Physical and Geographical Description of the Boka Kotorska Bay

Sreten Mandić, Ivica Radović, and Dejan Radović

Abstract Compared to other parts of the Adriatic Sea, the Boka Kotorska Bay represents a unique and specific entity with its geographical position and geomorphological, climatological, hydrological and biotic characteristics. The sea deeply penetrates into the continent making it a unique fjord with the Mediterranean climate. The bay coastline length is 105.7 km, and the entire bay can be divided by its geographic–hydrographic properties into three entities: (1) the Kotor–Risan Bay, (2) the Tivat Bay and (3) the Herceg Novi Bay.

In biogeographical terms, the area of the Boka Kotorska Bay belongs to the Mediterranean region of the Adriatic–Ionian subregion of the Adriatic province characterised by sclerophyllous forest vegetation of the *Quercion ilicis* community and its derivatives in the form of shrubby formations of the type maquis, garrigue and rocky vegetation.

In the interior of the bay, in the base of mountains Lovćen, Orjen and Vrmac, there are small picturesque settlements creating an atmosphere of a nostalgia for history with all the magnificent old palaces, churches, cathedrals, towers, fortresses, defensive walls and similar. Almost 70% of all historical and cultural monuments of the whole of Montenegro are situated on the territory of the Municipality of Kotor.

The Boka Kotorska Bay (inner part from the Verige Strait: the Kotor–Risan Bay) was included in the UNESCO's list of cultural and natural heritage of the humankind at the conference held on 22–26 October 1979, in Cairo-Luxor, for the purpose

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of preservation and valuation of authentic geological, geomorphological, biological and cultural heritage.

Keywords Aquatorium (hydrographic and oceanographic characteristics), Boka Kotorska Bay, Geographical features (morphogenesis, geomorphology, hydrology, climatology), Terrestrial ecosystems, vegetation

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1 Introduction

South Adriatic – that the Boka Kotorska Bay is a part of (Fig. 1) – is differentiated from other parts of the Adriatic by the biggest water mass of 26,000 km^3, compared to the total of 32,000 km^3 of the sea in the entire Adriatic, with the deepest part of the sea at 1,330 m, the fastest sea currents (42–88 cm/s, which is up to 6 times the speed of the current in other parts of the Adriatic), the more intensive direct water exchange with the Mediterranean as well as the greatest water transparency, reaching up to 60 m [1–3].

Indeed, all these abiotic parameters provide conditions for diversity in flora and fauna of the South Adriatic, which is incomparably higher than the biological diversity in the northern part. As an illustration of the biodiversity of the South Adriatic, or more specifically – Montenegrin Coast, we can present the fact that out of 435 fish species in the Adriatic, the South Adriatic is inhabited by 402 species, while out of 101 species of Echinodermata of the Adriatic, 57 species are found in the Montenegrin Coast and 42 species are present in the Boka Kotorska Bay [4–6]. The Montenegrin Coast itself covers a narrow strip of land extending from Debeli Brijeg on the north-west to the Bojana River on the south-east, with the total coastline length of 294 km, of which 105.7 km belongs to the Boka Kotorska Bay. To the north and north-east, the Montenegrin Coast is surrounded by steep slopes of the mountains Orjen (1895), Lovćen (1749), Sutorman (1180) and Rumija (1595) that divide it from the hinterland – the karst area and the Zetsko–Skadarska

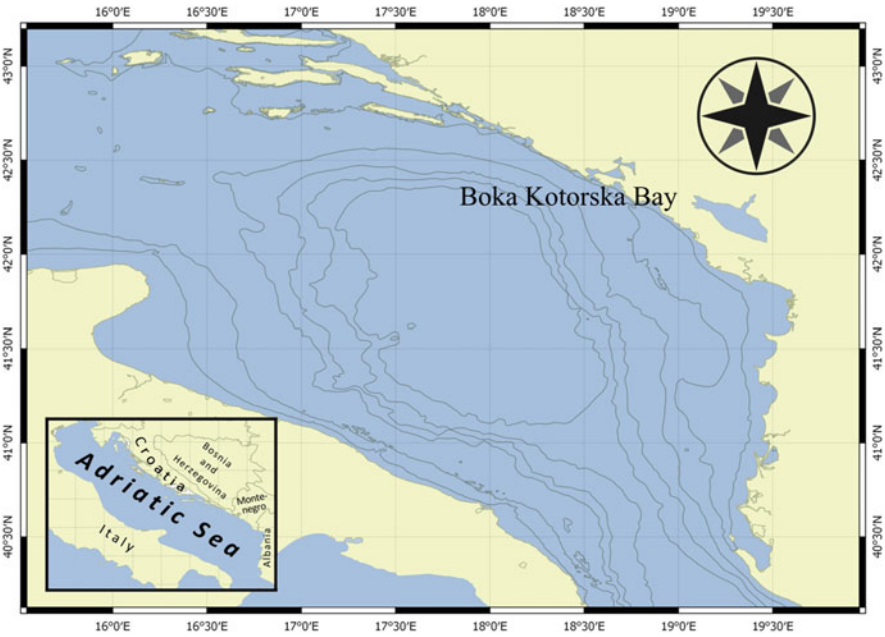

Fig. 1 South Adriatic and position of Boka Kotorska Bay [34]

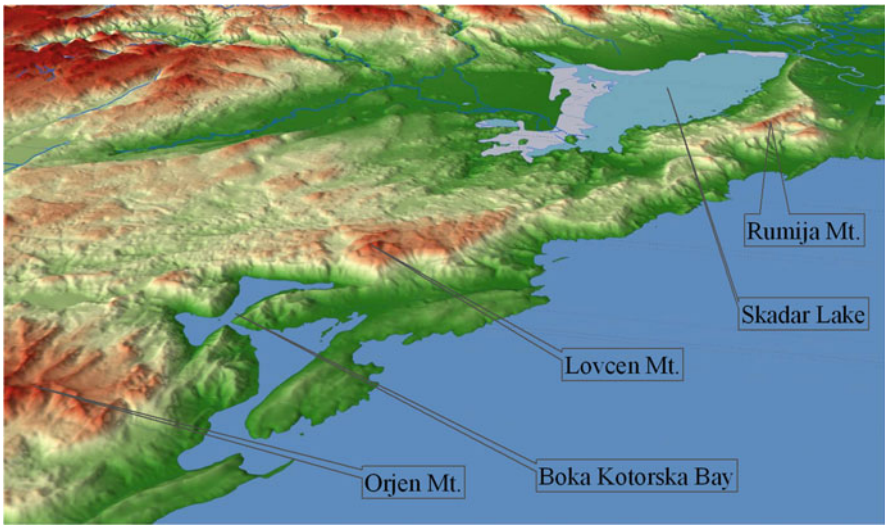

Fig. 2 Montenegrin Coast with the Boka Kotorska Bay [23]

depression (Fig. 2). There are numerous bays, inlets, flysch-like and sandy parts of the coast (beaches) with limestone capes (cliffs), spurs and crests, famous for numerous rock shelters and caves [7, 8].

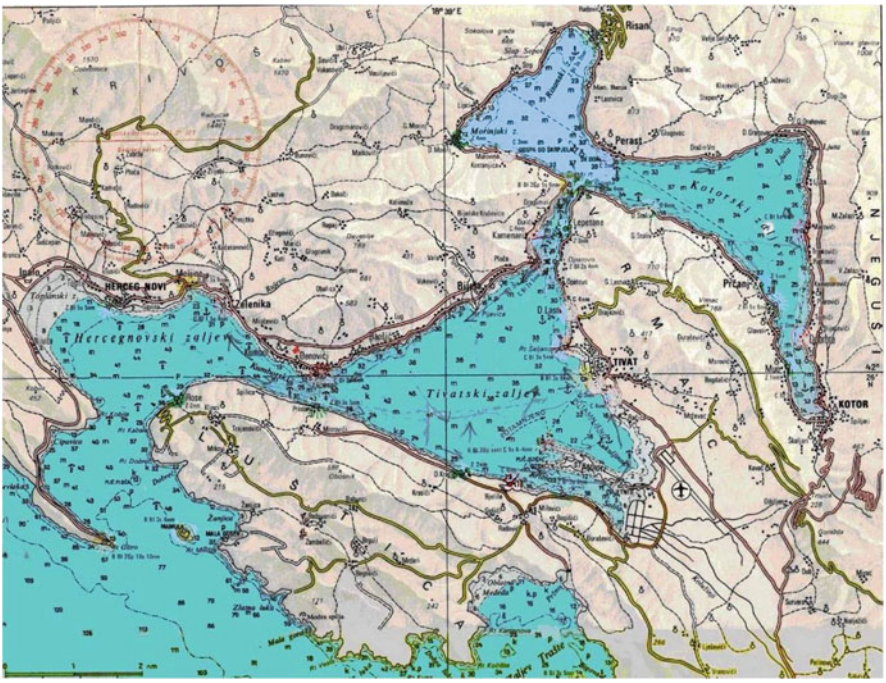

Fig. 3 The Boka Kotorska Bay – topographic map [34]

The Boka Kotorska Bay – one of the most beautiful, not only in the Adriatic, but in the Mediterranean – is clearly distinct in the indented coastline of this part of the Adriatic Sea. Compared to other parts of the Adriatic Sea, the Boka Kotorska Bay represents a unique and specific entity with its geographical position and geomorphological, climatological, hydrological and biotic characteristics. The sea penetrates into the continent deeply (a unique fjord with the Mediterranean climate) through two narrow channels (Kumbor and Verige), after which bays with expansion of around 36 km^2 open up (Fig. 2) [7, 9, 10]. In the interior of the bay, in the base of mountains Lovćen, Orjen and Vrmac, there are small picturesque settlements creating an atmosphere of a nostalgia for history with all the magnificent old palaces, churches, cathedrals, towers, fortresses, defensive walls and similar. Almost 70% of all historical and cultural monuments of the whole of Montenegro are situated on the territory of the Municipality of Kotor. These are surrounded by Mediterranean vegetation of olive, oleander, laurel, pomegranate, evergreen oak and chestnut trees (Fig. 3).

Due to all stated above, it is more than justified that the Boka Kotorska Bay (inner part from the Verige Strait, the Kotor–Risan Bay) was included in the UNESCO's list of cultural and natural heritage of the humankind [11] (Fig. 4), by the World Heritage Committee at the conference held on 22–26 October 1979, in Cairo-Luxor (Egypt), for the purpose of preservation and valuation of authentic geological, geomorphological, biological and cultural heritage.

Fig. 4 UNESCO, World Heritage, Kotor [11]

2 Geographical Features

2.1 Morphogenesis and Geomorphological Characteristics

As already stated, the Boka Kotorska Bay consists of an intersection of intertwined gorges and steep, almost vertical escarpments, surrounding four sub-entities within the bay. The sea penetrates deepest into the continental limestone mass in the base of the Orjen and the Lovćen, thus making the overall geomorphological structure quite diverse and specific.

Complex hydrological and hydrogeographical characteristics of the karst in the Montenegrin Coast resulted in quite pronounced differences in the explanation of morphogenesis and formation of the Boka Kotorska Bay. Thus Savicki, 1912 [from

10], believes that "detailed forms of the Bay were formed by river erosion, but tectonic predisposition must not be forgotten". An identical view is shared by Milojević [12] who underlines that this area was most probably formed by a combined action of tectonic forces and fluvial erosion.

According to Cvijić [13, 14], the Boka Kotorska Bay was formed by the rising of surrounding mountains during the Pliocene and Pleistocene. Before that, in Cvijić's opinion, the Grahovska River used to flow there, "karsted parts of which are protected from Grahovo, along Dvrsno and Krivošije to Risan", followed by the flooding of two parallel valleys – the Hercegnovski–Tivatska and the Morinjsko–Kotorska, considered to be mouths of the former Grahovska River and other smaller watercourses. These two valleys are connected with the erosion rupture Verige, 300 m in width.

However, Radjičić [10, 15, 16] challenges this explanation of the Boka Kotorska Bay formation, stating that today there are no traces of a canyon valley that should have been preserved in the limestone had the "Grahovska River" ever flowed through it. In his view, the Boka Kotorska Bay, just like all the fields in karst, was created in the Pliocene by denudation and fluvial erosion on flysch and intensive corrosion in limestone in zones of contact with flysch.

Steep slopes of the Orjen and Lovćen create the dominant framework of the Boka Kotorska Bay, as well as ridges that connect them. Their parts from Morinj to Kotor, as pronounced karst areas, have very steep cliffs, while in other parts, they lean on younger flysch sediments in the form of overlap faults and overthrust (Figs. 2 and 5). In difference to pronounced karst slopes, flysch slopes are much milder, and in some places, they develop into small basinlike and plain-like parts. The Orjen itself is a quite distinct mountain massif with steep slopes spreading in all directions, except towards the Bijela Gora. It is characterised by quite pronounced forms of karst relief formed by erosion and glaciation. These are primarily depressions and sinkholes, but many other karst relief forms are also present. Glaciation process on the Orjen was intensive, and glaciers had significantly modified the karst relief in their respective directions of movement [17].

The Lovćen and the Orjen rise above the Boka Kotorska Bay almost vertically and then descend more gently towards the hinterland – the plateau of the Katunski Krš, with Njeguško and Cetinjskog Fields, as well as the plateaus Krstac and Ivanova Korita, numerous depressions, hillocks, etc. (Fuštić, Đuretić, 2000) (Fig. 5). Glaciation process on the Lovćen was less intensive than on the Orjen. Nevertheless, glaciation traces can be seen primarily in moraines towards Njeguši, Krstac and Cetinjskog Fields [18].

Eocene flysch parts occur in several places on the territory of the Boka Kotorska Bay. First of all, Sutorinsko–Grbaljska flysch zone can be distinguished, spreading from the Debeli Brijeg through Sutorina and then from Tivat to Jaz. Flysch zones can be seen also around the Morinjski Bay and around Risan, Orahovac and St. Trinity above Kotor [19]. Sutorina is a valley around 7 km in length and 3.5–4 km in width. From the valley, along its right side, the headland and ridge Oštra (361 m) rises, ending with the ridge Kobila and the Prevlaka. Numerous plateaus, floors and slopes spread in various elevations from Sutorina to Morinj.

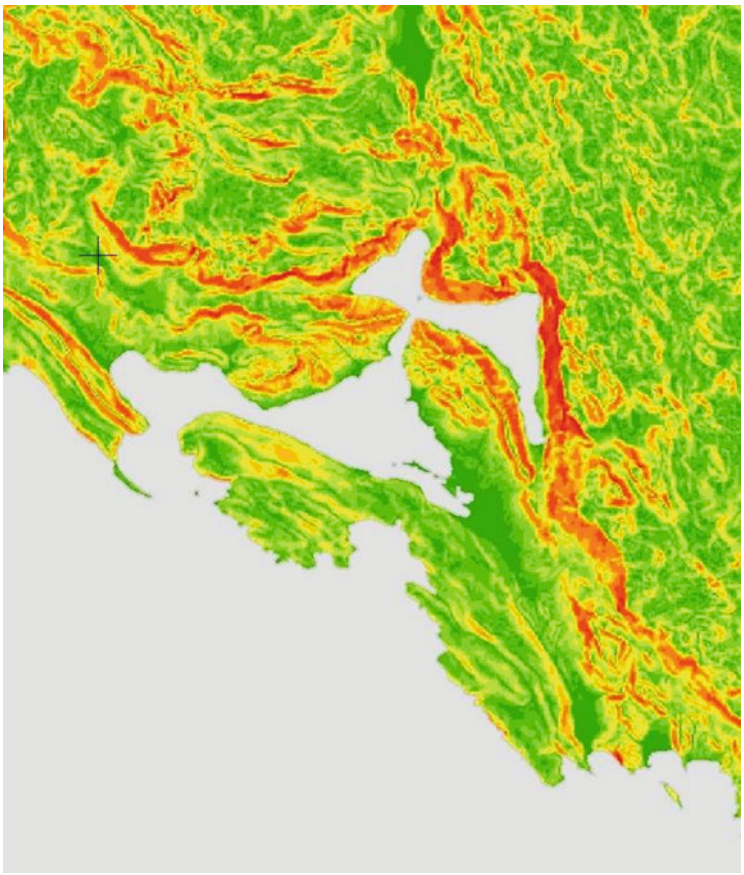

Fig. 5 Boka Kotorska Bay – terrain slope angles [23]

Relief forms are milder from Igalo to Savina, as well as around Zelenika. Steeper terrain can be found on the Devesilj Hill, western slopes of which descend steeply towards Zelenika; south and east slopes descend towards Đenovići, Baošići and Bijela; and on the northern side towards Morinj. The flysch steep terrain spreads further to Vrmac (768 m), northern slopes of which are characterised by a large number of parallel gullies. East of the Tivat Bay towards Jaz, Tivatsko, Grbaljsko and Mrčevo Fields spread out. From these fields, the flysch zone gradually rises towards the Lovćen through mild slopes, terraces and rounded hummocks. The transition from the Tivat Bay and Tivatsko Field into the Luštica Peninsula (around 50 km^2) is also gradual. The Luštica is a flat land with several sinkholes, depressions, passes and ridges. Towards the inner part of the Boka Kotorska Bay, the Luštica Coast is steeper and unindented, while the part towards the open sea has a larger number of capes (8) and coves (9). The Grbaljsko Hill has a similar relief, with a depression stretching over the middle part from the Trašte Bay to the Trsteno

Bay, while the relief towards the open sea is characterised by a large number of capes, coves and steep cliffs.

2.2 Climatological Characteristics

Climatic factors having a major effect on the climate of the entire Montenegrin Coast and hence the Boka Kotorska Bay are latitude and vicinity of the sea and the vegetation cover. Montenegrin coastline belongs to modified Mediterranean or Adriatic climate. The water mass of the Mediterranean and its part of the Adriatic Sea has a more than distinctive effect on the climate of this area. Namely, intense cyclone activity over the Mediterranean in the colder half of the year – and over Africa throughout the year – brings rainfall. On the other hand, during summer period, high-pressure field forms above the Mediterranean Sea, causing calm, warm and sunny weather. Furthermore, it is also necessary to state that the Adriatic Sea belongs to warm seas, so that too is one of the important parameters of climatic characteristics of the Boka Kotorska Bay [20]. The specific and very dynamic relief of the Boka Kotorska Bay also has a significant effect on climatic characteristics. Mean annual temperatures decrease for every 100 m of altitude by 0.6°C, while precipitation rises to an elevation of up to 1,100 m. The climate is also influenced by the direction of relief forms, their concavity, slope angles and exposition. All of this results in higher daily and annual temperature amplitudes in sites and locations farther from the sea.

Mean annual air temperatures of the entire Montenegrin Coast, including the Boka Kotorska Bay, are high, ranging from 14.8°C Tivat, 15.6°C Bar and Ulcinj, 15.7°C Herceg Novi and 15.8°C Budva [7, 21, 22]. Summer periods are long in the entire Montenegrin Coast as the Adriatic Sea, being a warm sea, does not have a major cooling effect on the coast. Mean air temperature in summer in Herceg Novi is 23.2°C, while the extreme maximum air temperature recorded in Herceg Novi is 42°C. Annual mean number of summer days (temperature above 25°C) in the Boka Kotorska Bay is around 110. Frosts occur rarely even in winters, so mean air temperature in winter period in Herceg Novi is 8.8°C, with extreme minimum temperature in Herceg Novi of −7°C (Fig. 6).

Annual rainfall distribution and precipitation are among the most important climatological parameters determining the climate of the Boka Kotorska Bay. Average precipitation on the whole territory of Montenegro is heterogeneous. Average precipitation in the wettest areas of Montenegro is almost 6 times average precipitation in the least rainy areas. It is the south-western part of Montenegro – the area of the Orjen Mt, with the highest annual average precipitation ranging from 3,000 to 5,000 mm. The highest precipitation in the area of the Orjen Mt. is in Crkvice (1,097 m) above the Risan Bay, with annual average precipitation of 4,742 mm, which is the European maximum rainfall. The maximum annual precipitation in Crkvice was recorded in 1,938–8,063 mm [10]. The mean rainfall in Herceg Novi is 1,940 mm (665 mm in winter, 190 mm in summer), while in Tivat it

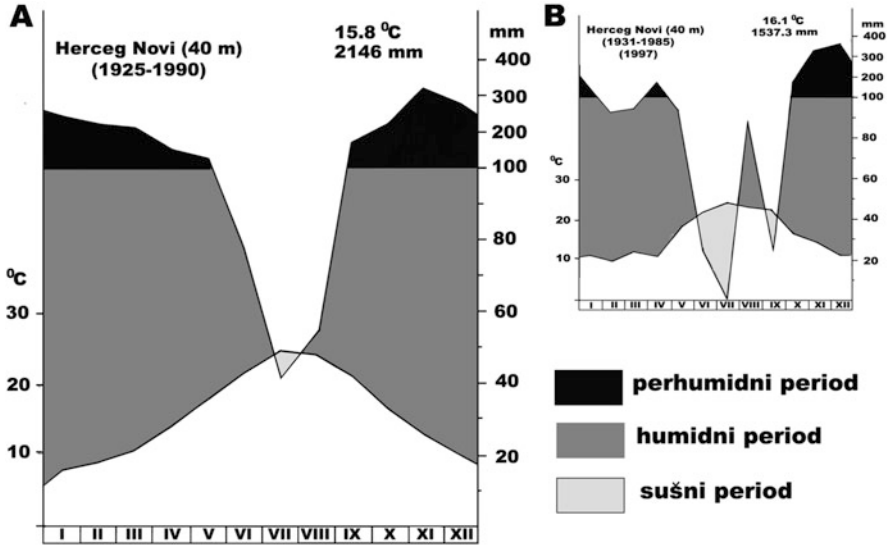

Fig. 6 Climographs of Herceg Novi, (**a**) for period 1925–1990, (**b**) for period 1931–1985 [24]

is 1,674 mm (55 mm in winter, 19 mm in summer). The highest mean monthly precipitation are in November and December in Crkvice – 706 mm. High rainfalls in the Boka Kotorska Bay can sometimes happen in just 1 day. There have been several occasions where rainfall of above 400 mm was recorded in a single day in Crkvice, and on 21 November 1927, the precipitation was 480 mm [10, 23] (Fig. 7).

The above-mentioned annual and maximum monthly precipitation results from air circulation from the south and the Orjen massif spreading perpendicular to the wind direction. In pluviometric regime, the Boka Kotorska Bay is characterised by pronounced aridity in summer periods. This is caused by low precipitation and high temperatures in late spring, summer and early autumn. In some years, dry period can begin in spring and last till late autumn. Such precipitation and rainfall distribution, along with complex geological composition, soil structure and relief not only cause specific and diverse hydrological phenomena and forms in the entire terrestrial part of the Boka Kotorska Bay, it also makes hydrological properties of the seawater of the Boka Kotorska Bay quite specific, almost unique, primarily in terms of high-salinity variation amplitudes (summer–winter period).

Apart from temperatures, it is the winds, their direction, frequency and notably intensity, that form an important climatic element of the Boka Kotorska Bay. It could be generally said for Montenegrin Coast that south-east and east winds prevail. Thus, in Herceg Novi the most frequent wind is east (11.9%), south-east (10.3%) and south (8.6%), while calm periods (no wind), resulting from its sheltered position, account for 40% [24] (Fig. 8). In general, locations in the Boka Kotorska Bay have far more calm periods during the summer period of the year than in winter, opposite to the inland parts of Montenegro where the number of calm periods is higher in winter [7]. Winds characteristic of the Boka Kotorska Bay are

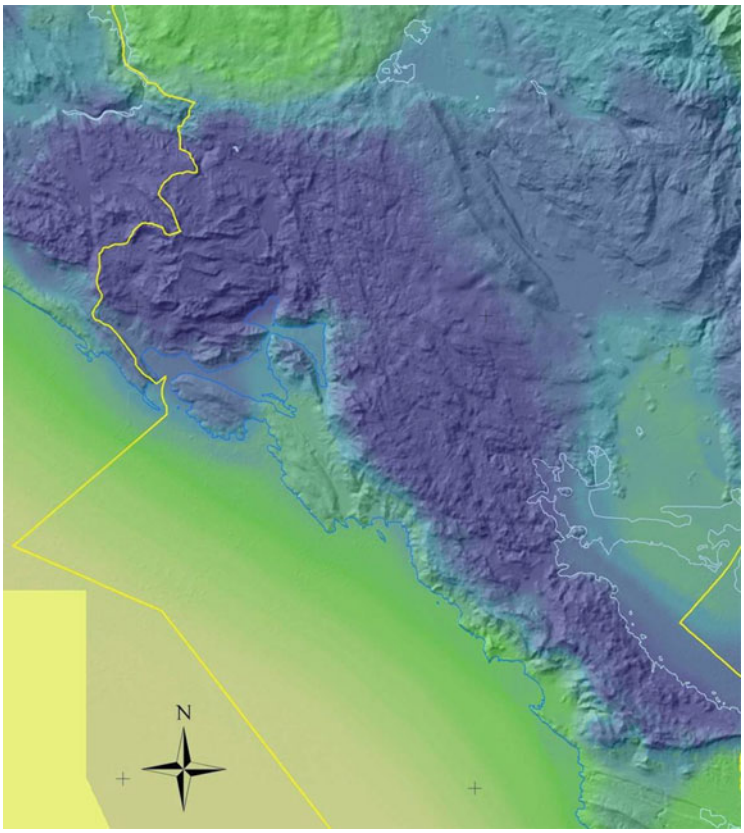

Fig. 7 Winter period precipitation on Montenegrin Coast [23]

Bora, Sirocco and Mistral. Bora blows from the north and north-east. It is mainly katabatic strong anticyclonic, rarely cyclonic wind, plummeting temperatures, reducing cloudiness and air humidity. In the area of the Boka Kotorska Bay, Bora "flows over" the mountain massifs of the Orjen and Lovćen bringing significant temperature drop. It usually blows 3–7 days. In the Boka Kotorska Bay, widely known by intensity are Orahovac Bora and Risan Bora. Bora as a wind has a significant effect on the seawater quality in the bay, since it creates short and strong waves, particularly in winter, which significantly contribute to seawater aeration, that is, increases dissolved oxygen levels.

Sirocco is a warm wind from the southern quadrant, bringing clouds and heavy rainfall. Sometimes it blows for several days at the same speed, as a strong, but rarely stormy wind. When a strong south flow of Africa, bringing volcano dust or volcano ash, penetrates the warm cyclone sector from the Western Mediterranean, it can cause yellow or red rain in the Montenegrin Coast. The air mass it carries, rising up in the coastal mountains Orjen, Lovćen and Rumija in the hinterland, gets the characteristics of the Foehn (south Foehn) and can cause a sudden rise in

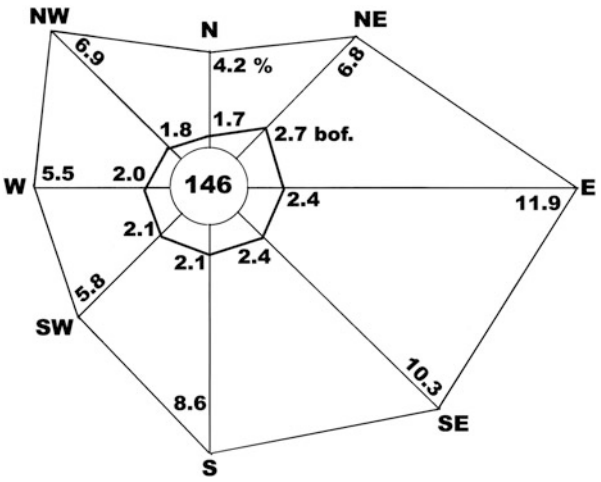

Fig. 8 Wind rose diagram for Herceg Novi [23]

temperatures in winters, followed by snow melting and flooding (typical for the Cetinjskog Field – flood of 1986). Bora and Sirocco blow throughout the year, but they blow more frequently during the winter half of the year [10].

Mistral is a south-west and west wind. It is an even, clear sky wind blowing from the sea towards the land, bringing pleasant refreshment in hot summer days. It is very good for sailing.

Burin, also known as night wind (*noćnik*), blows from the shore towards the sea at nights, particularly after the rain, in mountains close to the sea.

The most frequent wind throughout the year in the Boka Kotorska Bay is south-west (15%), with N, NE and SE equally represented with around 8% each; all other directions are much less frequent. On average, the strongest are N and NE winds with the mean Beaufort force 3.9 and 3.2, respectively [9].

In general, according to the Koppen climate classification, the Boka Kotorska Bay climate belongs to the Mediterranean climate, characterised by hot summers and pronounced summer droughts. Average temperature of the coldest month is above −3°C and below 18°C. Average temperature of the warmest month is above 22°C. This climate type is characteristic for the entire Montenegrin Coast and the area of the Zetsko–Bjelopavlicka Plain [22, 24]. More specifically, the climate of the Boka Kotorska Bay belongs to a perhumid Mediterranean climate type, characterised by high rainfall in winter and spring and even higher in autumn and winter, with a very short dry period in July–August (Fig. 9).

2.3 Hydrographic and Hydrological Characteristics

The entire area of the Boka Kotorska Bay belongs to the Adriatic Sea Basin, and it could be said that it has a poorly developed network of surface watercourses,

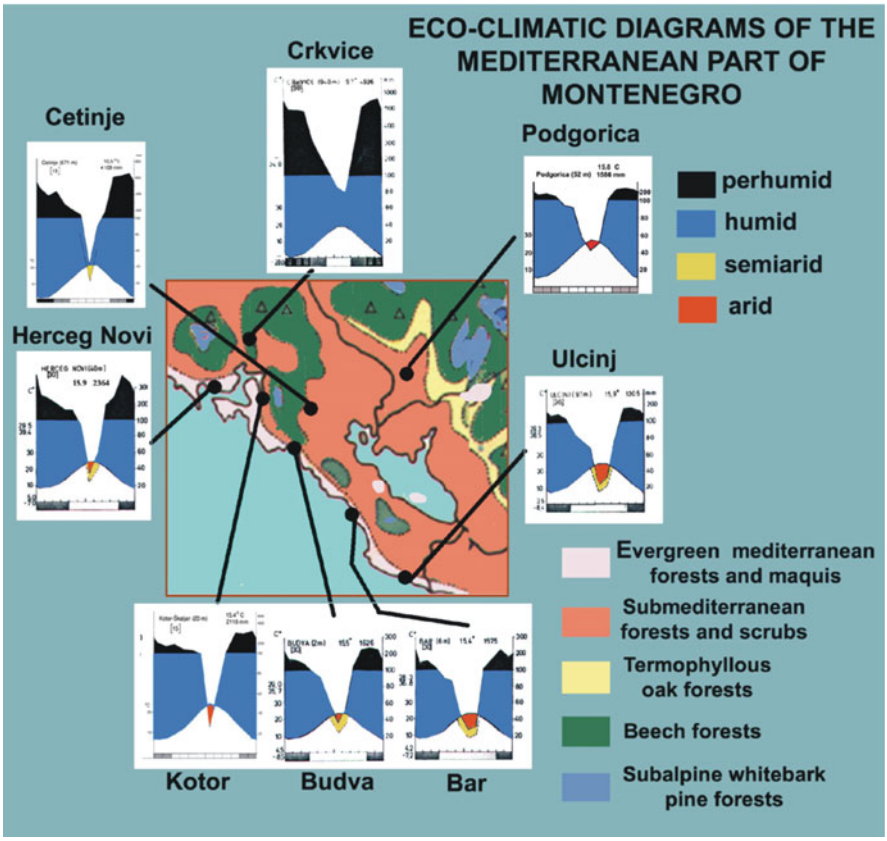

Fig. 9 Ecoclimatic diagrams of the Mediterranean part of Montenegro [24]

resulting primarily from geological structure of the terrain dominated by carbonate rocks, where waters are lost to the highest depths. As regards surface watercourses, in the area of the Bay of Boka Kotorska it consists of a network of short rivulets and brooks, the largest of which is the Sutorina River, in the vicinity of Herceg Novi. On the other hand, groundwaters and ground watercourses in karst are quite specific and complex. Development and circulation of ground holes in limestone take place to their lower limit, often several hundred and even thousand metres below sea level. In the area of the Boka Kotorska Bay, three directions of groundwater movement have been identified. An underground hydrological network was identified between the Grahovska River and Spila well in Risan. Karst valley Trešnjevo drains underground towards the Ljuta well near Orahovac, and underground hydrological connections between the well Ljuta and swallow hole Erakovići in Njeguško Field have been identified. The swallow hole Erakovići supplies the wells Škurda and Gurdić in Kotor with water. Gurdić well receives water by underground conduits from the pit Duboki Do in Njeguško Field, as well as from the swallow hole in Ivanova Korita [10].

Wells and springs are doubtlessly the most interesting forms of all hydrological phenomena in the karst of Montenegro and hence of the Boka Kotorska Bay. Well systems occur in karst, where karst erosion or tectonics created deep gorges where the extensive network of groundwaters is collected. In the area of the Boka Kotorska Bay, there are Morinjska wells, Sopot and Spila near Risan, wells Škurda and Gurdić in Kotor and well Ljuta near Orahovac. In winter part of the year, these wells give approximately 230 m/s of water, on average. In addition to these six wells, the narrow coastal strip between Kotor and Morinj (25 km), 200 m in width, also has a larger number of smaller brackish (briny) wells, so the total number of wells is much higher than anywhere else in the Adriatic–Dinaric Coast [10, 21].

Submerged springs present a specific hydrological phenomenon in karst and they are a special type of springs. These are freshwater springs occurring on the bottom of the sea. They occur when the pressure of freshwater in the underground canal is higher than the pressure of seawater on the canal opening. Well Gurdić in Kotor has characteristics of a submerged spring, and in rainy period of the year, it is rich in freshwater bursts below the sea level. In addition to Gurdić, submerged springs occur in the Boka Kotorska Bay under the steep slopes of the Lovćen between Ljuta and Perast, as well as under the slopes of the Orjen between Risan and Morinj. Submerged spring Risanska, immediately below the Sopot well, is among the most interesting in this area.

In the farthest north-west part of the Boka Kotorska Bay, the major wells can be found in the area of Mokrin, Sutorina and Mojdež. Mokrin wells, extending from the north-west towards south-east, are joining the Morinj wells. The abundance of Mokrin wells is illustrated by the fact that they are included in the water supply system for the population of Herceg Novi. The spring Opačica is situated in the suburban zone of Herceg Novi (Zelenika); it is a spring cave with a complex hydrological network below the sea. Opačica is the only well in the Boka Kotorska Bay whose water does not get salty in summer. In winter, with higher inflow, Morinjska wells supply freshwater, and that is the period when smaller wells (submerged springs), up to 800 m away from the shore, become active. Sopot (by the road Morinj–Risan, 800 m from Risan) is a very specific well. It bursts at the elevation of 40 m from a cave with the entrance of 10 m in width and 4 m in height. Risanska submerged springs are just in front of Sopot and they are hydrologically connected below the sea level. During heavy rainfall, channels of submerged springs cannot absorb all the water, and a part of it bursts via sinkhole channels through the Sopot well, whose water flows into the sea in the form of a waterfall from a height of 40 m. During heavy rainfall, in winter, the abundance of the Sopot can reach 150 m^3/s [10]. Apart from Sopot, Risanska wells include also Spila, north-west from Risan, 300 m from the coastline. The spring orifice is approximately 10 m above the sea level, 8 m in width and 3 m in height. Hydrological explorations identified a connection between the Spila well and the swallow hole in the Grahovsko Field. In rainy period, Spila waters are used to supply Risan with water [10].

The most important well in the area of Orahovac is Ljuta, which is the most abundant brackish well in the Boka Kotorska Bay. The well bursts in the immediate

vicinity of Orahovac, on the road to Kotor, between large, steep blocks of rock, above which vertical slopes around 900 m rise. Its abundance is estimated at 300 m^3 /s of water during the periods of heavy rainfall. In rainy period, watercourse Ljuta, around 100 m in length, is formed from the well to the shore.

Kotorska wells – Tabačina, Škurda and Gurdić – are situated immediately by the walls of the Old Town of Kotor. Wells Tabačina and Škurda are captured wells and used to supply the town of Kotor with water (until construction of the regional waterworks supplying water from the Skadar Lake). In times of heavy rainfall, up to 230 l/s of water was pumped. In summer, salinity rose and water could not have been used for drinking. After the catastrophic earthquake struck the Montenegrin Coast in 1979, attempts were made to prevent the influence of the sea and salinisation during summer by injection curtain, but the attempt resulted in a complete failure due to complexity and integrity of the underground hydrological network of Kotor. Hydrological exploration identified an underground connection between the swallow hole Duboki Do in Krstac and these wells. The third of Kotorska wells is Gurdić, located in front of the east gate of the Old Town, and it is a complex well system – brackish well, estavelle and submerged spring. The well orifice is located 12 m below the sea level. It is supplied with freshwater from the Lovćen (Njeguško Field and Ivanova Korita) and its highest abundance is approximately 30 m^3/s. In summer months, when inflow of freshwater is reduced, the estavelle is filled with seawater [10].

In addition to these wells, between Morinj and Kotor, the Plavda well on the road between Lepetane and Tivat should be mentioned; its waters had been used for supplying a part of waters to Tivat. In rainy periods, watercourses Gradiošnica, Vodolježnica and Koložun are formed in the Grbaljsko Field, in the base of the Lovćen. A short Jaška River that flows into the sea in the Jaz cove flows through the Mrčevo Field.

As far as river flows in the area of the Boka Kotorska Bay are concerned, the Sutorina is the main river of the region of Herceg Novi. The river source is below Nagumanac (Debeli Brijeg), watersheds towards Konavle and flows into the sea west of Igalo. Throughout its course smaller tributaries flow into it from the left bank, formed from the well and source Mojdež. Mineral water source Slatina is situated in south-western part of the alluvial plain of Igalo and its water is believed to have healing properties. The largest spring is used for the needs of the Institute Dr. Simo Milošević in Igalo, and the second largest is the source next to the Hotel Complex Njivice [10].

3 Terrestrial Ecosystems and Vegetation

In biogeographical terms, the area of the Boka Kotorska Bay belongs to the Mediterranean region of the Adriatic–Ionian subregion of the Adriatic province characterised by sclerophyllous forest vegetation of the *Quercion ilicis* community and its derivatives in the form of shrubby formations of the type maquis, garrigue

and rocky vegetation. What makes the Boka Kotorska distinct from the rest of the Mediterranean region of the Montenegrin Coast is the presence of laurel forests (*Laurus nobilis*) on one side and relatively low sub-Mediterranean xerophilic deciduous forest and shrubby vegetation and pseudo-maquis on the other. Effect of winds from the surrounding mountains and high rainfall resulted in widespread Mediterranean phanerophytes resistant to temperature fluctuations, such as a number of sub-Mediterranean deciduous species like *Quercus pubescens*, *Castanea sativa* (in flysch and acid soils), *Ostrya carpinifolia*, *Quercus trojana*, *Carpinus orientalis*, *Punica granatum*, etc., while evergreen elements are relatively rare (*Quercus ilex*, *Arbutus unedo*, *Phillyrea latifolia*, *Spartium junceum*, *Rhamnus alaternus*, *Smilax aspera*, etc.). Present are also *Fraxinus ornus*, *Juniperus oxycedrus*, *Olea oleaster*, *Myrtus communis*, *Pistacia lentiscus*, *Rosa sempervirens*, *Punica granatum*, *Asparagus acutifolius*, *Lavandula officinalis*, *Salvia officinalis* and *Origanum vulgare*. As regards cultured plants, lemons, oranges, tangerines, figs (*Ficus carica*), almond (*Prunus amygdalus*), carob (*Ceratonia siliqua*) service tree (*Sorbus domestica*), pomegranate and olives are grown (countries bordering Mediterranean grow olives most). The Luštica Peninsula is an area with typical Mediterranean perennial vegetation [25].

From the shoreline towards the tops of the Orjen, and partly Lovćen, the following vegetation zones can be observed, in the following order. The lowest zone consists of the Euro-Mediterranean evergreen sclerophyllous forests and maquis formations that are consistent with the Adriatic climate effects and rise up to about 500–600 m. The second zone consists of the sub-Mediterranean thermophyllous oak forests and scrub formations. This zone rises up to beech forests, which make the third zone. Finally, the fourth elevation zone is orobiome which is characterised, mainly in Orjen, by coniferous species *Pinion heldreichii* and *Pinion peucis* (subalpine whitebark pine forests) [24, 26–29].

A larger number of different habitat types can be discerned on the territory of the Boka Kotorska Bay [26] as follows:

- Low tidal highly saline mudflats overgrown by communities from the *Thero-Salicornion* and *Arthrocnemion fruticosi* association. Solila Bay in the Grbaljsko Field, by the Tivat Airport. Formerly used for salt exploitation (saltworks in Tivat).
- Hard-leaved scrub – maquis from the *Quercion ilicis* and *Oleo-Ceratonion cocciferae* and *Oleo-Lentiscetum* association. Maquis is widespread around Igalo, from Zelenika to Morinj, Vrmac, Luštica and Grbalj.
- Community of low shrubs of Euro-Mediterranean and sub-Mediterranean region and thermophilic limestone terrain of the continental part are partly covered by *Chrysopogoni-Satureion*, *Satureion subspicatalae* and *Satureion montanae* associations.
- Mediterranean-sub-Mediterranean herbaceous associations, often mosaically interchanging with rocky grounds: *Vulpio-Lotion* and *Cymbopogono-Brachypodion ramosi*.

- Mediterranean and sub-Mediterranean laurel forests from the *Laurion nobilis* association. Notably present along the line Risan–Morinj–Kostanjica. A protected reserve of laurel (*Laurus nobilis*) and oleander (*Nerium oleander*) community is just above Sopot, towards Risan.
- Mediterranean forests of holm oak forests from *Quercion ilicis* association (community type *Orno-Quercetum ilicis*) as a result of a millennium-long exploitation (from the Roman period for galley building to Venetians for sailing ships) practically do not exist in a preserved form. Today, there are just individual trees or small groups of this oak, primarily on the Luštica. Renewal of these forests could have a major effect on revitalization of original values of coastal areas.
- Natural or artificial Mediterranean forests of Aleppo pine (*Pinus halepensis*) and stone pine (*Pinus pinea*).
- Thermo-mesophilic chestnut forests on acid substrate (seen immediately by the sea –Kostanjica, Stoliv). Within them, laurel and chestnut community is particularly interesting.
- Broadleaved deciduous forests (sub-Mediterranean): beech, sessile oak–hornbeam and sessile oak–Turkey oak and Hungarian–Turkey oak forests (Orjen).
- Sub-Mediterranean xerophilic forests of the Mediterranean hinterland from the *Ostryo-Carpinion adriaticum* association.
- Subalpine forests of Bosnian red cone pine on limestone from *Pinion heldreichii* associations and Macedonian pine forests on silicates from the *Pinion peucis* association (typical of high areas of the Orjen, quite localised on the Lovćen).

4 Hydrographic and Oceanographic Characteristics of the Boka Kotorska Bay Aquatorium

From the geographic and oceanographic viewpoint, the Boka Kotorska Bay is a semi-closed basin with specific hydrographic characteristics. This results in major annual, seasonal, monthly and daily changes of physical oceanographic sea parameters; thus, determining the pattern of certain changes and processes is quite a complex undertaking. Communication of the bay with the open part of the Adriatic takes place through the Cape Oštra–Cape Mirište passage. The bay coastline length is 105.7 km, and the entire bay can be divided by its geographic–hydrographic properties into three entities: (1) the Kotor–Risan Bay, divided from the rest of the bay by the Verige Strait; (2) the Tivat Bay, divided from the rest of the bay by Verige and Kumborski Straits; and (3) the Herceg Novi Bay, divided from the rest of the bay by Kumborski Strait and from the open sea by a junction of Cape Oštra and Cape Mirište [9, 30].

4.1 Bathymetric Characteristics

The main bathymetric characteristic of the entire bay is a relatively great depth in bays and communication straits between certain entities and the entire area with the open sea (Fig. 3, Table 1). The greatest depth of about 60 m at the entry into the bay is gradually decreasing further in, ranging between 40 and 45 m in larger part of the bay. The maximum depth was determined in the Kotor Bay during an exploration of the Boka Kotorska Bay by the Hydrographic Institute of Montenegro's Navy, as a narrow indentation, 64 m in depth, south-east of Perast [31].

The characteristic of all bays is that depths increase towards the central zone and greater depth isobaths are getting closer to the shoreline. Thus, for example, the 20 m isobath follows the configuration of the shoreline at a distance of 200–300 m, except in the eastern part of the Tivat Bay and western part of the Herceg Novi Bay. Such vertical profile of the bay enables a clear stratification of specific oceanographic parameters and creation of a thermocline and pycnocline in specific seasons throughout the year.

Bottom Type According to Lepetić [32], clay is typically found in sea bottom in the Kotor Bay and Risan Bay, while sandy clay is found just in front of the town of Risan. In addition to clay, clayey–loamy sand can be found in the Tivat Bay, while the sea bottom of the Herceg Novi Bay is covered by clay, loamy clay, sand and clayey sand [33]. Central parts of the bay are covered by fine terrigenous mud with detritus elements [30]. Craggy sea bottom with submerged reefs and sinkholes is found in the coastal strip of the inner part of the Boka Kotorska Bay, particularly from Orahovac to Perast and from Risan to Morinj. Submerged reefs can also be found at the entry into the bay and in the Verige Strait. Between the reefs, at the entry into the Boka Kotorska Bay, sandy and muddy elements occur, and in the Verige, the bottom is covered by terrigenous mud [2, 32, 34].

Bay Water Volume The total volume of the Boka Kotorska Bay is approximately 2,412,306,300 m^3, divided into the following entities (Table 2).

Based on annual precipitation, size of the drainage basin area gravitating to the bay as well as freshwater inflow through submerged springs, the average annual inflow is estimated at approximately 15–18 m^3/s, though it varies from 3–4 m^3/s to 180–200 m^3/s. Immediately above the Risan Bay is the area with the highest precipitation in Europe (Crkvice with 4,742 mm annual average for the period

Table 1 Average and maximum depths, by bays [9, 31]

	Average depth (m)	Maximum depth (m)
The Boka Kotorska Bay (as a whole)	27.6	64.0
The Kotor Bay	26.0	64.0
The Risan Bay	25.7	36.0
The Tivat Bay	25.5	46.0
The Herceg Novi Bay	31.0	60.0

Table 2 Volume values of the Boka Kotorska Bay [35]

	%	Volume (m^3)
The Kotor Bay	18.2	439,039,747
The Risan Bay	8.5	205,046,035
The Tivat Bay	36.9	878,079,493
The Herceg Novi Bay	36.4	890,141,025

1961–1990). In fact, such and thus intensive inflow of freshwater is saving the Boka Kotorska Bay from the eutrophication process. Namely, according to the data available, it is estimated that annual inflow of wastewaters into this area is around $5 \times 10\ m^3$, which is around 0.2% of the total water mass of the Boka Kotorska Bay. Such hydro-meteorological situation imposes the need to place diffusers of submarine main drains much farther from the coast, i.e. to conduct all wastewaters from the Boka Kotorska Bay into the open sea [35].

In that regard, any form of new industrial pollution can aggravate the situation further. As already known, the facility for unloading, storage and loading of fuels in Lipci, the Port of Zelenika, overhaul facility in Tivat, shipyard in Bijela (still active), as well as a large number of vessels posed particular risk to the bay water quality in recent history, not only because of continuous pollution of the pelagic and benthic zones but also because of the risk of serious accidents that could have an irreversible effect [25]. Continuous and uncontrolled discharge of wastewaters from households, tourist facilities and urban settlements is particularly intensive in the summer period, when the hydrodynamics of the water exchange in the Boka Kotorska Bay is reduced to the minimum. The quality of the water intended for recreation and mariculture thus significantly deteriorates.

4.2 Physical Characteristics

The values of the basic physical characteristics of seawater surface throughout the year, temperature, salinity and transparency, are given for the Kotor–Risan Bay (Table 3) [1, 36].

4.2.1 Sea Temperature

As regards temperature, the Adriatic Sea as a whole, including the Boka Kotorska Bay, belongs to the group of moderately warm seas with temperatures ranging from 12 to 25.2°C [3, 36, 37]. Since the Boka Kotorska Bay is a quite closed and shallow basin, with an inflow of a large quantity of freshwaters, the temperature regime dynamics is very pronounced. A pattern in this area is that mean temperature values increase from the Kotor towards Tivat and Herceg Novi Bays, primarily due to the freshwater inflow [38].

Table 3 Hydrographic data for the Kotor Bay – SURFACE [1, 36]

Month	Temperature (°C)	Salinity (ppt)	Oxygen (mg/l)
X	21.7	34.2	6.39
XI	18.1	27.7	7.97
XII	7.0	9.5	9.88
I	8.3	12.21	8.69
II	9.9	9.8	8.81
III	11.5	9.43	9.31
IV	13.6	12.0	8.81
V	16.4	9.2	9.11
VI	25.4	22.3	8.01
VII	22.7	34.7	8.07
VIII	25.5	35.2	7.67
IX	24.7	32.8	8.11

In the Kotor–Risan Bay, average surface temperatures throughout the year range from 7.00 to 25.5°C, in the Tivat Bay average sea temperatures range from 12.05 to 26.62°C, and in the Herceg Novi Bay from 11.93 to 25.60°C. However, on 30 July 1998, sea surface temperature in the Kotor Bay (Prčanj) reached the whole of 31.4°C, which is the highest temperature measured since the beginning of temperature recording in this area [1, 3, 36]. On the other hand, in winter, due to the high inflow of freshwaters, the lowest surface temperatures occur in the Kotor and Risan Bays, where as a result of smaller depths and higher inflow of freshwater surface layers cool faster than those in the outer parts – Herceg Novi Bay. Some parts of the Kotor Bay (from Orahovac to Perast) as well as of the Risan Bay in winter may be covered also by a thin ice layer at air temperatures below 0°C.

In intermediate layers (between 10 and 30 m), summer temperatures range between 17.8 and 20.8°C. These temperatures are particularly highlighted because they are important for the water quality in the Boka Kotorska Bay. Summer periods are in any way the most loaded season in the year, when apart from sea heating and calm weather without wind (calm), the population number multiplies (due to the increased number of tourists) along with the wastewater quantity that is discharged untreated into the bay, average depth of which is just 27.3 m [1, 36].

4.2.2 Salinity

Salinity values in the Boka Kotorska Bay vary throughout the year, which can be seen in particular when values are analysed by layers. The highest oscillations occur in the shallow waters of Kotor Bay and Risan Bay, cutting deeply into the land, ranging from 9.2 to 35.2 ppt on the surface, naturally depending on the rainfall and inflow of freshwater from the shore and submerged sources. In the Tivat Bay, oscillations are much lower, ranging from 12.68 to 37.39 ppt, with the lowest ones in the Herceg Novi Bay, ranging from 18 to 37.67 ppt [1, 3, 34, 36].

4.2.3 Oxygen Concentration

Oxygen concentration (ml/l) in the sea shows seawater ventilation, but also the oxygen production by the phytoplankton community in the photosynthesis process. Since production cannot take place in the absence of nutritive salts in the sea, the oxygen values indirectly indicate also the presence of nutritive salts in the sea that are, for the most part, brought into the coastal seawater through sewerage deposits from land. Average oxygen quantities in the Kotor–Risan Bay range between 6.39 and 9.88 ml/l. Average oxygen quantities in the Tivat Bay range between 5.33 and 7.14 ml/l and in the Herceg Novi Bay between 5.00 and 7.49 ml/l. The values stated at the Boka Kotorska Bay in entirety indicate, at the same time, good ventilation and high production, compared to the Adriatic as a whole, where these values are usually around 6 ml/l [1, 3, 36].

4.2.4 Oxygen Saturation

Oxygen saturation is quite high in the entire Boka Kotorska Bay, and it is rather balanced, considering high production. Oxygen saturation values at the level of the bay and in entirety range between 95.08 and 162.63% at the sea surface, which is the result of intensive photosynthetic phytoplankton activity, but also the result of meteorological factors – wind and sea currents [1, 3].

4.2.5 Colour

Seawater colour in the Boka Kotorska Bay (according to Forel–Ule scale) ranges from blue (IV) to greenish (V–VI), particularly in the Kotor part, and then, regardless of the season, during heavy rainfall, it can become yellow brown (XIX–XX). In the Tivat part, colour usually ranges from blue green (VII–VIII) to umber green (XIII–XIV) and, in the Herceg Novi part, from dark blue green (III–VI) to umber (XXI) [1, 3].

4.2.6 Transparency

Sea transparency in the Boka Kotorska Bay is typically lowest in the most indented part – the Kotor Bay – and the highest in the Herceg Novi Bay. However, in summer, transparency is often reduced even in the area around Herceg Novi, from the Hotel Plaža to Njivice (first of all, due to significant inflow of sewage waters). In some years, transparency ranges between 3 and 16.15 m and is never above 20 m. Just as transparency, the sea colour depends, among others, from the quantity of dispersed particles in water, in areas with high production and inflow of

freshwater, such as the Kotor Bay (particularly its border parts); such transparency distribution is no surprise [1, 2, 34].

4.2.7 Circulation

Water mass circulation in the Boka Kotorska Bay is rather uneven and depends mainly on the tides and free oscillations, so-called seiches [9]. Wind and water pressure as well as fresh and saltwater mixing have the major impact on the direction and intensity of currents in the Boka Kotorska Bay (Fig. 10). Intensive water mass dynamics for the Boka Kotorska Bay aquatorium in entirety is significant, for the most part, in its surface layer. It is most intensive at the times of maximum freshwater inflows (rainfall, drainage from the shore, submerged sources). In this period, intensive circulation is present only in the surface layer, up to 5 m in depth, which is more a result of surface delevelling than of continuous circulation system, so adequate compensation current in deeper layers and hence the continuous exchange of water mass cannot be relied on. Circulation in deeper layers is mainly the result of effect of tidal currents, causing a low net transport of water masses throughout the bay. In the summer seasons, circulation intensity is even lower, and this particularly refers to the peripheral parts of a number of bays (the Port of Kotor, Risan, Krtole and Topla Bays).

On the other hand, winds and their direction and intensity have a significant effect on seawater circulation. Thus, a high percentage of calm (windless) days on

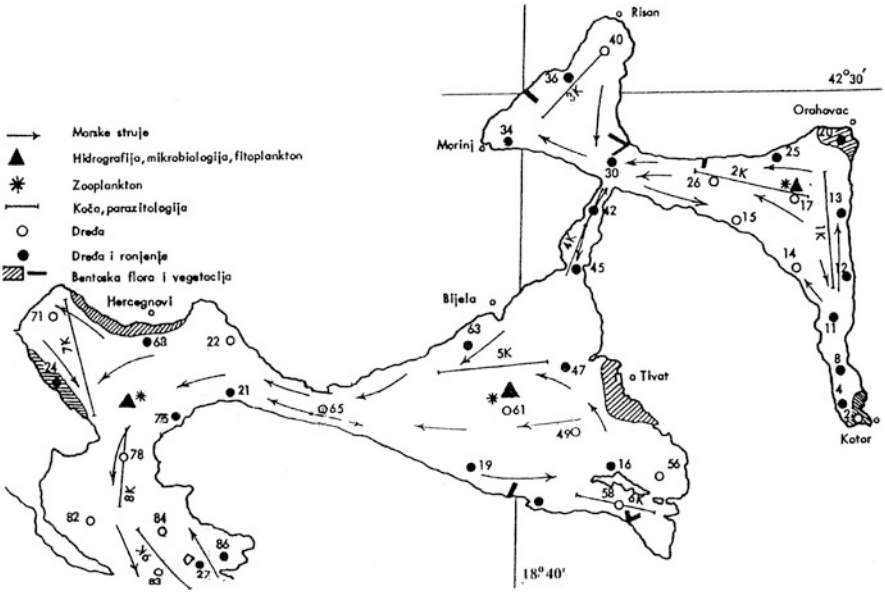

Fig. 10 Seawater circulation in the Boka Kotorska Bay [9]

one side and high frequency of winds blowing towards the shore and the outgoing current significantly reduce the intensity of seawater circulation and purification of the bay. These phenomena actually press the surface layer water towards the shore and thus create unfavourable conditions for wastewater discharge. This is particularly noticeable in summer period in the Tivat Bay, when winds from the west sector, along with calms, account for almost 80%. Similar situation, somewhat more favourable, is typical also for the Herceg Novi Bay, particularly its Topla part. In summer, currents are weak, while in autumn, winter and in spring, they are quite strong. Incoming current, moving in the north-west direction, is stronger in summer. Furthermore, from October to May, vertical water circulation occurs in the Boka Kotorska Bay, quite noticeable in the inner part of the bay. These currents raise deposits of nutritive salts and detritus from the bottom and thus contribute significantly to the increase in quantity of nutrients and productivity in general. In the Kotor and Risan Bays, strong turbulent currents are noticeable, intensity of which grows with the higher inflow of freshwaters, and they are typical also for areas where larger quantities of freshwater flow into – Morinj and Orahovac [39].

In the Kotor–Risan Bay, in months with a relatively low inflow of freshwater on the surface, the circulation flow takes an outward direction, with lowest speeds in peripheral parts of the bay. In the central layer, at the depths of 5 and 10 m, currents maintain the outward direction, but their intensity is much lower. Water circulation speed in the Verige Strait is around 0.66 knots (34 cm/s). In higher inflow of rainfall and spring freshwater, the circulation dynamics becomes more intensive. Dynamics is still the lowest in the peripheral part of the bay, while circular flow currents occur at times, as a result of shore configuration. Speed ranges from 0.1 to 0.5 knots (5 to 26 cm/s). In the Verige Strait, strong outward currents can reach from 0.9 to 1.1 knots (46 to 5 cm/s) [35].

Exploration of diversity of early developmental stages of fish (ichthyoplankton) in the Boka Kotorska Bay confirmed the presence of a large number of eggs and larvae of pelagic fish species, highest percentage of which belong to economically important fish species. It was found that 38 different fish species spawn in the Boka Kotorska Bay (28 genera and 18 families), while diversity analysis shows a high degree of diversity in certain points with pronounced water circulation (Kumborski and Verige Straits) [40].

4.2.8 Tides

As regards analysis of seawater dynamics of tides (high tide–low tide) based on mareograph measuring, it can be said that water level oscillation is slightly more intensive in the area of the Kotor and Risan Bays than in other areas due to the shape of the basin, low-intensity communication with the open seas and higher inflow of rainfall waters. Thus, the value of mean daily amplitude is 25.1 cm and maximum multiannual 125.5 cm, which is approximately 20 cm more than those in the Herceg Novi Bay. In the Herceg Novi Bay, mean daily amplitude is 22 cm, with maximum multiannual amplitude of 106.5 cm [9].

5 Conclusion

Compared to other parts of the Adriatic Sea, the Boka Kotorska Bay represents a unique and specific entity with its geographical position and geomorphological, climatological, hydrological and biotic characteristics. The sea penetrates into the continent deeply (a unique fjord with the Mediterranean climate).

Complex hydrological and hydrogeographical characteristics of karst in the Montenegrin Coast resulted in quite pronounced differences in explanation of morphogenesis and formation of the Boka Kotorska Bay. Thus Savicki, 1912 [from 10], believes that *detailed forms of the Bay were formed by river erosion, but tectonic predisposition must not be forgotten*.

The climate of the Boka Kotorska Bay belongs to a perhumid Mediterranean climate type, characterised by high rainfall in winter and spring and even higher in autumn and winter, with a very short dry period in July–August. Annual rainfall distribution and precipitation are among the most important climatological parameters determining the climate of the Boka Kotorska Bay. The highest precipitation in the area of the Orjen Mt. is in Crkvice (1097 m) above the Risan Bay, with annual average precipitation of 4742 mm, which is the European maximum rainfall.

The entire area of Boka Kotorska Bay belongs to the Adriatic Sea Basin, and it could be said that it has a poorly developed network of surface watercourses, resulting primarily from geological structure of the terrain dominated by carbonate rocks, where waters are lost to the highest depths. Groundwaters and ground watercourses in karst are quite specific and complex. Development and circulation of ground holes in limestone take place to their lower limit, often several hundred and even thousand metres below sea level.

In biogeographical terms, the area of the Boka Kotorska Bay belongs to the Mediterranean region of the Adriatic–Ionian subregion of the Adriatic province characterised by sclerophyllous forest vegetation of the *Quercion ilicis* community and its derivatives in the form of shrubby formations of the type maquis, garrigue and rocky vegetation.

From the geographic and oceanographic viewpoint, the Boka Kotorska Bay is a semi-closed basin with specific hydrographic characteristics. This results in major annual, seasonal, monthly and daily changes of physical oceanographic sea parameters; thus, determining the pattern of certain changes and processes is quite a complex undertaking.

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