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Coastal Management Tools and Databases for the Sevastopol Bay (Crimea)

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Abstract

The Bay of Sevastopol is one of rare natural inland harbours of the coast of Crimea on the Black Sea that has being serving as a marine shelter and residence for human civilizations for over 25 centuries. This bay has been under very heavy anthropogenic and industrial pressure for several decades, though it is an area that is vitally valuable for recreation and inhabitation. The Bay of Sevastopol has become and remains a subject of intensive oceanographic investigations and quarterly monitoring since 1997, though some data goes back to as far as the 1970's. We have been intensively studying various issues of the Sevastopol Bay physics, biogeochemistry, biology, and pollution. In 2010, the EC FP7 PEGASO project was launched to address

Integrated Coastal Zone Management (ICZM) issues, to provide a regional assessment of environmental conditions, to evaluate local conditions and introduce tools and mechanisms (platform) for implementation of the ICZM Protocol. Current results of the long-term monitoring and implementation of the PEGASO project are reported here.

Introduction

The Bay of Sevastopol (Fig. 1) is one of rare natural inland harbours of the coast of Crimea on the Black Sea that has being serving as a marine shelter and residence for a sequence of human civilizations for over 25 centuries starting with Ancient Greek city Khersoness that was found here in the 6th century B.C.

This bay has been under very heavy anthropogenic pollution for several recent decades, though it is an area that is vitally valuable for recreation and inhabitation (Fig. 2). This bay that is several hundred meters wide in its seaward part goes inland for about 8 km providing excellent conditions for ship docking, harbouring, and other maritime activities. This is the very reason that Sevastopol as a navy base has been settled around the bay. This bay had also been used for intensive fishing and harvesting other marine biological resources before Navy related activities and pollution almost completely destroyed its ecosystem and minimized its biodiversity to a state of a polluted marine desert.

The modern history of the Sevastopol Bay goes back to 1783, when Russian Navy entered the bay to set up the navy base and the city itself. Initial oceanographic studies were limited to the bay's bathymetry, characteristics of the bottom sediments, and mapping the bay's coastline and surrounding coasts of Crimea. These data have been used in the first hydrographical atlas of the Black Sea, published in 1841 (cited from Sailing Directions: Black and Azov seas, 1892).

Fig. 1: The Sevastopol Bay.

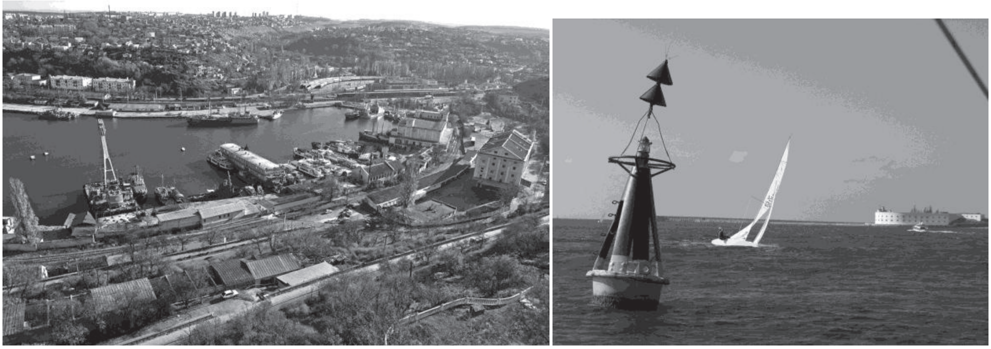


Fig. 2: Anthropogenic (left panel) and recreational (right panel) activities in the Sevastopol Bay.

Zernov S.A. was probably the first to study biological properties of the bay in 1910-1911 and to warn in 1913 that the bay's biodiversity is vulnerable to anthropogenic influences (Zernov, 1913). Indeed, negative changes in biological and biogeochemical properties have been reported since the 1930's (Mironov et al., 2003).

There was a period from 1951 to 1958, when seasonal monitoring of physical, biological, and biogeochemical properties was undertaken (Dobrzhanskaya, 1960). Though seasonal behaviour of oxygen and nutrients remained similar to the open sea, the concentrations of nutrients and biological oxygen demand increased and they were 1.5 to 4 times higher, as compared to other pristine coastal regions of Crimea.

Results of the bay's surveys in the 1960's demonstrated a sharp increase in the year-round concentrations of nutrients, very high values of biological oxygen demand, intensive eutrophication of the bay (Ermakova and Velichkevich, 1968). That was the period when hypoxia was first detected and reported in the bottom layer of waters: the level of oxygen saturation dropped to 42% and the oxygen concentration was as low as 2.19 ml/l. That was the result of increased primary production, as the oxygen saturation reached 190% in the euphotic layer. Concentrations of nutrients in the bay increased up to 100-fold and the biological oxygen demand increased 6-10-fold from the 1950's to 1960's. The situation in the biological structure of the bay's ecosystem was catastrophic. The Sevastopol Bay was lost for any commercial harvesting of marine resources.

The situation became worse in the 1970's and 1980's, as dams were constructed at the bay's entrance in 1976-1977 decreasing the water exchange between the bay and the sea by 50%, while anthropogenic pollution and eutrophication were in progress (Hydrometeorology and hydrochemistry of the seas of USSR, 1996). Biogeochemical conditions in the bay's environment became so extreme that hypoxia was a regular feature of the inner part of the bay on summer time. To make matter worse, sediments became sulfidic and serve as a source of hydrogen sulfide for the bottom layer of water and destroying benthic communities. Yet, oxygen deficit in the bottom waters, anoxic conditions in the bottom sediments, extreme concentrations of nutrients were not discussed because more severe ecological problems emerged. The concentration of oil and heavy metals could exceed 10-fold the maximum possible concentrations for the coastal waters, but data was classified because the bay became the USSR Navy stronghold and the bay's ecological problems were subdued.

After the USSR collapsed in 1991 and its economy and navy degraded in the 1990's, the ecosystem of the bay was presumably recovering, but very limited data and publications were available (Morochkovsky and Kovalchuk, 1993). Though navy activities declined after 1991, the Sevastopol Bay gradually became a place for a big and intensively growing seaport, ship docking, and sea-land transportation of various goods. Recreational business was developing. The population of Sevastopol of about 400,000 permanent residents might easily double on summer time. Still, the major part of municipal and industrial sewage waters (~10,000 m^3 per day) was discharged to the bay via ~30 sewers without or after minimal treatment. This has already resulted in further anoxic (sulfidic) conditions from bottom sediments (Orekhova and Konovalov, 2009b) to near-bottom layers of water, where the concentration of sulfide has already reached 40 μM (Konovalov, 2009).

The Bay of Sevastopol has become and remains the subject of regular oceanographic investigations and monitoring since 1997. It has been initiated by several international projects (INTAS 96-1961, INTAS 99-01390, INTAS 03-51-6196) and it is currently supported by national ("Marine Expeditions", "Fundamental Oceanography", "Ecoshelf", "Interaction" 05-05-10У) and international (EC FP7 "Hypox" #226213) projects. Various issues of the Sevastopol Bay meteorology, hydrology, biogeochemistry, biology, and chemical pollution have been intensively studied. These data have been traditionally summarized in the form of oceanographic atlases (Konovalov et al., 2009). Though these atlases are a valuable source of scientific information, its form has always limited its utilization to scientific studies leaving stakeholders and managers with the problems of data accessibility and utilization of data of different nature for integrated coastal zone management.

The FP7 PEGASO project (2010-2014, #244170) has been recently launched to investigate different aspects of and local conditions for integrated coastal zone management (ICZM) and application of the ICZM Protocol in the Mediterranean and Black Seas. The Bay of Sevastopol has been chosen as one of the sites (CASES) for practical application of the results of the project, to assess local conditions and provide practically useful end-products for the purpose of ICZM implementation. Thus, when the ICZM Protocol is developed, adopted, and put in force, the local stakeholders will have practical tools to implement the ICZM principles.

This publication is to present data of oceanographic monitoring of the Sevastopol Bay and tools for coastal management of the Bay of Sevastopol, which are developed within the PEGASO project and placed on web to remain available after the PEGASO project expires.

Results and Discussion

Monitoring of the Sevastopol Bay and its results (data bases and atlases)

Regular oceanographic studies and monitoring of environmental conditions of the Sevastopol Bay have typically been carried out at 32 oceanographic stations (Fig. 3) at a quarterly basis since 1997.

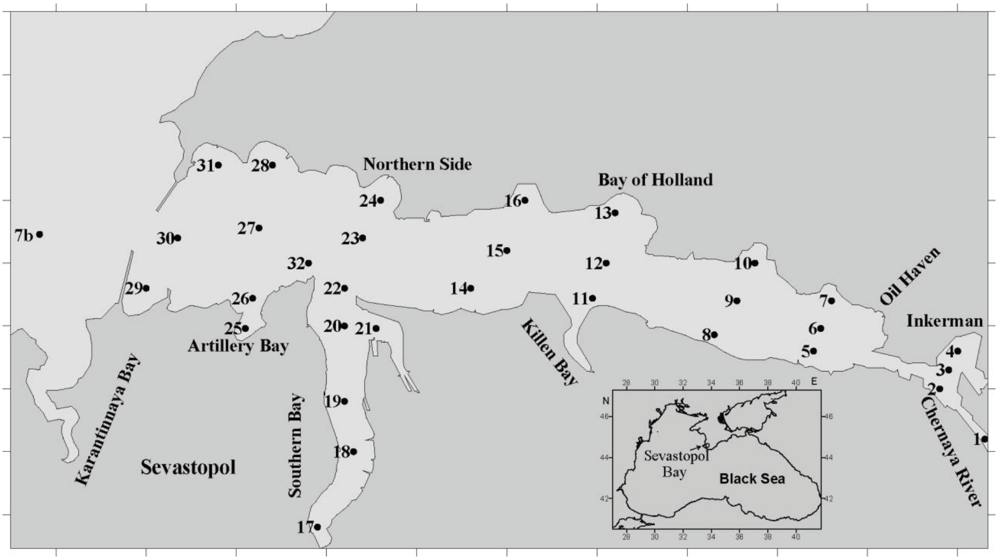


Fig. 3: Oceanographic stations in the Sevastopol Bay.

Results of monitoring have been contributed to data bases of the National oceanographic centre of Ukraine (http://www.nodc.org.ua/) and presented in a number of publications and, in particular, in the form of "Atlas of the Sebastopol Bay oceanographic properties" (Konovalov et al., 2009). This has made possible a detailed oceanographic description of the Sevastopol Bay.

Thermohaline structure and water dynamics

There is an average transport of water from the bay to the sea due to the incoming riverine and coastal waters to the bay. Yet, there is a transport of water from the sea to the bay in the bottom layer. Incoming waters of a higher salinity are mixed with the surface waters of a lower salinity to form the observed distributions of salinity (Fig. 4). This mixing is restricted on summer time due to the presence of the seasonal thermocline and a weaker wind stress. As the result, both salinity and temperature support a two-layer structure with warmer and less saline waters in the upper layer and colder and saltier waters in deeper layers of the bay. Mixing is far more intensive on winter time, when cold surface waters down well and intensify mixing between the surface and bottom waters. As the result, the thermohaline structure reveals a lateral stratification on winter time with colder brackish waters in the inner part of the bay and warmer and saltier waters in the seaward part of the bay.

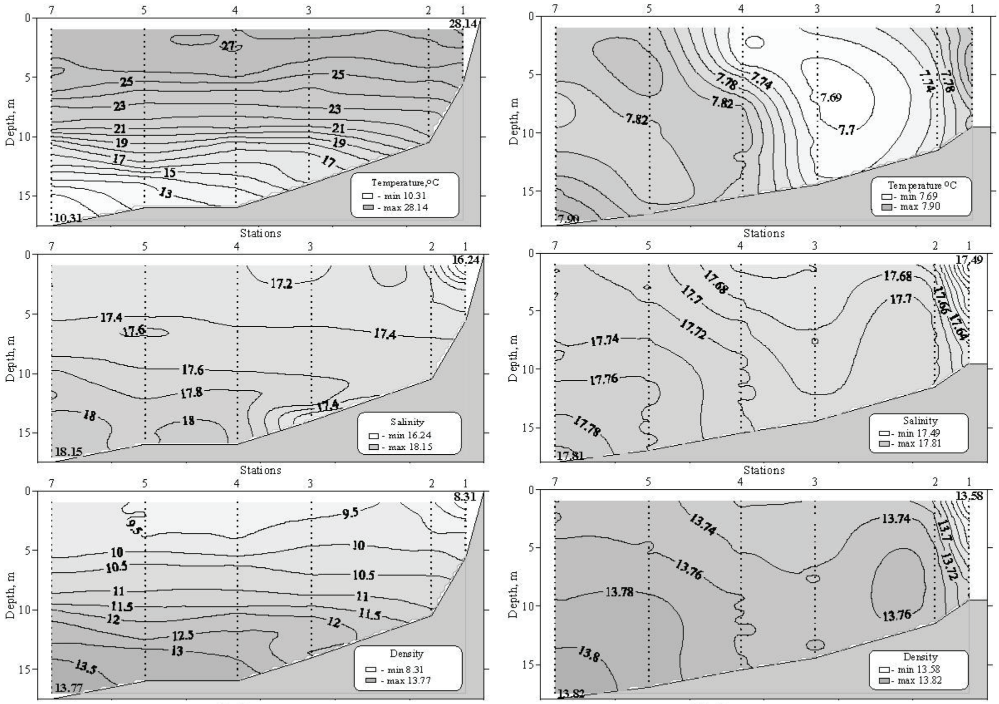
These features of the water stratification are of extreme importance for the chemical structure and its seasonal changes.

Biogeochemical properties

The bay's waters are usually well saturated with oxygen on winter time. The level of saturation varies from ~90% in the bottom layer of waters close to the river mouth to 100% in the surface layer (Fig. 5). Saturation of the surface waters remain slightly below 100% due to intensive cooling of waters and increasing solubility of oxygen with decreasing temperature. Yet, the level of saturation can be substantially lower for "warm" winters and it could be as low as 75%.

On summer time, the level of oxygen saturation for the surface layer varies from 95 to 130% (Fig. 5), yet the highest traced by now value has been 294%. The level of oxygen saturation at the depth of 1 m above the bottom usually varies 70 to 105%, yet the lowest traced value has been 27%. The traced concentrations of oxygen have varied from 5.1 to 15.2 ml/l in the surface layer and from 1.4 to 8.0 ml/l at the depth of 1 m above the bottom. The deepest 10 cm layer of water regularly becomes anoxic and even sulfidic on summer time. Results of recent voltammetric profiling of the bottom sediments (Orekhova and Konovalov, 2009a) have revealed that penetration of oxygen does not exceed 2-5 mm, but sulfide is in the deeper layers and it can and does reach the surface of sediments and may easily consume oxygen from the bottom layer of waters.

February and March are two months, when hypoxia events in the bottom layer have not yet been observed. These are two most cold months and intensive vertical convective ventilation provides the downward flux of oxygen that is enough to meet the current oxygen demand. All other months are the part of the year, when hypoxia events have been detected, but the extent and intensity of hypoxia depends on various conditions. Still, the most extreme hypoxia events have been and are regularly detected in July and August, when all further discussed issues contribute to oxygen consumption and/or limit the oxygen flux.



July February

Fig. 4: Summer (left panel) and winter (right panel) distributions of temperature, salinity and density.

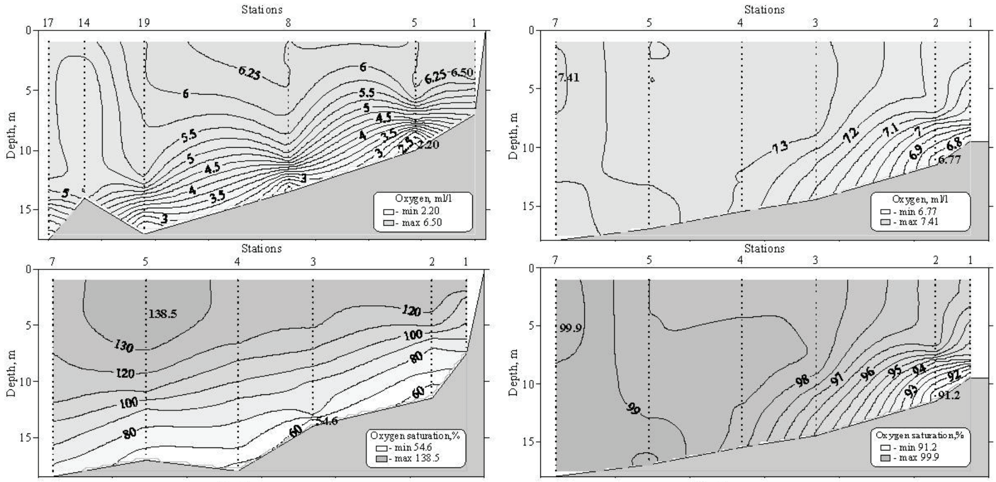


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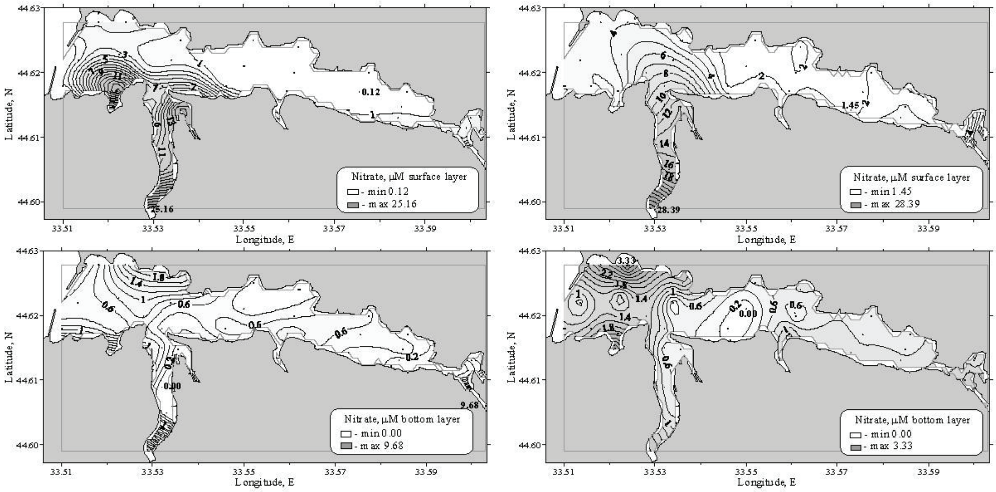
Fig. 5: Summer (left panel) and winter (right panel) distributions of oxygen.

Hypoxia and anoxia in the bottom layer of water on summer time is a result of a number of physical, biological, biogeochemical, and geochemical processes:

- Strong vertical stratification due to the presence of warm and brackish riverine surface waters limits the vertical mixing and the downward flux of oxygen to the bottom waters;
- Weak winds limit lateral exchange and ventilation of the bottom layer with the sea waters;
- Artificially limited water exchange between the open sea and the bay due to coastal dams supports a longer residence time of the bay's waters, thus a smaller flux of oxygen to the bay;
- Anthropogenically supported load of nutrients and organic matter to the bay's waters is the reason of a dramatically increased export production and the flux of organic carbon to the bottom waters and sediments;
- Increased concentrations of organic carbon in the bottom sediments result in anoxic/sulfidic conditions and support the flux of dissolved sulfides from sediments to the bottom layer of water.

Nitrate and phosphate are the most important forms of inorganic nutrients in the waters of the bay (Ivanov et al., 2006). The major sources of these nutrients are related to anthropogenic activities at the coast, while the sources of silicates are natural and related to its load with riverine and underground waters. Processes of primary production, sinking and respiration of organic matter in the water column, and burial of organic matter in sediments are the major processes governing the spatial and vertical distribution of nutrients in the bay's waters and seasonal changes in these distributions.

As a typical example, the distribution of nitrate (Fig. 6) reveals that its maximum concentrations are typically traced in the surface layer and in those parts of the bay, where anthropogenic sources are most expected.



July February

Fig. 6: Summer (left panel) and winter (right panel) distributions of nitrate.

Seasonal variations in the distribution of nitrate are the result of several processes:

- Intensive mixing of waters in winter results in higher concentrations of nitrate in the bottom waters of the major part of the bay;
- Anthropogenically supported load of nutrients and organic matter to the bay's waters is the reason of dramatically increased concentrations of nitrate in some inner parts of the bay;
- Intensive production of particulate organic matter in summer and its sinking and respiration below the thermocline result in elevated concentrations of nitrate in the bottom waters of those parts of the bay, where organic matter is produced or discharged;
- Strong vertical stratification and weak wind stress in summer result in conservation of spatially uneven distribution of nitrate.

Generally, the nitrate varies from analytically undetectable concentrations to as much as 141 μM with the average concentration of 3.8 μM. This values is really high and it exceeds more than 100-fold the nitrate concentrations in the coastal waters outside the Sevastopol Bay.

Pollution Level Index

Another dimension of the work on monitoring the Sevastopol Bay oceanographic properties is addressed to developing of pollution level indexes (PLI) that can be and are used to estimate the level of pollution and to identify provinces according the level of pollution (Fig. 7). These indexes are applied to the bottom sediments.

There are very many currently monitored chemical parameters in the bottom sediments of the Sevastopol Bay and individual analysis of all of them is exhausting and folds up the picture in numerous details. The only known option (Tomlinson et al., 1980) is to generate an index that would be a combination of several considered parameters and that would let to join parameters of different nature, scale and importance for the state of the monitored environment. There are several proposed indexes and we have used two of them.

$$PLI_i = C_i / C_b, \qquad (1)$$

where PLI_i is a value of PLI for an individual contaminant, C_i is the measured concentration of a contaminant and C_b is a background concentration of this contaminant.

$$PLI = \sqrt[n]{\prod_{i=1}^{n} PLI_i}, \qquad (2)$$

where PLI is a general index for *n* contaminants.

This PLI makes possible to trace the major sources of contaminants and to identify the most polluted areas of the bay (Fig. 7).

PEGASO tools for the Sevastopol Bay

We are actually developing several tools for coastal management of the Bay of Sevastopol, which are placed on web (http://www.iczm.org.ua/ and http://wiki.iczm.org.ua/) and will stay after the PEGASO project expires. This is a web-portal and a stand-alone GIS type electronic system downloadable from http://wiki.iczm.org.ua/en/index.php/Download_the_latest_version_of_the_atlas and available on CD (sergey_konovalov@yahoo.com).

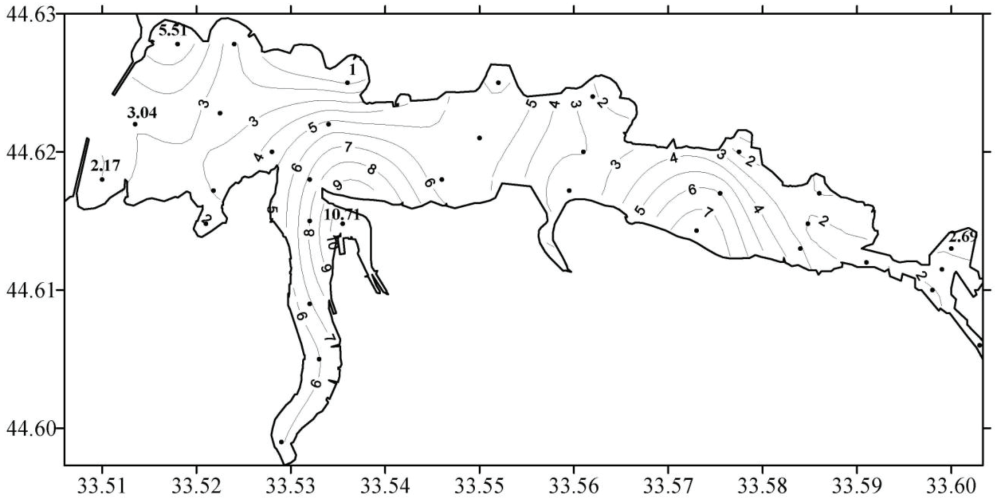


Fig. 7: PLI of the Sevastopol Bay sediments.

This system incorporates an electronic version of the atlas (Fig. 8) and an interactive electronic atlas with a possibility to construct maps and apply various indexes (Fig. 9) of the state of the marine environment. It also incorporates various national and international legislative documents and regulations for environmental protection.

Scientific support, which is one of the components of ICZM, assumes participation of various specialists and utilization of various data depending on a specific task. These specialists are to use their experience and available data in order to extract the needed information, to transform it, and to evaluate available information for the purposes of ICZM. The major disadvantage of traditional sources of data, which are atlases and data base, is the need to address various specialists. Geographic Information Systems (GIS) are more helpful, but they are still oriented on data presentation, rather than data analysis. Besides, Geographic Information Systems rarely allow data manipulating. This is the reason that we have designed the system incorporating all known digital atlas and GIS features, but also allowing interaction with data and application of different ISZM tools. The major of these tools are indexes and scenarios. While interaction with data makes possible to construct different maps, which have not existed and/or been preloaded, tools make possible to analyze data. This allows a manager to limit the number of scientists involved in the ICZM process, but more important a possibility to verify different options without additional interactions with scientists. Thus, for example, a "traffic light" index (Fig. 9) has been constructed and applied in order to analyze the reasons of and possible responses to persistent deficit of oxygen in the bottom waters of the Sevastopol Bay. Information on the municipal structure, locations and characteristics of waste–water discharges, the thermohaline structure of the water column has been combined with the generated digital maps and indexes in order to show the anthropogenic nature of this ecological problem.

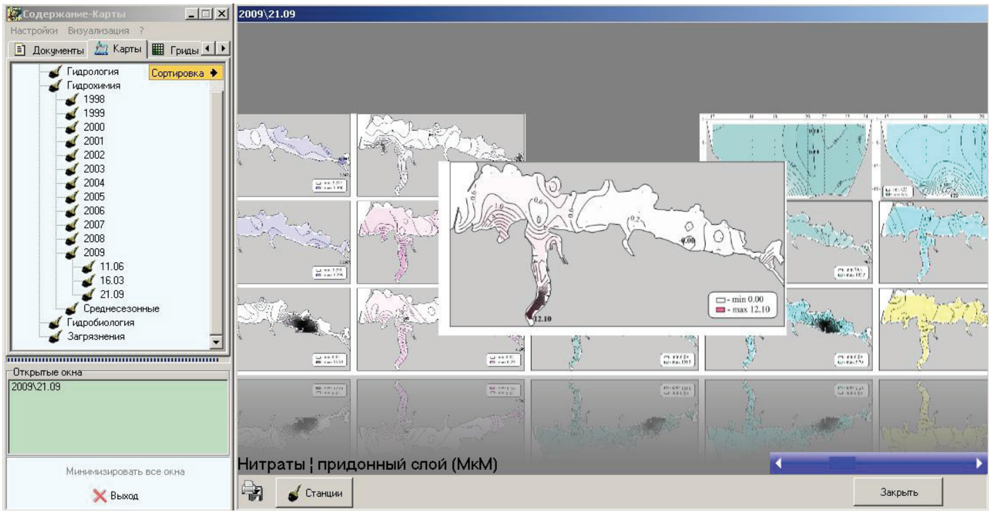


Fig. 8: An example of maps in the electronic version of the atlas of the Sevastopol Bay.

Ultimately, this system will also incorporate possibilities to construct and evaluate possible scenarios depending on coastal and maritime spatial planning and urban development issues. The major purpose of these activities is to support stakeholders with data and tools for implementation of the ICZM Protocol and its principles.

Conclusions

Regular oceanographic studies and monitoring of environmental conditions of the Sevastopol Bay have typically been carried out since 1997. Results of monitoring have been contributed to data bases of the National oceanographic centre of Ukraine (http://www.nodc.org.ua/) and presented in a number of publications and, in particular, in the form of "Atlas of the Sebastopol Bay oceanographic properties" (Konovalov et al., 2009).

Several tools for coastal management of the Bay of Sevastopol are developed within the EC FP7 PEGASO project. These tools are placed on web (http://www.iczm.org.ua/ and http://wiki.iczm.org.ua/) and will stay after the PEGASO project expires.

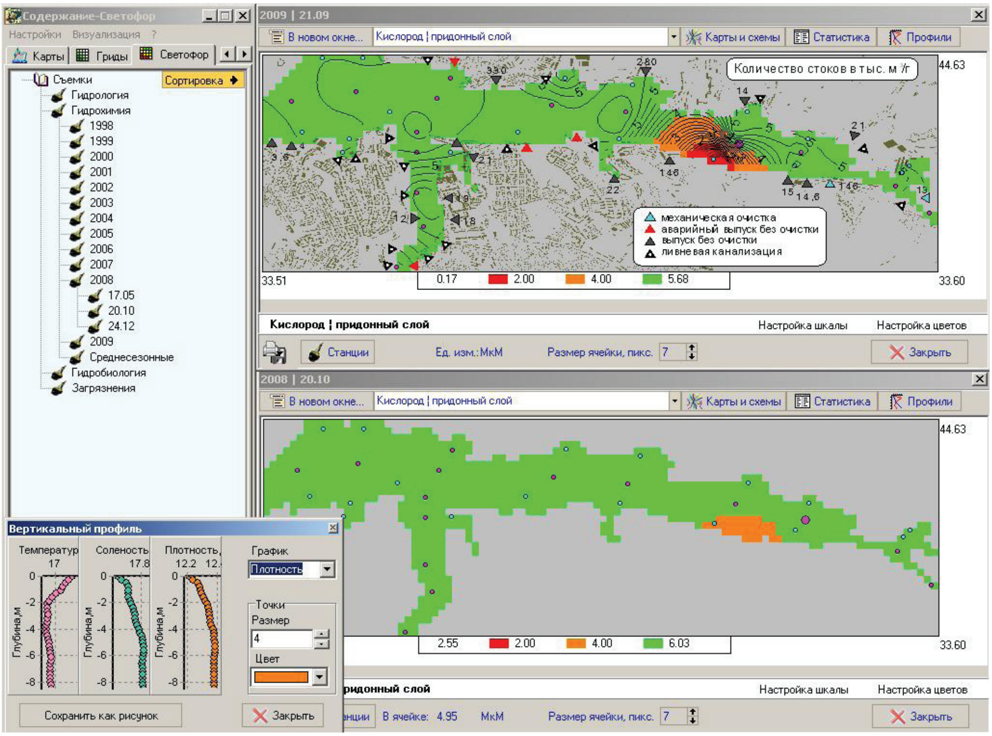


Fig. 9: An example of index maps and application of GIS features for evaluation of environmental conditions in the Sevastopol Bay.

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