biomass) of marine microzooplankton [163].

Heterotrophic and colourless thecate flagellates (Peridinea) are planktonic forms in the absolute majority of cases. They occupy an intermediate position between prokaryotes and eukaryotes and belong to ancient forms of life. Their flagellum located along the longitudinal body axis allows the forward motion, while the second one, located perpendicularly to the first one, performs the rotating motion. During swimming, flagella perform a screw-like motion.

The sea sparkle *Noctiluca scintillans*, which often reaches high densities, occupies a special place among the colourless thecate flagellates or zooflagellates of the Black–Azov Sea basin. It has a spheroid body up to 2 mm in diameter and it feeds heterotrophically by swallowing and digesting different suspended particles (detritus and small-sized unicellular algae and protozoa). During the summer months, *Noctiluca* can undergo mass development in MPs and bays aquatories, reaching densities of up to 3×10^6 ind. m^{-3} and a biomass in the range of dozens of grammes per cubic metre of water. *Noctiluca* is practically not used as a food by other planktonic organisms [66].

In the pelagial zone of MPs, infusoria (Infusoria) have a high importance among protozoans. It is considered that they originated from flagellates. Infusoria have sizes from 10 μm to 2–3 mm and can reproduce asexually (by cell division) and sexually. Many of them can form cysts resting on the bottom. Various distributed lines of cilia cover their body during their whole life or at some stages of the life cycle. Some species have bunches of cilia grouped into organs of movement called cirri that are used for swimming and moving on a substratum. The swimming speed of infusoria reaches 1–2 mm s^{-1} . In MPs aquatories undergoing water desalination, rotifers (Rotatoria), belonging to pseudocoelomate animals, quite often reach high quantities. Their body is sacciform or spheroidal, with sizes from

10 μm up to 2.0 mm, with dimensions in the range 100–300 μm being most common. Some planktonic rotifers are the smallest representatives of multicellular animals.

Rotifers have a rotatory ciliary apparatus on the anterior end of their body. Ciliary action resembles the rotation of a wheel. In coastal zone, the large group of rotifers comprises species which can swim, crawl and temporarily attach to different substrata, including macrophytes. Numerous swimming rotifers are able to perform relatively long and sudden jumps allowing them to escape from enemies, in particular from planktonic crustaceans, larvae and juvenile fish hunting them. With regard to feeding habits, rotifers are divided into microphages, or “pacific”, and predators. Microphages consume microalgae, bacteria, detritus, spores and fragments of fungal mycelia. Predators feed mainly on infusoria and other rotifers [145]. If needed, numerous predators switch to feeding on microalgae. The large majority of rotifers species is polyphagous, i.e. it is not highly selective in its food items. However, there are also monophagous species feeding only on detritus or exclusively on certain species of microalgae. On average, rotifers live from a couple of days up to 3–4 weeks. In MPs aquatories, rotifers of the genus *Synchaeta* and *Brachionus* are most often observed.

Flagellate and ciliate ways of motion are characteristic for most small-sized pelagic animals. These motion strategies are most effective only at body sizes of a fraction of millimetre and at low Reynolds numbers. Using flagella and cilia, organisms rotate around their own axis during swimming. They do not move linearly, but along a screw-like trajectory. Ciliary motion is also typical for the pelagic larvae of many benthic animals (worms, molluscs and others).

The relative speed of microplanktonic forms using ciliar and flagellar motion exceeds that of multicellular, large invertebrates. For bigger planktonic forms, the movement via body curving was more advantaged. It is typical for Annelides and Scolecida, prolarvae and fish fries. Swimming folds, fins and lever extremities, i.e. various swimming legs, appeared at a later stage in the development of motion strategies.

For the medusoid generations of small-sized pelagic coelenterates of the class Hydrozoa, a decreased or increase in salinity causes a reduction of the contraction rate of the umbrella and, thus, of motion activity. Contraction of umbrella is the main mechanism of jellyfish reactive type displacement in water and moving velocity depends, first of all, on the contraction frequency. Similar changes in the contraction rhythm are characteristic for the class of Scyphozoa. The moon jellyfish *Aurelia aurita* moves into the deeper water layers by reducing the umbrella's contractions frequency. Such behaviour of jellyfish and other zooplanktonic organisms is called “passive avoidance” [136].

Depending on the ontogenetic stage, gelatinous organisms such as hydrozoan and scyphozoan jellyfish can belong to various size groups of zooplankton, from mesoplankton to megaplankton. The moon jellyfish, saucer jelly or common jellyfish (*A. aurita*), barrel jellyfish, dustbin-lid jellyfish or the frilly mouthed jellyfish (*R. pulmo*) have planktonic and benthonic stages. While *A. aurita* performs mainly vertical displacement, *Rh. pulmo* is considered a quite good swimmer among

planktonic organisms and can actually move in any direction. The diameter of *A. aurita* umbrella is usually up to 20 cm and that of *Rh. pulmo* can reach 60 cm. In MPs aquatories ecosystems, large-sized jellyfish individuals could be ascribed to megaplankton as well as to nekton.

In open waters, *A. aurita* mainly feeds on unicellular algae (32%), copepods (24%) and chaetognaths (20%). The moon jellyfish, being a food “opportunistic” like the majority of gelatinous organisms, is able to consume big numbers of micro- and mesoplanktonic organisms of various groups as well as eggs and fish larvae. In coastal waters, *A. aurita* feeds on unicellular algae, bacterioplankton and microplankton. It can also consume SOM and DOM [14].

The jellyfish *A. aurita* and other gelatinous organisms mainly use the same food as many organisms from micro- and mesoplankton as well as representatives of these complexes themselves. Gelatinous organisms can achieve a high biomass, but serve as food for hydrobionts of higher trophic levels only rarely. The BM accumulated in them returns into the biological cycle mainly after decomposition by microbes.

The planula, i.e. the pelagic jellyfish larva, has cilia located in a belt-like fashion around the whole body, allowing it to actively move in the water column. However, they are not able to feed. Planulae have positive phototaxis and naturally accumulate in the near-surface layer. After some time, their attitude towards light changes and they immerse into the near-bottom layer. Here, they actively swim for a couple of days and then attach to hard substrata, including concrete surfaces of MPs HTS, by their anterior body end. Two or three days after fixation, the planula transforms into small polyps called scyphistoms. The attached scyphistoms feed on infusoria, planktonic crustaceans and others. In winter months, the quantity of scyphistoms fixed on HTS can reach dozens and even hundreds of individuals per 1 m² in the 0.5–2.0 m water layer. After concluding their development under attached conditions, the jellyfish larvae (ephyra) move back into life in the pelagial zone. Hydroids (Hydrozoa) resembling small-sized jellyfish are also observed in MPs plankton.

Besides jellyfish, other gelatinous organisms in the plankton composition of the Black–Azov Sea MPs aquatories are represented by three species of the phylum Ctenophora: *Pleurobrachia rhodopis* and the recent invasive species *Mnemiopsis leidyi* and *Beroë ovata*. The body length of *P. rhodopis* is about 5–7 mm, while that of *M. leidyi* and *B. ovata* is usually up to a couple of centimetres. Some *Mnemiopsis* individuals grow up to 10–11 cm. *M. leidyi* and *B. ovata* spread particularly during the period 1980–2000. As in case of jellyfishes, their biomass becomes a peculiar nutritional dead-end for a relatively short period.

The gelatinous organisms can perform not only vertical migrations, but also move horizontally in the water column. In some hydrological situations, they enter MPs aquatory together with water masses and get trapped in the zones farther away from the port’s passage. The biomass of gelatinous organisms in such places is quite often calculated in kilograms and dozens of kilograms per one cubic metre of water. For a whole MP aquatory, values up to 8000–10,000 tonnes can be reached, as in Grigorievsky Liman in 2012. These organisms cannot abandon ports’

aquatories and eventually die in them. Big-sized jellyfish such as *Aurelia* and, especially, *Rhizostoma* create strong water flows while moving. The influence of these flows manifest over distances of dozens of centimetres, thus mixing big volumes of water. In MPs, the artificial increase of depths facilitates the retention of gelatinous organisms in the water column, where they usually die when arriving at the bottom.

Introduction of the comb-jelly *M. leidy* has disturbed the whole trophic structure of pelagial subsystems of the Black and Azov Seas and of big open limans for a couple of decades [154]. In eutrophic waters, *M. leidy* can reach huge biomass. The comb-jelly *B. ovata*, which can use other species of comb-jellies as food, reaches its mass development in a basin after *M. leidy*. By grazing *M. leidy*, *B. ovata* not only increased its own biomass, but also reduced the quantity of the first one enough to undermine its own forage base at the same time. Breakouts of *M. leidy* stopped after the first years following its introduction because of the pressure from *B. ovata*. At the same time, the quantity and biomass of *B. ovata* decreases because of the reduced forage base. A kind of balance between comb-jellies species was thus established in the ecosystems of the Black–Azov Sea basin.

Eight longitudinal comb rows are located on the surface of the transparent body of comb-jellies. Each row comprises swimming plates oriented transversally to the axis of the row. Along the outer edge, each plate is split into combs formed by agglutinated cilia of epithelium whose length reaches a couple of millimetres. Row lines represent the locomotor apparatus of these animals and the row plates work like oars. Comb-jellies swim slowly with their mouthpart forward. They have pelagic larvae.

Catching tentacles with numerous branches able to elongate are located laterally. Tentacles and branches are covered by glue cells (colloblasts). In the nutrition process, small-sized planktonic organisms get stuck to the tentacles and are brought to the mouth edge. The comb-jellies are predators, also consuming eggs, larvae and early fries of fish. *B. ovata*, as already mentioned, also feeds on other smaller comb-jellies.

The comb-jellies actively graze micro- and mesoplankton in the upper layer of the MPs water column reaching high quantity and biomass (up to couple of dozens kilograms per 1 m³), as in the case of jellyfish. Because of the presence of numerous HTS in MPs aquatories, the bodies of comb-jellies are easily damaged by rubbing and blowing against hard surfaces, even at relatively low agitation, and form a gelatinous mass in the near-wall layer. High amounts of comb-jellies are destroyed during ships navigation.

In MPs, individuals of *Oicopleura dioica*, belonging to solitary pelagic tunicates (Appendicularia) are quite often registered. They have a transparent body with a length of up to 1 mm and a tail which is nearly fourfold longer than the body. They feed on small-sized flagellates, peridininian algae, coccolithophores and diatoms.

In MPs, larvae of sedimentary ascidians or sea squirts (Ascidiae) rise up and freely swim into the water column for some time.

In MPs aquatories ecosystems, both free-living and sessile (i.e. attached to substrata) infusoria play a huge role. These organisms belong to the number of the

most small-sized mass heterotrophs and mainly feed on unicellular algae and bacteria. Species that usually feed on algae quite often switch, in their absence, to bacteria consumption. Some large infusoria, the so-called macrophages, are actively and selectively able to seize food of a defined size and form. Many infusoria species can simultaneously feed on algae and bacteria. The speed of infusoria cells division, i.e. reproduction, depends on the amount of food as well as on its quality [128] and varies from a few hours to a dozen of hours.

The community of planktonic infusoria (ciliata plankton) actively participates in the production and transformation of OM and in the functioning of the planktonic trophic web. It also contributes to the foraging basis for zooplankton, pelagic larvae and fries of fish in all coastal ecosystems of the Black–Azov Sea basin, including MPs aquatories located at the open seashore as well as in the harbours of estuarine type and in limans.

The protoplasmatic body of tintinnids (Tintinnidae) infusoria is enclosed in a transparent strong lorica, consisting of OM. Different species have loricas of different forms. Extraneous inclusions could be present on the lorica surface in the form of incrustations. Tintinnids bodies usually have a conic or bell-shaped form. Ciliates tintinnids feed on phytoplanktonic organisms: diatoms, dinoflagellates and coccolithophores. In turn, they serve as a food for noctiluca, rotifers and other planktonic predators, including larvae and fish fries.

Grazing of vegetal food by infusoria in the coastal zone of Sevastopol Bay represents 3.8–9.6% of the total phytoplankton biomass. In the bay's neck, grazing is lower and does not exceed 3.2% of phytoplankton biomass [128]. This fact gives grounds to consider that phytoplankton grazing by zooplankton intensifies in protected aquatories and MP harbours.

Infusoria serve as food for some mass marine invertebrates: planktonic copepods such as *Acartia clausi*, larvae of barnacles (*B. improvisus*) and of gastropods, in particular *Rissoa splendida* [128].

In Sevastopol Bay and in the aquatories of other MPs, infusoria are represented mainly by ciliates and tintinnids. With regard to taxonomy, the composition of heterotrophic flagellates in Sevastopol Bay is considerably poorer than in the Black Sea. However, their abundance occasionally increases up to values typical for eutrophic and hypereutrophic regions, regardless of the season [3].

In microzooplankton composition of bays and gulfs (and therefore ports) of the Black Sea, various complexes of infusoria comprise, on average, about 50% of the whole biomass, but this share quite often increases up to 80–90%. Besides planktonic species of infusoria, “free-swimming” larvae of benthic and periphytic infusoria species are also found in MPs aquatories. The “free-swimming period” of the larvae (called telotroch) of attached infusoria species is short and lasts from a couple of minutes up to 2–6 h. Telotrochs stay mainly near the settlements of adult individuals and, as a rule, appear in the upper water layers only accidentally. When tearing away from parent individuals, telotrochs stay in the water column where they can be picked up even by weak flows. Attached species of infusoria are present in the fouling all year round. They are mainly represented by species of the genus *Zoothamnium*, *Vorticelia*, *Ephelota*, *Acineta* and *Follicilina*. The quick division rate

of some species, equal to that of diatoms, implies that infusoria remain a constant component of the fouling community, regardless of its developmental stage. Telotrochs released from the fouling constantly replenish zooplankton so that adult infusoria, as well as their telotrochs, are used as food by various macrofoulers. It was also determined that infusoria, especially the genus *Ephelota* and *Vorticelia*, are able to utilize DOM [24].

In the Black Sea, Tuapse port aquatory is one of the most polluted with very high content of oil products. Their concentration in bottom sediments reaches $2543 \mu\text{g g}^{-1}$, which exceeds the permissible level by 51-fold [155]. In the plankton of Tuapse port, the dominant infusoria are very small-sized species of the genus *Strombidium* (smaller than $20 \mu\text{m}$) and big-sized loricate, phytophage infusoria *Favella ehrenbergii*. The average density and biomass of infusoria in port waters ($72.8 \times 10^3 \text{ ind. dm}^{-3}$, 640 mg m^{-3}) were almost half of those outside its borders [155]. Studies have showed that, in Tuapse MP ecosystem, more than 90% of the energy flow passes through the detritus food web. Its key link is the community of heterotrophic bacterioplankton. Most of phytoplankton production and rests of dead OM are consumed by and subject to bacterial destruction. In spite of the abundance of bacteria, the production of biomass by infusoria communities, which are their main consumers, is not high. It is possible to surmise that this is connected with excessive pollution [155].

Ilyichevsk and Yuzhny MPs, located in the NWBS, were built later than Sevastopol and Tuapse ports and their aquatories are less polluted. In Sukhoy Liman (Ilyichevsk port aquatory), 37 species of infusoria were identified in the water column. In the innermost, desalinated part of the basin one freshwater species of infusoria (*Strombidium viridae*) was found. In the central and southern parts of the liman, marine pelagic species predominated: *Strombidinopsis chechiri*, *S. lan-genula*, *Tiarina fucus*, *Pelagostrobilidium spirale* (including the form *coxiella*), *Eutintinnus lususundae* and *Metacylis mediterranea*. These species feed mainly on dinoflagellates, which agrees with the high quantity of peridinin algae in phytoplankton. Middle- and big-sized infusoria were dominating and gave relatively high biomasses ($57.7\text{--}199.2 \text{ mg m}^{-3}$) at relatively low densities for the NWBS ($2.2\text{--}26.9 \times 10^6 \text{ ind. m}^{-3}$). In the summer of 2001–2002, average values of density and biomass for the deepest southern part of Sukhoy Liman were $(3.27 \pm 1.66) \times 10^6 \text{ ind. m}^{-3}$ and $113.23 \pm 49.82 \text{ mg m}^{-3}$, respectively [154].

In the plankton of Grigorievsky Liman (Yuzhny MP aquatory), 35 infusoria species were found and dominating ones were typical of non-specific complexes (eurytopic and benthic): *Euplotes balteatus*, *Euplotes* spp., *Litonotus* sp. and *Prorodon* spp. The majority of euplanktonic forms were represented by euryhaline species and species of brackish water complexes: *Askenasia stelar*, *Rimostrombidium caudatum*, *R. velox*, *Cyclotrichium sphaericum*, *Strombidium vestitum* and tintinnids. Quantity and biomass reduced during the spring–summer period: from 4.0×10^6 up to $0.012 \times 10^6 \text{ ind. m}^{-3}$ and from $78.5\text{--}134.9 \text{ mg m}^{-3}$ up to 0.87 mg m^{-3} , respectively. A high density of predatory infusoria was registered in Grigorievsky Liman. A considerable part of algophagous infusoria was represented by diatomophagous ones [98, 154].

As a rule, no more than 10 infusoria species are constantly present in the NWBS pelagial during one year. In total, about 50 species belong to mass ones and develop with various intensities in different seasons. The majority of the registered infusoria belongs to widespread species that are common in the pelagial zone of seas, oceans and estuaries. The ratio of marine, brackish water, euryhaline and freshwater species is relatively stable during the year, although the share of freshwater species somewhat increases in spring because of the influence of river floods. A total of 184 taxa of infusoria were identified in the NWBS, while the corresponding figures for Sukhoy and Grigorievsky Limans were 37 and 35 species, respectively [98].

In the NWBS, 57.5% of the occurring species are euplanktonic. In Grigorievsky and Sukhoy Limans, euplanktonic species represent 81.1–94.6% of the total [98]. Apparently, such differences are mainly determined by a more marked stratification of the water masses inside the limans. In the water column of MPs aquatories, the presence of infusoria non-specific for planktonic complexes (as well as of benthic unicellular algae) could be connected with their presence in the fouling community on the lateral surfaces of various HTS. These structures accomplish the function of a vertical bottom for infusoria. Active mixing of the whole water column during strong storm winds and during the passage of deep-draft ships can also play a role in this process.

In the NWBS, the size distribution of planktonic infusoria varies from nanoplanktonic forms with a cell volume around $600 \mu\text{m}^3$ to mesoplanktonic ones with volumes of $6\text{--}12 \times 10^5 \mu\text{m}^3$. The most common size class (75.0% of the total) is represented by species with volumes of $1\text{--}50 \times 10^3 \mu\text{m}^3$ (more than 50.0% from them having cells volumes up to $2.5 \times 10^4 \mu\text{m}^3$) usually belonging to “small-sized” groups. These are the mass species *Myrionecta rubra*, *S. vestitum*, *S. emergens*, *Urotricha* spp., *Rimostrombidium* spp. and *Holophrya pelagica*. With few exceptions, the indices of quantitative development of infusoria in the surface water layer of 0–0.5 m and in the near-bottom layer (3.5–4.0 m overlying the bottom) are higher than in other regions near the surface. In the surface layer, small-sized species prevail [98].

Infusoria are divided into four main trophic groups: 1—microphages (ration basis: picoplankton, detritus, dissolved and suspended OM), 2—algophages (food basis represented by various microalgae), 3—predators (mainly feeding on other infusoria), 4—mixotrophs (having photo-endosymbionts). Some obligatory mixotrophs species energetically depend on photo-endosymbionts, while others are facultative mixotrophs using photo-endosymbionts only when food is lacking. Overall, mixotrophs comprise about 13.0% of all infusoria species registered in the NWBS [98]. However, it could be considered that mixotrophs have a stabilizing role in the trophodynamic processes of coastal ecosystems.

Algophages and microphages are the most numerous groups over the year. In spring, the ratio among trophic groups changes due to a sharp increase in the quantity of mixotroph species which reach more than 90.0% of the whole infusoria quantity. The maximal development of phytotrophic infusoria occurs in winter (December–March). Diatomophagous infusoria prevail from December until the beginning of February, leaving room for consumers of flagellate plankton in February–March [98].

In the NWBS, the algophagous groups represent 62.3% of all infusoria species. Microphages (8.6% of all species) develop predominantly in summer, while the maximal diversity of mixotrophs (4.7% of all species) is registered in autumn and winter at temperatures not higher than 18 °C. As a rule, predators (4.4% of all species) are not abundant. The ratio among trophic groups in Sukhoy and Grigorievsky Limans is similar to that in the NWBS open zones. In general, the trophic structure of Odessa Gulf (including Odessa MP) is characterized by the prevalence of algophages and mixotrophs in terms of density and biomass.

In Grigorievsky and Sukhoy Limans, algophagous infusoria dominate in density and biomass. A positive correlation between the quantitative development of planktonic infusoria and a complex of three factors (temperature, salinity and dissolved oxygen content) was found in these MPs aquatories, with dissolved oxygen showing the highest correlation. In MPS aquatories located in limans, a reduction in the quantity and biomass indices of planktonic infusoria is registered in the near-bottom layer of the deepwater zones [98].

In the NWBS, the ratio among the biomass of various trophic groups of infusoria is shifted towards dominance of algophages during the year. In comparison with phytophages, infusoria-microphages are much smaller and do not reach a considerable biomass despite their high quantity. In general, the contribution of mixotroph forms to quantity as well as to biomass remains relatively constant during the year. Compared with their quantity, the contribution of predatory infusoria to biomass is more noticeable owing to their bigger sizes [98].

For those infusoria which are obligatory mixotrophs, chlorophyll content and photosynthesis level are similar to those of microplanktonic algae [98].

It was determined that Odessa MP aquatory is characterized by a low yearly variability of infusoria trophic structure compared with the adjacent waters. The level of phytoplankton consumption by infusoria is usually much higher in limans and MPs aquatories than in the open zones of the sea. The degree of connection with the sea largely influences the size and species composition of the infusoria community in aquatories. The annual dynamics of planktonic infusoria quantitative development shows two regular maximums in spring and summer. The first one corresponds to the spring “bloom” of phytoplankton and the second one to the warmest period and OM mass destruction [98].

During the vegetative period (May–October), infusoria of the NWBS plankton daily consume from 31.3 to 190.3 mg m⁻³ of algae and 15.1–39.9 mg m⁻³ of bacterial biomass [98].

In the Odessa Gulf and other regions of the NWBS, phytophages and mixotrophs infusoria consume up to 1677 mg of algae and up to 456 mg of bacterial biomass per day and per 1 m³ of water. Predatory infusoria graze up to 406 mg of “pacific” species [98].

Production indices of planktonic infusoria vary from negative values, when predators prevail in the community, up to 585 mg m⁻³ day⁻¹ in Odessa Gulf and up to 364.1–2299.6 mg m⁻³ day⁻¹ in Sukhoy and Grigorievsky Limans. Most of the infusoria production (82.0–88.0%) is formed by species belonging to the size range of food objects for mesozooplankton and fish larvae. In Odessa Gulf and in

Sukhoi and Grigorievsky Limans, the maximal values of production are characteristic for the summer period [98].

In coastal marine ecosystems (including MPs aquatories), infusoria play a leading role in the energy transfer to all heterotrophic plankton components. Compared with invertebrates, the average indices of planktonic infusoria production during the vegetative period (May–November) are 1.4-fold higher and the metabolic expenditures 7.0-fold higher, in spite of the much lower biomass of infusoria. The contribution of planktonic infusoria to heterotrophic and total destruction is 0.84 and 0.82%, respectively. The food rations of infusoria comprise 1.0% of bacterial production and 6.5% of net primary production of phytoplankton corresponding to 0.5 and 18.0% of their biomass [98].

In the NWBS open regions and limans, the expenditure of infusoria on metabolism has similar values and does not exceed 10.3% of the consumed food energy. The transmission efficiency of energy to higher levels is low and, on average, only 12.5–14.1% of the ingested food transforms into production. The majority of consumed food returns into the environment in a transformed form and renews the OM stock circulating in the system $\text{DOM} + \text{OM} \rightarrow \text{bacteria} \rightarrow \text{protozoa} \rightarrow \text{DOM} + \text{SOM}$ [98], i.e. the so-called “microbial loop”.

The relatively low levels of resources used by ciliatoplankton in coastal marine ecosystems of the NWBS, particularly in MPs aquatories, may be explained by the high absolute quantity of phyto- and bacterioplankton from one side and by pollution and anthropogenic transformation of MPs aquatories from another. The latter changes environmental conditions and affects the natural structure of hydrobionts communities [9, 40, 156].

Dominance of big-sized diatom algae in phytoplankton is considered to reduce its total forage value for zoo- and ichthyoplankton. The speed of phytoplankton utilization by zooplankton generally depends on temperature and biochemical composition of food, as well as from its concentration in the water column.

In MPs aquatories located in desalinated regions of the Black and Azov Seas, water fleas (Cladocera) with the size up to 1 mm quite often play a noticeable role in meroplankton. These crustaceans move by short leaps mainly with the help of the second pair of antennae that they can swing abruptly. They feed on small algae and detritus particles that they filter out of water using thoracic, leaf-like appendages equipped with numerous hairs or setae. These structures collectively form the filtration apparatus. Cladocerans usually cannot sort edible particles from inedible ones. They are themselves a valuable food supply for fries and juvenile fish and play an important role in zooplankton composition (especially forage) of the Black Sea in general and of MPs aquatories in particular.

Small-sized cladocera, especially copepods, are able not only to stay in a defined horizon, but also to actively move in the water column and usually spend their whole life in the pelagial zone. Over a day, each population of planktonic copepods has a well-defined living depths [158]. Without compensation of gravitational settling by active motion, many cladocera and copepods would sink deeper than their optimal living depths, or even to the bottom, owing to their negative buoyancy [164]. As already mentioned, oxygen deficit and appearance of hydrogen sulphide

quite often occur in the near-bottom layer of MPs. Such conditions harm the generally oxyphilous planktonic crustaceans to a various degree.

Among pelagic copepods, eggs carried by adults hatch into nauplius larvae. There are 11–12 larvae stages, out of which 5–6 are naupliar and 6 copepodid. The last copepodid stage is sexually mature. Copepods larvae stay in the near-surface layer. Naupliar and younger copepodid stages usually do not perform vertical diurnal migrations. In the case of calanids (Calanida), the swimming speeds during vertical migrations are in the range $10\text{--}30\text{ cm min}^{-1}$ [135, 136].

In MPs aquatories of the Black–Azov Sea basin, the most common groups of copepods include representatives of the genera *Acartia*, *Oithona* and *Paracalanus*. For example, *Acartia* accounts for 81.0–91.0% of the zooplankton composition in Novorossiysk MP, while its contribution ranged from 34.6 to 63.0% in open part of the bay [156].

In MPs ecosystems, copepods are one of the main links along the food chain. They ensure the transfer of matter and energy from the phyto- and bacterioplankton to the higher trophic levels. Copepods are important food objects for fish larvae and juveniles. Representatives of the genus *Acartia* are the main copepod group accomplishing this function in the coastal zone and in MPs aquatories. In the Black Sea, *A. clausi* is a typical inhabitant of gulfs, bays and limans. Its eggs rest on bottom sediments.

During the last years, the relatively recently introduced copepod *Acartia tonsa* occupies a prominent place in MPs ecosystems. In Novorossiysk MP, *A. tonsa* populations are present in plankton from June until November. They appear at temperatures around $18.0\text{--}18.5\text{ }^{\circ}\text{C}$ and disappear at temperatures lower than $15.0\text{--}18.0\text{ }^{\circ}\text{C}$. From the end of June, the abundance of *A. tonsa* can even exceed that of the eurybiontic *A. clausi*. Its development peak occurs in July–September with $24\text{--}26 \times 10^3\text{ ind. m}^{-3}$ in the port and $6\text{--}8 \times 10^3\text{ ind. m}^{-3}$ in the open part of Novorossiysk Bay [156].

Free and colonial forms of diatoms do not have a high forage value for copepods or other zooplanktonic organisms. Copepods feed mainly on nanoplanktonic dinophytes which are a more suitable food owing to their soft, round-shaped and small-sized cells which are free from the hard theca typical of diatoms [136, 156].

Three types of predators are distinguished among copepods consuming animal food: ambush, examiners and suspension feeders. The “examiner strategy” is common to the majority of calanids. They have an evident selectivity towards preys of a defined size. In the majority of cases, the body length of preys is within 4.0–40.0% of the predator’s body length and 0.1–8.0% of its mass. However, there are exceptions in which the predator–prey body ratio approaches one [136].

Copepods feed by using appendages to create water flows directed toward their mouth apparatus. These appendages work at low Reynolds numbers (0.01–0.001) and practically create laminar flows. Studies performed over the last decades showed that feeding on vegetal food by passive filtration is an exception, if it exists, because it is not possible in a water mass with Reynolds number <0.1 . Algal cells are trapped separately and, in principle, copepods have a discontinuous, discrete feeding and not one based on filtration. The feeding process is based on active

regulation processes, i.e. individuals distinguish density gradients, size, form, algal physiological state and biochemical composition of metabolites surrounding the cells. Some copepod species show a distinct avoidance reaction towards algal species containing toxins such as *Gonyaulax grindleyi* [136].

Experimental studies showed that copepods move by leaping, consisting in a proper leap followed by inertial motion. The lengths of a proper leap and associated inertial motion are about 0.88 and 0.52 cm, respectively, giving a full leap length of about 1.40 cm. Depending on the situation, leaps could be short and long. The last ones are characteristic during avoidance of dangers and during diurnal vertical migrations [136].

Besides intermittent motions, copepods are capable to actively slide and float. In the pauses between movements, individuals with a slightly negative buoyancy sink passively with speeds varying from 0.3 mm s^{-1} for *A. clausi*, 0.6 mm s^{-1} for *Paracalanua parvus* up to $1.0\text{--}2.5 \text{ mm s}^{-1}$ for bigger calanoid copepods. For the majority of the studied species, the passive phase exceeds the active one both in the presence and in the absence of food in the environment [136].

It is important to emphasize that among the copepods of the genus *Acartia*, most frequently registered in MPs aquatories, the speed of passive immersion is relatively low and allows them to stay in the more desalinated epipelagial layer. Different movement types such as abrupt leaps, short leaps and sliding are characteristic for *Acartia*, as well as for other copepods. All of them are performed by sharp movements of the second pair of antennae. Short, frequent leaps (with a speed of $0.02\text{--}0.03 \text{ mm s}^{-1}$) and abrupt leaps ($0.4\text{--}0.8 \text{ mm s}^{-1}$) prevail among copepods; while smooth gliding is rarely observed [130].

Acartia are not able to escape to a significant distance from light and are forced to constantly stay in the well-illuminated layer, accomplishing short migrations to accessible depths [130, 132].

In MPs aquatories, both live and dead *Acartia* are an important food supply. In the case of *A. clausi*, body density decreases from 1.0497 to 1.0256 g cm^{-3} during decomposition, which favours the accumulation of their dead bodies in the near-surface layer [164].

The lower the aquatory depth, the higher the energy that planktonic organisms must spend to remain in a given horizon [164]. When alternation of passive immersion and active emersion periods becomes too frequent, crustaceans die from inanition or sink to the bottom where they either die or are grazed. In MPs aquatories, dredging ameliorates the living conditions of many planktonic crustaceans and other hydrobionts.

It is well known that emerging in warmer water requires relatively low energetic expenses [164]. Apparently, this is also one reason why, in MPs aquatories, small-sized species of planktonic crustaceans have a propensity for the epipelagial zone.

Big-sized calanoid copepods, which are usually registered in MPs aquatories during winter months, could cover a distance of a couple of dozens metres (and up to 71 m) during 1 h. In this time, individuals of the coldwater species *Calanus helgolandicus* were moving by leaps for 5.9 min and were sliding for 7.4 min, i.e.

they were spending 13.3 min, or less than 0.25 h, on active movements [164]. Periods of passive immersion are always considerably longer than time of active motion as for other pelagic copepods.

Marine arrow worms (*Sagitta*) have a transparent body with a length of 10–20 mm (resembling plumage arrow) and are registered in the plankton composition of many MPs. They have a caudal fin at the body end opposite to the mouth as well as anterior and posterior tail fins on the lateral parts of their body. With the help of fins, arrow worms can perform rush leaps exceeding their own length by several fold.

During feeding, marine arrows are able to seize preys which are bigger than their own body. As a rule, they feed at night and eat mainly crustaceans, fish larvae and their own juveniles. Juvenile individuals feed on bacteria and unicellular algae.

In MPs, isopods (Isopoda) from the genus *Idotea*, *Sphaeroma*, *Jaera* and *Eurydice* are often observed in the near-wall layer of HTS. Isopods specifically feed on macrophytes and diatoms fouling them, bacteria, protozoans and other microscopic organisms.

In MPs, shrimps from the genus *Palaemon*, opossum shrimps (Mysidacea) and hooded shrimps (Cumacea) move from benthal and periphytal zones into the near-surface water layer at nighttime. Shrimps can crawl and swim by pushing themselves with the help of pleopods. During such movements, antennas and thoracic (walking) legs are pressed against the body and the abdominal segments are straightened. At the approach of a danger, shrimps accomplish leaps frontwards by using the posterior part of their body. Abdominal segments are sharply bent and the telson and the uropods are used to create the thrust. Shrimps are mainly predators, but can feed on dead hydrobionts.

Shrimps and crabs larvae are quite good swimmers and pass 4–5 weeks in the water column during their development process. During the zoea stage, larvae use thoracic appendages for swimming and zoea can cover a distance of 0.5–1.0 m per minute. During the subsequent stages, pleopods become the organs of motion. Equipped with pleopods, larvae swim with their anterior body end forward. Decapods larvae feed on planktonic organisms such as algae and animals.

The semi-transparent mysids, being similar in appearance to small-sized shrimps, have lengths of 10–20 mm. At daytime, they stay near the bottom and near HTS walls. They swim with the help of thoracic legs whose anterior pair presents maxillipedes. Mysids mainly feed by filtration or by selectively seizing suspended particles and small-sized animals. They are also able to consume fragments of macrophytes and crustaceans' dead bodies.

Opossum shrimps perform regular vertical (diurnal) and horizontal (seasonal) migrations during which they form shoals of various sizes. Mysids stay in the shaded near-bottom or near-wall water layers during the day and rise up towards the surface for feeding at dusk.

Cumaceans usually spend day time burrowed into the silty-sand or sandy sediment; going out from sediment and swimming in the water column during evening hours and at night. Females swim using external branches of thoracic legs and males also by swimmerets. Swimming is also favoured by bending and

straightening of the abdominal segments. Individuals with a length of about 3 mm can move to surface with a speed of 1 m s^{-1} [67].

In MPs, and particularly in Sevastopol Bay, some representatives of meiobenthos, including harpacticoids and nematodes regularly move from the bottom into the water column during night hours [70]. This behaviour could be connected with both nutrition and nocturnal oxygen deficit at the bottom. Sorokin [161] surmised that nocturnal migrations of some bottom organisms into the thermocline layer are caused by the presence of increased concentrations of dead OM, i.e. food, in this zone. We have observed amphipods migrations towards the water surface in early morning hours, which was undoubtedly caused by oxygen deficit.

Excessive enrichment of ecosystems with food supplies decreases species diversity, increases the abundance of few species and quite often causes a reduction in the size of the individuals of such species [41, 47]. These phenomena manifest most clearly in heavily polluted MPs aquatories.

In MPs aquatories, the observed mass mortality of bottom invertebrates and other organisms is caused by lack of oxygen in the bathypelagial and benthal zones. Oxygen depletion is often connected with phytoplankton and macrophytobenthos hyperproduction in the periphytal zone. Mortality of bottom invertebrates is compensated by an increased survival of their typically pelagic larvae which find themselves in improved trophic conditions [5].

The pelagic larvae of bottom invertebrates and HTS foulers play an important role in the life of many plankton, benthos and periphyton representatives of MPs owing to their mass character and role in food chains. Due to their participation in diverse biological links and food chains with numerous components, they not only ensure species survival, but also contribute to OM turnover between the benthal and pelagial, periphytal and pelagial, and benthal and periphytal zones.

In MPs, the mass reproduction of benthic invertebrates with pelagic development usually occurs during spring and summer in plankton and is directly connected with intensive development of phytoplankton. Diurnal migrations of zooplankton are also synchronized with development of unicellular algae in the near-surface sea horizon.

In the afternoon, when the intensity of illumination decreases, zooplankton starts migrating towards the water surface. The maximal quantity of zooplankton is observed in the surface 10 cm layer at nighttime around 10 p.m. The reverse redistribution of zooplankton from the surface layer into deeper horizons takes place later at night [161].

Being in plankton and subject to phenomena of “local transfer” near the coast, larvae of bottom invertebrates serve as a potential reserve for reestablishing the normal structure of bottom communities in coastal zones affected by pollution after amelioration of living conditions [116]. Being in protected MPs aquatories, pelagic larvae of bottom invertebrates quickly settle on recently installed artificial HS and restore damaged settlements.

Pelagic larvae of bottom invertebrates have tight and diversified relations with benthos, plankton, neuston and nekton and participate in the system of biotic links among them, in particular via food relationships. In this way, pelagic larvae of

bottom invertebrates contribute to the constant turnover of OM between the water column and the bottom [116]. In MPs, additional links with other groups exist thanks to the presence of a periphytal zone and its population, which is recruited mainly from benthos composition.

Pelagic larvae of bottom invertebrates significantly influence the biological cycle and structure of plankton, neuston and nekton communities inhabiting the water column, where they temporarily live during the pelagic stage of their development [116].

The Black Sea decapods' larvae, as well as adult individuals of some species, lead a benthic life and perform vertical diurnal migrations.

Adult shrimps *Crangon crangon*, *Palaemon elegans* and *P. adspersus* are registered at night in the hyponeuston layer at the water surface. In some cases, adults (both females and males individuals) of the mud shrimp *Upogebia pusilla* have been reported to rise towards the surface light of electric lamps at nighttime. While adult shrimps' individuals rise up towards the surface only in some cases, their larvae stay in the surface layer at any time of the day in the same way as the larvae of the majority of decapods' species of the Black Sea. The majority of decapods larvae (zoaea, megalope) exhibits a positive phototaxis. Decapods larvae have special adaptations for remaining in the hyponeuston layer [109]. Shrimps accomplish mass seasonal migrations from MPs aquatories into the deeper sea regions, thus eliminating a part of BM from MPs ecosystems.

Vagile invertebrates inhabiting the MPs periphytal (amphipods, isopods, cumaceans, mysids and shrimps) move along the lateral surfaces of HTS during both day and night and can move away from HTS at distances ranging from a couple of centimetres to couple of metres. Because a large quantity of land-based nocturnal sources of light is present around MPs and in MPs aquatories, various insects concentrate and die there in greater number than in adjacent sea zones. Insects get into port aquatories at some meteorological situations and during mass migrations period. They accumulate mainly at the water surface in the apex zones of aquatories. Some of them are eaten by fish, but most of them end up enriching MP ecosystems in dead OM. In MPs, the night sources of light attract various species of vagile hydrobionts to the surface layer.

In MPs of the Black–Azov Sea basin, constant (holoplankton forms) as well as temporal (meroplankton forms) inhabitants of the pelagial zone are registered in the zooplankton composition during all seasons. The presence of inflowing rivers has a significant influence on the zooplankton horizontal distribution in MPs; especially during the high water season. Freshwater zooplankton organisms can be locally found in MPs. In the NWBS, the river influence is so high that salinity in the aquatory of Odessa port sometimes decreases to 3.5–4.0‰. In the case of Ilyichevsk and Yuzhny MPs, the composition of fauna is influenced by their location inside limans and by their geographic proximity to the main source of desalinated water in the eastern part of the NWBS: the Dnieper-Bug Liman.

In the aquatories of Grigorievsky Liman and Odessa Gulf, many species of planktonic animals and fish, which cannot survive for a long time in seawater, appear during periods of intense desalinization. Cape Bolshoy Fontan diverts

seawards the desalinated waters coming from the Dnieper-Bug Liman, thus decreasing the possibility for such organisms to enter the aquatory of Sukhoy Liman [16, 154, 196].

Quantitative and qualitative composition of Yuzhny, Odessa and Ilyichevsk MPs zooplankton is significantly enriched in benthic animals larvae compared with the open sea. The same peculiarity is also typical for other MPs, irrespectively of their location in limans (as for Yuzhny, Ilyichevsk and Varna-West MPs), bays of the estuarine type (as Sevastopol in Sevastopol Bay and Sevastopol fishing port in Kamishovaya Bay) or on open seashore (as Odessa, Mariupol, Novorossiysk, Tuapse, Sochi and others) [16, 154, 196].

With respect to species composition, the population of the pelagial zone in Sukhoy and Grigorievsky Limans and in Varna and Beloslav Lakes became richer after the construction of shipping channels, but the importance of freshwater and brackish water species has reduced. Genetically the modern composition of zooplankton in these water basins comprises representatives of three complexes: freshwater, brackish water and marine [7, 54, 117].

In the 1990s, the average long-term zooplankton quantity in Grigorievsky Liman comprised $35,347 \text{ ind. m}^{-3}$ for a biomass of 292.14 mg m^{-3} (excluding the comb-jellyfish *Mnemiopsis*). The highest density of zooplankton ($53,693 \text{ ind. m}^{-3}$) was registered in spring and was followed by a progressive decrease during the other seasons ($30,893 \text{ ind. m}^{-3}$ in summer, $12,437 \text{ ind. m}^{-3}$ in autumn and 4436 ind. m^{-3} in winter). Zooplankton biomass increased from spring (198.79 mg m^{-3}) towards summer (376.65 mg m^{-3}), reaching its maximum in autumn ($10,282.70 \text{ mg m}^{-3}$). The winter period was characterized by the lowest biomass (103.81 mg m^{-3}). In spring, representatives of the genus *Synchaeta* prevailed in terms of quantity and biomass. Their quantity remained also high in summer, when the role of the sea sparkle *N. scintillans* and of meroplankton, especially *B. improvisus*, was increasing. In autumn, the role of *N. scintillans* decreased, larvae of barnacles remained present in significant amounts and the role of the tunicate *O. dioica* markedly increased. In early winter, the sea sparkle dominated plankton in terms of quantity and biomass.

In Grigorievsky Liman, representatives of Cladocera (11 species), Copepoda (11) and Harpacticoida (11) were registered in the composition of forage zooplankton. In 2003, besides *A. clausi*, the calanoid fauna copepod *Acartia tonsa* (new for the Black Sea) was registered in the southern part of the liman. In the 1990s and 2000s, Rotatoria and Copepoda composed the main structure of the zooplankton in the basin. Species of the genus *Brachionus* dominated among rotifers and *Synchaeta* and *Calanoida* among copepods. The holoplanktonic forms (77 taxa) comprised 73.8% of the total number of taxa and meroplanktonic ones (27 taxa) 26.2%. Among holoplanktonic forms 4.8% are Caspian relicts (*Centropages pen-goi*, *Cornigerius maeoticus*, *Podonevadne trigona*, *Hetercope caspia* and *Calanipeda aquae-dulcis*).

The number of zooplankton species in Grigorievsky Liman has increased threefold between the 1960s, when there was no shipping channel, and the 2000s. As a consequence of spring floods from the Dnieper-Bug Liman, the spring

zooplankton of Grigorievsky Liman became the most abundant group as to taxa number and was substantially represented by rotifers. In the 1970s, after construction of the channel, the role of *N. scintillans* and *A. clausi* in the zooplankton composition of Grigorievsky Liman increased and these two species became dominant. The quantity and biomass of meroplankton increased significantly. The zooplankton development in Grigorievsky Liman reflects its development in the adjacent part of the Black Sea [196].

Unlike Yuzhny MP, which is located in Grigorievsky Liman, Odessa MP is situated on the open coast of Odessa Gulf and is connected with the sea by three passages having a total width of more than 900 m. Fifty-three taxa, excluding meroplanktonic forms, were identified in the zooplankton structure of Odessa port: larvae of Polychaeta, Cirripedia, Bivalvia and Gastropoda. The most abundant were copepods (30%) and cladocera (9%). Representatives of *A. clausi* and meroplankton forms (larvae of Polychaeta, Cirripedia, Bivalvia and Gastropoda) were always present. A slightly lower percentage of occurrence frequency was registered for *Sagitta setosa* (79%), *Pleopis polyphaemoides* (79%), *O. dioica* (77%) and *N. scintillans* (75%). Larvae of *B. improvisus* (9805 ind. m⁻³, 58.3 mg m⁻³) and *N. scintillans* (1295 ind. m⁻³, 61.38 mg m⁻³) were the most abundant in terms of quantity and biomass. Rather high densities were observed for *P. polyphaemoides* (876 ind. m⁻³), polychaetes larvae (840 ind. m⁻³), bivalves larvae (627 ind. m⁻³) and *Synchaeta baltica* (420 ind. m⁻³). During August–December 2001, 53 taxa were registered in the zooplankton composition of Odessa port aquatory, compared with only 16 taxa in the adjacent coastal region [16].

Sukhoy Liman was quickly colonized by new zooplankton organisms after its junction with the sea. The number of taxa increased from 26 in 1967 to 48 after 2 years [20]. In the 1990s, the zooplankton of Sukhoy Liman was represented by 24 species and subspecies during the various seasons. The highest quantity and biomass were registered during the summer months: 73,286 ind. m⁻³ and 306.70 mg m⁻³, respectively. These indices were decreasing towards autumn (17,965 ind. m⁻³, 65.54 mg m⁻³) and reached their lowest values in early winter (2178 ind. m⁻³, 22.54 mg m⁻³). *A. clausi* and *N. scintillans* were the dominant species in the 1960s and 1970s, but in the 1990s, the role of *Noctiluca* considerably reduced and the role of barnacles larvae increased in all seasons and especially in summer. The highest indexes of zooplankton were registered for the southern and central parts of Sukhoy Liman. In September 2002, mass development of *Favella ehrenbergii* (56,283 ind. m⁻³, 258.90 mg m⁻³) occurred. The average quantity of zooplankton (without comb-jellies) comprised 679,594 ind. m⁻³ for a biomass of 477.75 mg m⁻³ [154].

In Odessa MP, representatives of coldwater complexes such as *N. scintillans*, ephyra stages of the scyphomeduse *A. aurita*, copepods *Pseudocalanus elongatus*, and comb-jellies *Pleurobrachia pileus* were found in compensatory waters after offshore winds in spring, late autumn and in summer.

It is evident that the increase in the importance of meroplanktonic forms in MPs is directly connected with the increase in the underwater surface area of berths, piers, breakwaters, floating docks and ships.

In Sevastopol Bay, 59 species of the classes Polychaeta, Gastropoda, Bivalvia and of the order Decapoda were found in the composition of meroplankton during the period 1987–1997. Compared with previous observations (1950–1970s), pelagic larvae of Bivalvia had decreased by 60% and species diversity of other three big taxa was also reduced by one-third on average.

In all zones of Sevastopol Bay aquatory, the meroplankton is an important component of zooplankton all year round. The highest biomass was registered for *B. improvisus* larvae, followed by Polychaeta [3].

In Sevastopol Bay, Copepoda (mainly *A. clausi* and larvae of benthic animals) form most of the biomass of summer mesozooplankton. The total zooplankton biomass has reduced after the construction of moles that restrict water exchange between the bay and the open sea. Larvae of the polychaetes *Neanthes succinea*, *Polydora cornuta* and *Capitella capitata*, which are resistant to anthropogenic pollution, were found in the plankton composition [3].

In Sevastopol Bay, organisms from benthic and fouling communities were found in the zooplankton composition: larvae of barnacles, mussels, pearlwrts and *Botryllus* ascidians. Nauplii and cypris of barnacles are the most numerous, while veligers of mussels occur in lower numbers. The role of fouling hydrobionts larvae in the zooplankton composition of the bay changes following reproductive cycles as well as peculiarities of the hydrological regime. Larvae of fouling hydrobionts occur all year round in plankton, but their mass development is observed from May to December, with some reduction in July–August. Because of the vertical migrations peculiar to the majority of species-foulers larvae, their quantity in the upper water horizons is twice as much at nighttime than in morning hours. The average quantity of larvae in the near-bottom water layer (depth 4 m) is relatively similar during the day- and nighttime, but considerably lower than the quantity observed at night in the upper horizon. In Sevastopol Bay, during the period of abundant development, larvae of fouling organisms comprise 20–43% of the total zooplankton mass [25].

Zooplankton quantitative composition in the NWBS coastal zone is similar from Novorossiysk to Sochi [50]. In strongly polluted areas of MPs, plankton is impoverished both quantitatively and qualitatively. Cladocera are particularly sensitive to pollution [52].

In 2004–2010, 71 taxonomic forms were found in the holoplankton composition of Novorossiysk Bay including 56 Copepoda, 4 Cladocera, 6 Porifera, 2 Ctenophora, 1 Dinophyceae (*N. scintillans*), 1 Chaetognata and 1 Appendicularia (*O. dioica*). Copepods composition consisted in 15 Black Sea species and 41 alien species.

In Novorossiysk port aquatory, holoplankton comprised 66.0–77.0% of the total zooplankton quantity compared with 73.0–88.0% in the open part of the bay. The maximal holoplankton biomass reached 0.4–0.8 and 0.8–2.0 g m⁻³ in the open part of the port during summer and at the beginning of autumn. In most cases, the amplitude of biomass fluctuations in port waters was lower than in the open part of the bay.

Oligotrophic forms of crustaceans, predators and others prevail in the planktonic communities of the open sea. On the other hand, organisms resistant to high OM concentrations such as the neritic forms of crustaceans, rotifers and meroplankton are most common in port waters rich in detritus. In Novorossiysk MP, the genus

Acartia accounted for 81.0–91.0% of the Copepoda abundance, compared with values of 34.0–63.0% in the open part of the sea. The total density of *Acartia* in the port aquatory was 1.5-fold higher than in the open part of the sea for similar values of biomass. In the apex part of the port aquatory, nauplii and copepodites were observed more often in the structure of *Acartia* populations. Reproduction of *A. clausi* occurs during the whole year, with exception of one or two months (August–September).

Mass development of cladocerans is registered in summer. In the open part of Novorossiysk Bay, their average long-term density is 7.8×10^3 ind. m^{-3} and their biomass 195.9 mg m^{-3} , which is two to fivefold higher than in the port aquatory. The small-sized *P. polyphaemoides*, which feeds mostly on detritus, was the most abundant species in the port aquatory.

In the port aquatory, the average long-term abundance and biomass of the sea sparkle (*N. scintillans*) was 1.7-fold higher (6.7×10^3 ind. m^{-3} , 0.4 g m^{-3}) in comparison with the open part of the harbour.

In Tuapse port, the holoplankton included 40 taxonomic forms, among which 26 Copepoda, 4 Cladocera, 5 Porifera, 2 Ctenophora, 1 Dinophyceae (*N. scintillans*), 1 Chaetognata and 1 Appendicularia. Copepods composition comprised 14 invasive alien species and 12 Black Sea species. In Tuapse port aquatory, the average long-term density of forage holoplankton was 10.6×10^3 ind. m^{-3} for a biomass of 137.6 mg m^{-3} , which is twofold lower than in Novorossiysk port. Holoplankton organisms comprised 80.0% of the total zooplankton quantity in the coastal zone adjacent to port and 65.0% in the port aquatory.

The long-term average annual density of the genus *Acartia* were $5.1\text{--}54 \times 10^3$ ind. m^{-3} . In ports aquatories, the indices of biomass (0.08 g m^{-3}) were 1.5-fold higher than in the open waters. The maximal density of populations of the neritic copepod species *A. tonsa* was 2.2×10^3 ind. m^{-3} and 0.9×10^3 ind. m^{-3} in port aquatory and in open part of the sea, respectively. The meroplankton, i.e. larvae of bottom invertebrates, is an important component of neritic zooplankton in various regions and MPs of the Black and Azov Seas. In Novorossiysk Bay, larvae of bottom invertebrates were present in plankton during all study periods.

In 2004–2010, the meroplankton of Novorossiysk Bay and Tuapse port was represented by 68 taxonomic forms out of which 23 belonged to Polychaeta, 4 to Cirripedia, 1 to Phoronida, 20 to Decapoda, 8 to Bivalvia, 10 to Gastropoda and 2 to Hydrozoa. The highest number of taxonomic forms (67) was registered in Novorossiysk Bay, while only 46 were present in Tuapse port.

In bays and ports of the NEBS, the season of mass reproduction of bottom invertebrates occurs from May to September. On average, meroplankton accounts for 23.0–26.0% of the total zooplankton quantity (15.0% in the central part of Tuapse port aquatory), reaching 50.0% and more during spawning peaks. In Novorossiysk Bay and Tuapse port, the complex of meroplankton dominant species comprised larvae of *B. improvisus*, *B. reticulatum*, *M. lineatus* and *Polydora* ssp. which are tolerant to pollution.

Larvae of the bivalves *Anadara inaequalvis* and *Chamelea gallina* as well as of decapods played a certain role in the meroplankton structure of Tuapse and Novorossiysk ports.

Non-uniform distribution of meroplankton in MPs aquatories is explained by the peculiarities of waters circulation and the formation of larvae accumulation in the apical stagnant zones of aquatories.

Meroplankton of the NEBS port aquatories is characterized by high densities and species diversity. Spatial and temporal changes in the composition of dominant species and their abundance are determined by periods of benthic animals spawning, circulation of water masses, and eutrophication levels of water and bottom sediments.

Observations in the estuarine zone of Tsemes river, in the north-western part of Novorossiysk port, showed, that rotifers (40,800 ind. m^{-3}) were the mass representatives of plankton in April at a temperature of 10.6 °C. Other organisms that developed in considerable amounts were *O. minuta* (1108 ind. m^{-3}) and *A. clausi* (11,887 ind. m^{-3}) among Copepoda and *B. improvisus* (9960 ind. m^{-3}) among larvae of benthic organisms. In May, at a temperature having increased to 19.5 °C, the most abundant zooplankton organisms were infusoria (1600 ind. m^{-3}), rotifers (444,400 ind. m^{-3}) and acartia (17,886 ind. m^{-3}). In plankton, the number of *O. minuta* (2984 ind. m^{-3}) and *P. parvus* (1372 ind. m^{-3}) significantly increased. Among benthic organisms' larvae, Polychaeta (3916 ind. m^{-3}) reached the maximum development, while the quantity of *B. improvisus* larvae, albeit decreasing, remained significantly high (3376 ind. m^{-3}). Thus, infusoria, rotifers and benthic organisms' larvae develop in mass quantity in the aquatory of Novorossiysk Bay during spring [51].

In Novorossiysk port, summer (June–September) is characterized by the most diverse species composition of zooplankton. The peak of its development is registered in June, at a water temperature of 21.6 °C, and a couple of mass developing species constitute the bulk of zooplankton quantity. In June, the maximum quantity of acartia (38,620 ind. m^{-3}) occurs and that of *O. minuta* increases by more than twofold to attain 6200 ind. m^{-3} . Among the other representatives of Copepoda, *P. parvus* (1174 ind. m^{-3}) is the most numerous. In June, the number of rotifers reduces by 10-fold. Barnacles larvae (4760 ind. m^{-3}) and Gastropoda (3448 ind. m^{-3}) are found in great quantity, while other species do not significantly contribute to zooplankton composition. In Novorossiysk port, the period July–September is the most unfavourable for zooplankton development, possibly because of the high water temperature (25.0–26.0 °C). In October, with water temperature lowering to 16.2 °C, the zooplankton species composition acquires the characteristics typical for the autumn period. The number of thermophilic forms reduces, the development cycle of all Cladocera concludes and the cryophile form *Oithona similis* appears again [51].

In the aquatory of Novorossiysk port, the species composition of zooplankton changes not only seasonally, but also across years. Two dominant species, *A. clausi* and *O. minuta*, account for most of the zooplankton quantity. With regard to benthic organisms, larvae of *B. improvisus* are recorded in mass quantity in April–

June and September–October. The development peak of gastropods larvae is registered in June and August and that of bivalves in October [51].

In Tuapse port, the abundance of holo- and meroplankton is 1.5–2.0-fold lower ($40,000 \text{ ind. m}^{-3}$, 371.7 mg m^{-3}) in the heart of harbours, near the berths, than in the central part of the aquatory and beyond its boundaries. Copepods from the genera *Acartia* and *Centropages*, predatory *Sagitta* and larvae of gastropod *Bittium reticulatum* represent most of the biomass [155]. An increased role of protozoans, infusoria, rotifers and larvae of some small-sized polychaetes has been observed in the zooplankton composition of MPs aquatories ecosystems over the last decades. This change is accompanied by a simplification of the zooplankton structure owing, first of all, to pelagic Copepoda, Cladocera and Decapoda larvae.

2.2.4 *Ichthyoneuston and Ichthyoplankton*

Fish have an extremely important role in aquatic ecosystems. Frequently, fish occupy the highest trophic level in food chains and transform the phytoplankton, invertebrates and small-sized fish biomass into valuable food resources for humans. The long-lived, large-sized predatory fish preserve BM in their biomass for a prolonged period of time, thus supporting the normal, stable functioning of ecosystems. Replacement of long-lived species by short-lived ones, as observed in the Black Sea during the last decades, testifies about excessive water eutrophication. The absolute majority of Black Sea fish has pelagic development stages, i.e. for some period of time fish become components of ichthyoneuston and ichthyoplankton.

For many fishes, MPs aquatories ecosystems represent a sufficiently nutrient-rich environment for the various stages of their ontogenesis. While there is no active fishery in MPs, they are at the same time eutrophicated and frequently polluted by various toxic substances.

In MPs aquatories, the vertical and horizontal distribution of ichthyoplankton is mainly connected with water hydrodynamics, especially with the surface micro-convection, Langmuir circulations, wind surface currents, and water density at various horizons and in the different harbours.

It is known that the survival ability of pelagic fish larvae significantly depends on how effectively individuals find food and graze zooplankton micro-accumulations, particularly copepod ones. Fish larvae with a length of 10 mm are able to detect their preys at a distance of about 10 mm [219]. It is important to consider that elements of gregarious behaviour appear in zooplankton organisms' accumulations. Individuals displace as a whole while preserving defined (1–2 cm) inter-individual distances. Aggregation “responds” to danger imminence, shading and other factors [136]. Fish larvae spend energy in search of food micro-accumulation because search of and feeding on single preys could be energetically insufficient and lead to death.

The majority of studied Copepoda form monospecific assemblages. In coastal zone, such assemblages often have an irregular spherical form and sizes of

centimetres to dozens of centimetres [136]. In aggregations, the copepods density reaches $24 \times 10^3 \text{ ind. m}^{-3}$. Copepods are the main food object of early larval stages of fish in the pelagial zone.

The basis of the Black Sea ichthyofauna is formed by more or less thermophilic fish of Mediterranean origin. They usually reproduce from the end of spring until mid autumn. The group of cryophile species, with pelagic eggs and usually spawning in March–April, comprises sprat *Sprattus phalericus*, whiting *Merlangius euxinus*, shore rockling *Gaidropsarus mediterraneus* and flounder *Platichthys lucsus*.

The changes in ichthyofauna composition, which took place during the last decades in the entire Black Sea and in its specific regions, also reflected in ichthyoneuston and ichthyoplankton composition of MPs aquatories. Many species have almost completely disappeared and others stopped to live and to spawn in the coastal zones of the whole NWBS.

Eggs, larvae and fries of different fish species can be found in the water column of MPs aquatories. Here pelagic spawn of fish reproducing directly in ports are recorded along with pelagic spawn entering port aquatories together with water masses. Prelarvae and larvae hatch from eggs which remain in the water column for some time. Here larvae and fries developing from demersal spawn are present together with spawn of ovoviviparous fish (Syngnathidae).

In the Black Sea coastal zones, the ichthyoneuston species composition is diverse due to eggs and larvae of the bottom and near-bottom fish. In the open regions of the sea, eggs, prelarvae, larvae and juveniles of fish mass species (khamsa, sprat, horse mackerel, goatfish, striped mullet, golden mullet, leaping grey mullet and other) are predominantly observed. The ichthyoneuston species composition in the eastern and southern part of the Black Sea and near the Crimean coasts is richer than in the NWBS. Studies showed that, at the early stages of development, some fish species reside in the near-surface sea layer over long time spans, while others rise up to the film of water surface tension only for a couple of hours. However, the neustonic stages of development are vitally important for all fish species. In the near-surface layer of the Black Sea, fish are present both during passive stage of development (spawn) and as active vagile forms (prolarvae, larvae and young fish) [38, 39].

The buoyancy of the eggs developing at the water surface depends on the relative densities of the eggs and of seawater. The important hydrostatic adaptation of marine pelagic eggs is their high content of low-density water and, often, the presence of large-sized fatty drops (striped mullet, golden grey mullet, leaping mullet, common bluefish, red mullet, horse mackerel, greater weever fish, annular seabream and others).

Observations of eggs from various fish species near the surface showed that the embryo occupies a quite defined position inside one egg, depending on the ratio between the densities of yolk and embryo and on the location of fat drop(s) (if present). In highly buoyant eggs, the embryo is located under the yolk-sac. In pelagic eggs of marine fish, the fatty drops occupy a position opposite to that of the embryo and are always located above it, which favours the quick return of the egg

to a stationary position in case of disturbances. In the near-surface layer, the conservation of a stationary position by fish eggs, exposed to intensive illumination by sun rays, apparently allows them to regulate irradiation with the help of pigment-containing cells located near the vegetative pole [38, 39].

Prelarvae of fish rise up from various horizons to the surface in variety of ways. Embryos developing from eggs laid on the bottom (as in the case of sand smelt, garpike, picarel, gobies and others) rise up with active body movements using the primal fin fold and pectoral fins. Prelarvae developed from floating eggs use the primal fin fold as a thruster, but do not yet possess the horizontal rudders represented by pectoral fins. Prelarvae move by undulations of body and fin fold, alternating periods of activity and rest. They swim up during periods of activity and slowly sink down while resting. Periods of activity and rest have approximately the same duration, but prelarvae sink slower than they rise up. This results in a gradual rising up of the prelarvae in the water column. After reaching the water surface, prelarvae accumulate there and periodically perform vertical displacements. Positive phototaxis undoubtedly favours the rising up of prelarvae and larvae which develop from bottom eggs.

The yolk sack, fatty drop and subdermal cavity of prelarvae developing from floating eggs favour their upward movement. At first, prelarvae hatching from pelagic eggs swim with their yolk sack upward. They turn into the back-up position only after the formation of the subdermal cavity and the almost complete resorption of yolk. Prelarvae of different fish species swim differently in the near-surface sea layer depending on the position of fatty drop(s) in the yolk sack. The red mullet, Black Sea horse mackerel, greater weever fish and others have a fatty drop located in the anterior part of the yolk sack. During activity and rest periods they are oriented with their head towards the water surface and move along steep vertical spirals. However, they cannot swim horizontally because of the insufficient development of pectoral fins that would function as horizontal rudders. The prelarvae of the striped mullet, golden grey mullet and Black Sea turbot have a fatty drop located in the middle part of yolk sack. They move along an almost straight line, directed at a slight angle towards the film of water surface tension, or emerge along a wide flat spiral rotating around body axis.

The subdermal cavity forms in the dorsal part of the prelarval body, mainly over the head, and takes the place of the yolk sack as the hydrostatic organ of the embryo.

Until the development of pectoral fins, the yolk sack, fatty drops and subdermal cavity of fish prelarvae and larvae are special organs of orientation and steering that lighten the anterior part of the prelarval body and assist it in floating up to the surface. Thus, the character of fish prelarvae movements, the precise direction of movements and the presence of organs of orientation and steering indicate that many the Black Sea fish prelarvae have an “inborn” ability to swim up.

It is known that the majority of sea bony fish larvae and fries have an air bladder, even if they lose it in adult state.

The primary function of an air bladder is to save energy while remaining in a defined sea horizon. It was determined that the initial filling up of the air bladder of

larvae and fries of physostomous and physoclistous fish takes place with atmospheric air. Air enters into the air bladder via an air passage (ductus pneumaticus), which, in physoclistous fish, is occluded after a couple of days. During subsequent developmental stages, gas regulation within the air bladder takes place via the circulatory system. If the primary intake of atmospheric air does not take place, then the gas regulation in the air bladder fails. Fish larvae with empty air bladders develop abnormally, experience delayed growth and die [38].

In MPs aquatories, fish eggs with a too high density and abnormally developing larvae and fish fries sink down to the pycnocline zone and become food for various hydrobionts. Heavier larvae and fries sink to the bottom.

Spawning of 17 species was registered in Odessa port aquatory: European anchovy *Engraulis encrasicolus*, sea mouse *Callionymus risso*, sand sole *Pegusa lascaris*, red mullet *Mullus ponticus*, horse mackerel *Trachurus ponticus*, sprat *S. phalericus*, greater weever fish *Trachinus draco*, the Black Sea turbot *Psetta maecotica*, shore rockling *G. mediterraneus*, striped mullet *Mugil cephalus*, golden grey mullet *Liza aurata*, sharpnose mullet *Liza saliens*, haarder *Liza haemotocheilus*, the European black scorpionfish *Scorpaena porcus*, stargazer *Uranoscopus scaber* and the Black Sea flounder *P. lucsus*. Larvae of grey mullet, leaping mullet, atherines, the Black Sea flounder, goby (Gobiidae), combtooth blennies (Blenniidae) and sea needles (Syngnathidae) were also caught [16].

In the 1950s, eggs of 16 fish species were reported to occur in the ichthyoplankton of Sevastopol Bay. This number had decreased to only 6 species in 1998.

In Sevastopol coastal zone, larvae of commercial fish with pelagic eggs comprised 80.0% of the total quantity of ichthyofauna in the 1960s. In 1988–2008, this type of larvae was sporadic or absent and the average percentage of larvae of fish with demersal eggs had increased up to 80.0% of the total, reaching 100% in some years [35].

Eggs, larvae and fries of various fish species were found in Novorossiysk and Tuapse ports' aquatories. At the end of the 1960s, eggs and larvae of 13 fish species were found in the plankton composition of Tuapse Bay during summer. Early stages of development of 13 fish species were also present in the ichthyoplankton of Sochi port aquatory. The qualitative composition of ichthyoplankton was similar in both ports [97]. Eggs of 10 fish species were found in the aquatory of Novorossiysk MP in the 1970s and at the beginning of the 1980s [23].

Anchovy eggs constituted 86.2% of the Tuapse port ichthyoplankton in August 2010. The average density of ichthyoplankton in the port was 2.5-fold lower than outside its boundaries (21 ind. m^{-2} in vertical catches, 163 ind. 100 m^{-3} in horizontal catches). The overall quantity varied from 0 to 104 ind. m^{-3} [155].

During the summer period, the majority of Black Sea ports aquatories is characterized by the presence of eggs and larvae of the European anchovy *E. encrasicolus*. Findings of eggs of the annular seabream *Diplodus annularis* are common in the eastern and southern part of the Black Sea ports aquatories and at Crimean shores.

Eggs of the Black Sea flounder *P. lucsus* are found in the aquatories of Sukhoy and Grigorievsky Liman in March–April. Larvae and low-pigmented fries of the Black Sea flounder stay in the surface layer and, after metamorphosis, approach the shallow waters and shift to the near-bottom way of life. Fries of the Black Sea

turbot *P. maeotica* and of the sand sole *P. lascaris*, that develop from pelagic eggs in the spring-summer period, behave in the same way.

In Sukhoy and Grigorievsky Liman, *Atherina pontica*, which deposit eggs on water vegetation, spawns in April–May. Its hatched larvae and, at a later stage, fries stay in schools in the upper water layer with the thickness of 0–10 cm, feeding in the coastal zone or near various HTS.

In the NWBS, the abundant fries of striped, golden grey and leaping mullets develop from pelagic eggs and, during the first 2 to 3 weeks of their life, remain under the surface tension film and feed on plankton. Juvenile fish subsequently migrate from the open sea towards the coast and enter into all shallow-watered gulfs, bays and limans; including MPs aquatories. After some time, their behaviour change and they start to feed mainly on periphyton. Moving alongshore in the Odessa region of the NWBS, the fries of haarder get in Odessa, Ilyichevsk and Yuzhny MPs aquatories. In Sukhoy and Grigorievsky Limans, shores zones not yet affected by hydrotechnical construction and suitable for their growing period are still preserved. The fries of haarder stay in MPs aquatories until late autumn. In Odessa MP, there are no conditions for grey mullets to switch from feeding on plankton to feeding on periphyton on the bottom surface. In all three MPs, 1-year-old grey mullets and grey mullets of older age live both in preserved shallow waters and near HTS lateral surfaces from spring until late autumn. The highest mass concentrations of leaping mullet and striped mullet fries, counting million of individuals, were registered in Odessa, Ilyichevsk, Khorly and Skadovsk MPs in winter. Until ice formation, the dense schools of juvenile individuals were concentrating in the upper water horizon along the port berths and under ships' hulls [149]. In winter, during the ice regime, mass concentrations of fries of mullets are found near the berths of Mariupol, Berdyansk, Henichesk and Temryuk ports [150].

In last years, fries of the recently acclimatized haarder *L. haemotocheilus* have acquired a significant role in the ichthyoplankton composition of Odessa port and Sukhoy and Grigorievsky Limans. At the end of summer and beginning of autumn, juveniles of the garfish *Belone euxini* are often observed in the near-surface water layer (0–10 cm) of the aquatories of all three ports in the Odessa region.

It is natural that fries of the black goby *Gobius niger* and of gobies from the genus *Pomatoschistus*, developing from demersal eggs, rise up to the surface water horizon for the first infill of the air bladder by atmospheric air. After a couple of days, they settle to the bottom. In MPs aquatories, some benthic fish with demersal eggs, as for example the tubenose goby *Proterorhinus marmoratus*, spawn in cracks and cavities of HTS as well as in cavities between the fouling of mussels' druses. The hatched fries of tubenose goby are registered in the water column near piers, breakwaters and berths. The combtooth blennies from the family Blenniidae and wrasses from the family Labridae behave in the same way.

In general, the larvae and fish fries species composition in ichthyoneuston and ichthyoplankton reflect the specific state of an MP ecosystem.

In Novorossiysk Bay, eggs and larvae from 31 taxonomic groups (14—migrating, 17—non-migratory) were found in the ichthyoplankton composition. In 2006, eggs and larvae of 27 fish species were found. In 2006, the average quantity

of ichthyoplankton in the aquatory of Novorossiysk MP comprised 9.2 ind. m^{-2} in vertical catches and 170 ind. 100 m^{-3} in horizontal ones. In July, spawns of anchovy (80.0%) and red mullet dominated. In July, the average quantity in the port decreased to 2.0 ind. m^{-2} and was 26.0 ind. m^{-2} outside it. These changes were likely connected with grazing of eggs and fish larvae by the zoophagous comb-jelly *M. leidyi* [156].

In 2007, eggs and fish larvae from 15 taxonomic forms were found, with eggs of anchovy (80.0%), horse mackerel and annular seabream being dominant. According to data of summer vertical catches, the average quantity of ichthyoplankton comprised 90.0 ind. m^{-2} in the port aquatory and 121.0 ind. m^{-2} outside the port aquatory. The ichthyoplankton density exceeded 100.0 ind. m^{-2} , which is similar to open waters indices, in most part of the port aquatory. However, the proportion of dead organisms and ichthyoplankton individuals with developmental anomalies was almost twofold higher (60.0%) in the port aquatory than outside its borders [156].

In 2008, 2009 and 2010, ichthyoplankton was represented by eggs and larvae of 11, 15 and 11 fish species, respectively [156].

In Tuapse MP, the species composition of eggs and larvae was poorer than in Novorossiysk MP and was represented by 17 species; 11 migratory ones and 6 non-migratory ones. The eggs of anchovy (70.0%), red mullet, horse mackerels and annular seabream prevailed [156]. Fifteen and 9 taxonomic forms were found in the port in 2009 and 2010, respectively [156].

In Tuapse port, the average quantity of ichthyoplankton was two to threefold lower and species composition poorer than in Novorossiysk MP in spite of the better water exchange [156].

The presence and abundance of forage zooplankton for larvae, juvenile and adult fish species in many respects determines the composition of ichthyofauna in MPs aquatories ecosystems. In MPs, the zooplankton biomass (mainly holoplankton) and its species composition fluctuate significantly over the years because of various causes, while species composition and concentrations of meroplankton are more stable.

Embryos, prelarvae, larvae and fries of fish are sensitive to different pollutants. In MPs, the amount of abnormal and nonviable prelarvae and larvae in ichthyoplankton composition increases because of constant or periodical pollution.

2.2.5 Nekton

In MPs aquatories, fish form the main mass of nekton; i.e. organisms able to swim actively in the water column, withstand water flow and cover considerable distances. Pelagic fish are typical nekton organisms of MPs. However, all fish species inhabiting on the bottom, pass some time in the water column. Many of them have pelagic stage of development and their larvae belong to nekton [4, 39, 40].

In marine ecosystems, feeding relationships are conditioned by the relative sizes of organisms. Although the ratio between the masses of predators and preys differs among species, the value of this ratio usually slightly exceeds 100. The corresponding ratio for predator vs. prey dimensions is approximately equal to 10. As both growth and mortality depend on age, the availability of food objects with the optimal target size decreases as the size of the predators increases. Big predators quite often encounter conditions in which they have to feed on preys with less than optimal sizes [103].

In MPs aquatories ecosystems, fish, like other big vagile organisms, are in constant search of food, while most of the mass forage planktonic or benthonic species are sedentary or completely motionless. Fish move to ecosystems zones with high densities of food, switching again to other regions when food density decreases below a certain threshold. This behaviour also allows the population of food objects to restore its biomass. In this scenario, fish and other big predators control aquatic ecosystems “from above” [8, 32].

Changes in the ichthyofauna composition of the Black and Azov Seas as a whole and also in their separate regions inevitably affect the biota of MPs aquatories. In the main Ukrainian MPs aquatories (Odessa, Ilyichevsk, Yuzhny), the quantitative and qualitative composition of ichthyofauna is tightly connected with processes occurring in the NWBS ecosystem (in particular in the estuaries and the near-estuaries zones of inflowing rivers) and directly in the Odessa region [39].

The peculiarities of underwater landscapes and hydrodynamics of MPs make them more attractive for fish of Mediterranean origin, inhabiting in stony and rocky regions that are not ecologically connected with the bottom. They mainly feed in the periphytal developing on HTS and include representatives of wrasses (Labridae), seabreams (Sparidae) and other families.

In MPs, fish species usually living on or near the bottom avoid hypoxia and anoxia by staying in the periphytal zone of HTS, where they feed and find shelter in the macrophyte belt and among bivalve druses.

In MPs, the summer season temperature is, as a rule, a couple of degrees lower at the depths of more than 5–10 m than at the surface. This circumstance allows coldwater fish such as the Mediterranean sprat *S. phalericus*, whiting *M. euxinus* and shore rockling *G. mediterraneus* to remain in deep layers of MPs water column.

We studied the ichthyofauna of MPs aquatories of the Black–Azov Sea basin in three ports: Yuzhny, Odessa and Ilyichevsk. These MPs are located in the Odessa region of the NWBS, between the mouths of Grigorievsky and Sukhoy Limans. Fish species composition in this region is determined by regional peculiarities of the ecosystems as well as by general seasonal and long-term processes, of both natural and anthropogenic origin, taking place in whole basin. About 150 fish species and subspecies were registered in the ichthyofauna of the NWBS. A couple of dozens of them have become extremely rare, or have completely disappeared, in the region. At the same time, there are data about the entrance of several other species in these waters. The presence of species found only in single specimen likely has a random character. More than 120 fish species directly inhabit in the NWBS [154].

Theoretically, all of them could be found in the aquatories of Odessa, Ilyichevsk and Yuzhny MPs.

Because of the run-off of the big rivers such as the Danube, Dniester and Dnieper with Yuzhny Bug into the NWBS, freshwater and diadromous fish can be found in the sea. Proper freshwater fish are represented by the families Cyprinidae (commonly called the carp family) and Cobitidae (commonly called the true loaches). The semi-anadromous fish could be ascribed to a special subgroup whose importance increases in desalinated waters and whose occurrence is delimited by the 10–12‰ isohaline. During strong floods, the freshwater diadromous and semidiadromous cyprinoids can reach the Odessa Gulf from the Dnieper-Bug Liman. Representatives of such fish include the following: vimba bream *Vimba vimba*, shemaya *Alburnus sarmaticus*, common bream *Abramis brama*, common carp *Cyprinus carpio*, sichel *Pelecus cultratus*, taran *Rutilus rutilus heckelii*, sheatfish *Silurus glanis*, pike *Esox lucius*, zander *Lucioperca lucioperca*, crucian carp *Carassius carassius* and other. In Yuzhny and Odessa MPs aquatories, they can survive for a couple of days to a couple of weeks.

Usually, up to 65–70% of fish of Mediterranean origin, the so-called Mediterranean immigrants, are present in the NWBS ichthyofauna composition. Their quantity decreases in desalinated regions.

Alien fish species occupy a special place in the ichthyofauna composition of the region. Prominent among them are the haarder *L. haemotocheilus*, especially brought from the Far East of Russia and perfectly acclimatized to the Black and Azov Seas, as well as the pumpkinseed sunfish *Lepomis gibbosus* which, apparently, was accidentally introduced.

The ichthyofauna of the NWBS has various reproductive strategies: (a) viviparous species (spiny dogfish *Squalus acanthias*, common stingray *Dasyatis pastinaca*); (b) fish spawning big capsules from which hatch formed fries with a length of about 12 cm (thornback ray *Raja clavata*); (c) fish producing bottom attached and protected (Gobiidae, Blenniidae, Gasterosteidae and Gobiesocidae) or unprotected (Belontiidae and Atherinidae) eggs; (d) fish producing bottom non-attached and guarded (Labridae) or unguarded (*Gimnammodytes cicerellus*) eggs; (e) fish carrying eggs on their body (Syngnathidae); and (f) fish producing pelagic eggs (Clupeidae, Engraulidae, Mugilidae, Mullidae, Sparidae, Scophthalmidae and others). Fish with pelagic eggs comprise about 30% of the entire ichthyofauna composition and usually reproduce far away from the shore [39].

According to their feeding strategy and food objects, fish present in the NWBS, can be divided into benthophagous (about 65%), plankton feeders (about 21%), predatory ichthyophagous fish (about 8%) and fish feeding on zoobenthos and other fish (about 7%). Species that feed on fouling and detritus (e.g. Mugilidae, Mullidae and others) are considered benthophagous.

In the NWBS, proper brackish water species constitute an important group. Among them there are typical species such as the Black Sea kilka *Clupeonella cultriventris*, the common percarina *Percarina demidoffi* and the large group of gobies (Gobiidae).

Marine temperate water fish are represented by eight species of the so-called Boreal-Atlantic relicts which are apparently remains of the Ice Age fauna. These are the spiny dogfish *S. acanthias*, the thornback ray *R. clavata*, the sprat *S. phalericus*, the Black Sea flounder *P. lucsus*, the haddock *M. euxinus*, the three-spined stickleback *Gasterosteus aculeatus*, the salmon *Salmo labrax* and the European eel *Anguilla anguilla*.

Marine thermophilic fish are the mass group of fish in the region. Among them there are highly euryhaline forms that enter even freshwaters, such as some sea needles (Syngnathidae) and grey mullets (Mugilidae). In general, these are Mediterranean immigrants. Part of them has evolved into Black Sea local subspecies, differing from initial forms by a series of morphological characteristics and with regard to size.

The gobies, herrings and sturgeons are most characteristic for the NWBS. The following species are recorded practically everywhere: the Black Sea sand smelt *A. pontica*, the Black Sea grey mullets (striped mullet, golden grey mullet, leaping mullet), haarder, red mullet *M. ponticus*, greater weever *T. draco*, stargazer *U. scaber*, the Black Sea flounder *P. lucsus*, spiny dogfish *S. acanthias*, anchovy *Engraulis ponticus*, sprat *S. phalericus*, whiting *M. euxinus* and others.

In the NWBS, the qualitative composition of ichthyofauna and its distribution depend on seasonal temperature changes which control spawning and feeding migrations. In autumn, the absolute majority of species moves away from the shore to return back to it in spring.

During the last decades, a significant reorganization in the quantitative and qualitative composition of the NWBS ichthyofauna took place because of different causes. The stocks of long-lived, large-sized commercial fish (sturgeons, the Black Sea turbot *P. maeotica*, large-size herrings, big-sized gobies) have sharply reduced and the Atlantic bonito *Sarda sarda*, the common bluefish *Pomatomus saltator* and the Atlantic mackerel *Scomber scombrus* have almost stopped to approach the shore.

Seventy-one fish species, belonging to 34 families, are indicated in the composition of the NWBS coastal ichthyofauna, including marine Mediterranean and Boreal species, Caspian relicts and acclimatized species. Near-bottom benthic forms prevail everywhere. Forty-one species of fish were found near Odessa city shores. In the aquatory of Grigorievsky Liman, subject to the strong influence of the Dnieper-Bug Liman waters, marine Mediterranean migrants comprise 59% of the total species [154, 184].

In various years and seasons, the following 48 fish species were found in various parts of Grigorievsky Liman after its junction with the sea: spiny dogfish *S. acanthias*, the Russian sturgeon *Acipenser guldenstadtii*, stellate sturgeon *A. stellatus*, the Black Sea sprat *C. cultriventris*, sprat *S. phalericus*, the Black Sea herring *Alosa pontica*, the Black Sea shad *A. tanaica*, European anchovy *E. encrasicolus*, the Black Sea salmon *S. labrax*, European eel *A. anguilla*, garpike *B. euxini*, rockling *G. mediterraneus*, haddock *M. euxinus*, the three-spined stickleback *G. aculeatus*, stickleback *Pungitius platygaster*, sea horse *Hippocampus guttulatus*, straightnose pipefish *Nerophis teres*, black-striped pipefish *Syngnathus nigrolineatus*, pipe fish *S. argentatus*, flathead grey mullet *M. cephalus*, haarder

L. haemotocheilus, golden grey mullet *L. aurata*, leaping mullet *L. saliens*, the Black Sea sand smelt *A. pontica*, horse mackerel *Trachurus mediterraneus*, picarel *Spicara flexuosa*, red mullet *M. ponticus*, grey wrasse *Symphodus cinereus*, ocellated wrasse *S. ocellatus*, rusty blenny *Parablennius sanguinolentus*, tentacled blenny *P. tentacularis*, sphinx blenny *Aidablennius sphynx*, transparent goby *Aphia minuta*, grass goby *Gobius ophiocephalus*, black goby *G. niger*, toad goby *Mesogobius batrachocephalus*, ginger goby *Neogobius cephalarges*, monkey goby *N. fluviatilis*, round goby *N. melanostomus*, ratan goby *N. ratan*, racer goby *N. gymnotrachelus*, Caucasian dwarf goby *Knipowitschia caucasica*, sand goby *Pomatoschistus minutus*, marbled goby *P. marmoratus*, tubenose goby *P. marmoratus*, the Black Sea turbot *P. maeotica*, the Black Sea flounder *P. luscus*, and sand sole *P. lascaris* [39].

In Odessa Gulf, other species rather exotic for the region were also observed besides those found in Grigorievsky Liman, including: common stingray *Dasyatis pastinaca*, sea scorpion *S. porcus*, painted comber *Serranus scriba*, annular seabream *D. annularis*, shi drum *Umbrina cirrosa*, sea mouse *C. risso*, European barracuda *Sphyaena sphyraena*, St. Pierre fish *Zeus faber*, flying gurnard *Cephalacanthus volitans* and beardless tadpole goby *Benthophiloides braueri* [154].

In the apical part of Sukhoy Liman, which experiences significant freshening influence from the Bolshoy Dalnik River, up to 11 species of freshwater fish have been recorded [162]. In Sukhoy Liman, marine fish of Mediterranean and Caspian origin and two species of sticklebacks constitute the basis of ichthyofauna.

The annular seabream occurring in Odessa MP aquatory can survive in the salinity range 8.0–37.5‰, but spawns only at salinities higher than 16.0‰. It is a typical inhabitant of the *Cystoseira* biocenosis [151] and it probably enters into Odessa Gulf with the cyclonic water circulation. It feeds on microfouling and, apparently, finds the food it needs in the periphytal zone of Odessa MP.

The transparent goby has a certain importance in the ecosystems of Odessa, Ilyichevsk and Yuzhny MPs. Schools of this nearly transparent fish, with a length of 3–4 cm, are found in the water column close to the lateral surfaces of HTS. Here also live fish from wrasses family (Labridae), needlefishes and sea horse (Syngnathidae). In MPs, combtooth blennies (Blenniidae) and some gobies (Gobiidae) are often observed. Most fish encountered in the water layer adjacent to HTS are big-sized grey mullets such as the striped mullet and the golden grey mullet.

In MPs, the silts contaminated by hydrogen sulphide are avoided even by bottom and near-bottom-dwelling fish that are resistant to lowered oxygen concentrations.

Fifty-eight species of marine fish are present in the composition of Odessa Gulf ichthyofauna. In Sukhoy Liman and in the adjacent part of the Black Sea, representatives of 58 fish species were also found during 40 years [154]. The ichthyofauna of Grigorievsky Liman comprises 48 fish species [196].

The aquatory of Grigorievsky Liman is characterized by the nearly constant presence of whiting which usually occurs in water masses with a temperature range from 5 to 15–16 °C. This euryhaline fish spawns in the upper water layer in winter.

Juvenile whiting lead pelagic life and feed on plankton. Adult individuals stay in the near-bottom water layer and are near-bottom pelagic predators. A significant number of whiting individuals is eaten by spiny dogfish, turbot and dolphins.

The whiting is an intermediate predator along the food chain. In the early stages of its development, it connects plankton with small-sized fish (sprat, anchovy, horse mackerel, gobies) and invertebrates (shrimps, crabs, etc.) and, in its adult stage, with big-sized predators (spiny dogfish, rays, turbot, dolphins) [30].

In Odessa, Ilyichevsk and Yuzhny MPs, the sand smelt and grey mullets are the most common mass nekton representatives. Mass entries of anchovy, sprat and horse mackerel are occasionally observed. Spiny dogfish and striped mullet are the biggest nekton organisms among fish of these ports.

In MPs aquatories, big-sized specimen of the jellyfish *A. aurita* and of the root-mouthed jellyfish *R. pulmo* can also be ascribed to nekton. The dice snake *Natrix tessellata*, which feeds mainly on gobies and creeps out on land with its prey, can be quite often observed in Sukhoy and Grigorievsky Limans. Small schools of the short-beaked common dolphin *Delphinus delphis* sometimes enter Odessa, Ilyichevsk and Yuzhny MPs aquatories in the spring-autumn period.

Nekton organisms actively participate in BM uptake from MPs ecosystems.

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