The North-western Black Sea: A Pilot Site to Understand the Complex Interaction Between Human Activities and the Coastal Environment

C. Lancelot, J.-M. Martin, N. Panin and Y. Zaitsev

Introduction

Coastal ecosystems are important spawning and nursery grounds for marine organisms, and are also of great value for recreational activities. In addition, coastal areas are the recipient of increasing amounts of nutrients and contaminants from human activities, including industrial effluents, agricultural runoff and municipal sewage. As a consequence, remarkable changes have been observed in coastal waters around Europe during the last few decades. The EROS (European River Ocean System) project is part of a long-term study to understand the biogeochemical processes and their alteration by human activity in the European coastal zone. The ultimate objective is to develop a predictive model of the land–ocean system to be used as a scientific tool for environmental management. It will thereby reduce the degree of uncertainty within current coastal zone management, where decisions are taken to achieve sustainable development of coastal and land-locked ecosystems.

Between 1994 and 1998, the EROS team focused its research on the lower reaches of the Danube and its delta, along with the north-western Black Sea. The Black Sea, with its unique features (it is the largest enclosed sea in the world receiving freshwater and sediment inputs from rivers draining half of Europe and parts of Asia), represents the ultimate example of deterioration of the coastal and marine environment in Europe (Mee, 1992; Zaika, 1992; Zaisev & Mamaev, 1997). It was chosen as a pilot site in order to understand the complex interactions between human activities and the marine environment. The Black Sea ecosystem has indeed experienced several changes over the last few decades caused by human impact on the coastal ecosystem itself and on the drainage basins of the rivers. Among these, the Danube River, receiving the effluents from eight European countries, is affecting the north-western Black Sea ecosystem, and represents the most significant source of river-borne pollution flowing into the Black Sea.

Assessing and predicting the response of the north-western Black Sea ecosystem to human interventions was the ultimate objective of the EU EROS-2000 and EROS-21 projects, bringing together biologists, geochemists and physicists of western, eastern and central Europe. Most specifically, the project addressed the following questions: What would be the consequences of a reduction of the river input of...
nuts for the eutrophication and the ecosystem structure of the north-western Black Sea? What are the sources, levels and fates of key organic/inorganic pollutants in the Black Sea environment? What is the significance of the Black Sea as a source of important greenhouse gases? What are likely to be the short- and long-term consequences of the regulation of river discharge for sediment erosion/transport/deposition and water stratification?

Project methodology

Historical data, field research and mathematical modelling

The complex interactions between the continental and marine coastal systems require definition and integration of the most natural and human-induced driving forces controlling the ecosystem variability. The EROS approach was to collect existing and new data in the Danube drainage basin and the north-western Black Sea, conduct process-level studies under field and laboratory-controlled conditions, and combine this with satellite data (Barale et al., 2002) to develop and validate numerical models describing ecosystem and biogeochemical transformations along the Danube–north-western Black Sea aquatic continuum. A number of field investigations were organized in the lower reaches of the Danube and its delta, at strategic coastal stations south of the Danube mouth, to monitor the seasonal evolution of nutrients and algal blooms. Two large expeditions were conducted in the Black Sea in summer 1995 and spring 1997 aboard the Ukrainian RV Professor Vodyanistsky. The ship was adapted for the collection of contaminant (inorganic and organic) samples under ultradean conditions. A total of 150 stations were occupied in the area of ‘Danube influence’ along eutroph–oligotroph gradients, as well as in the central basin. A sediment-trap mooring was deployed there from August 1995 to October 1996 to measure sedimentation rates and the nature and composition of sinking particles (Reschke et al., 2002). Process-level studies were conducted on the rate of microbial degradation of organic matter in both the water column and the sediment (Bequevort et al., 2002; Ivanov et al., 2002; Lein et al., 2002). These experiments were combined with biomarker and isotopic measurements in an attempt to discriminate organic matter of continental and marine origin (Galimov et al., 2002; Saliot et al., 2002), including the production of organic matter by anaerobic activity (Galimov et al., 2002; Ivanov et al., 2002). For the first time, investigations on the structure and functioning of the planktonic food-web were conducted in an integrated comprehensive way. Studies of the relationship between dominant phytoplankton communities and nutrient availability (Ragueneau et al., 2002) were combined with experimental investigation of the feeding ecology of key planktonic organisms and of the gelatinous carnivores, Mnemiopsis and Aurelia (Weisse et al., 2002). The rate of sedimentation and the processes occurring within three sediments and at the water–sediment interface were also studied (Friedel et al., 1998; Friedrich et al., 2002) and modelled (Wijsman et al., 2002). For the first time in this area, a benthic lander was used to measure nutrient exchanges at the sediment–water interface (Friedel et al., 1998; Friedrich et al., 2002). The knowledge gained was progressively integrated in a hierarchy of off-line coupled physical–biogeochemical models of different spatio-temporal and trophic resolution. Together, these models describe biogeochemical transformations of carbon and nutrients along the Danube River–north-western shelf-central basin aquatic continuum as a function of meteorological forcing and human activities (Beckers et al., 2002; Garnier et al., 2002; Lancelot et al., 2002).

Pollution assessment focused on metals (Guieu & Martin, 2002), organochlorine compounds (Maldonado & Bayona, 2002) and radioactivity (Gulin et al., 2002). The emission of biogases (methane, nitrous dioxide and dimethylsulphide) into the atmosphere was measured during the summer season (Amouroux et al., 2002).

Results

Sensitivity of the Black Sea ecosystem to human impact: phenomenological analysis and model reconstruction of historical data

Since the early 1960s, noticeable alterations have been observed at various trophic levels of the Black Sea ecosystem, and are well documented. In less than 30 years, the Black Sea ecosystem has evolved from a highly biodiverse ecosystem characterized by rich biological resources to a low biodiversity ecosystem dominated by a dead-end gelatinous food-chain (e.g. Mee, 1992). During the late 1980s, there was an almost total collapse of fisheries, which coincided with an unprecedented increase of the jellyfish, Aurelia, and also the exotic comb jelly, Mnemiopsis, unintentionally introduced to the Black Sea in the mid-1980s. At the time, it was thought that these gelatinous carnivores—lacking predators and feeding on zooplankton, fish eggs and larvae—dramatically reduced the recruitment of fish to the adult stocks and were, therefore, claimed to be responsible for destabilization of the ecosystem.
The re-analysis of existing data, in combination with a model reconstruction making use of Flow Network Analysis (Güçü, 2002) and mechanistic modelling (Lancelot et al., 2002), however, suggests that the successful development of the undesirable gelatinous carnivores is a result of combination of the following human interventions, occurring almost synchronously in both the drainage basin of the Danube River and the marine system: the manipulation of hydrological regimes of outflowing rivers (Bondar, 1977; Jipa & Panin, 2002), urban and industrial expansion and the intensive use of agricultural fertilizers (Bologa et al., 1984; Gomoiu, 1990; Garnier et al., 2002), the introduction of exotic species such as the gelatinous Ctenophora Mnemiopsis sp. (Vinogradov, 1992; Mütlu et al., 1994), and selective and excessive fishing (Ivanov & Beverton, 1985; Bingel et al., 1993; Septnowski et al., 1993; Güçü, 1997). Both our model results (Güçü, 2002; Lancelot et al., 2002) show that over-fishing following eutrophication played a role in the destabilization of the Black Sea ecosystem reported for the years 1989–1991, which indicates that human-induced changes in the watershed were the driving force.

Human-induced changes in the river watershed and along the Danube River since the 1970s have dramatically reduced the sediment discharge to 30–40% of its initial value (Panin & Jipa, 2002) and have, therefore, modified the quantitative and qualitative nutrient supply to the coastal phytoplankton. Urban extension and agricultural and industrial development have increased the nitrogen and phosphorus loads, while increased eutrophication in the river system has decreased silicate discharge to the sea (Garnier et al., 2002). This contrasts with Humborg et al.’s (1997) analysis, which attributes the decrease of silicate inputs to the Iron Gates construction in 1970. After 1970, nutrient changes stimulated the development of numerous summer phytoplankton blooms in the marine environment and, in general, the phytoplankton community was dominated by non-diatom species, some of which were of little palatability for mesozooplankton. As an immediate response to increased primary production, large developments of herbivorous copepods and carnivorous predators (fishes) were subsequently observed (Porumb, 1989). Higher fish availability led to an increase of fish catches and, as a matter of consequence, greater fishing pressure (Güçü, 2002). By decreasing fish stocks, the Black Sea fisheries indirectly stimulated the development of the predatory gelatinous carnivores. Aurelia and the alien Mnemiopsis competing with fish for copepods (Güçü, 2002). This situation accelerated in an explosive way due to the lack of known predators of these gelatinous carnivores and to their voracious feeding on fish eggs and larvae. Most of the organic matter produced by primary producers was thus deviated to a trophic dead-end. Organic matter deriving from dead organisms further intensified the development of bacterial populations, with subsequent oxygen-deficiency problems, and increased the bulk of organic matter reaching the sediment. This process was associated to high values of methane production in coastal sediments, especially during summer time. The δ13C signature of the methane demonstrated its microbial origin (Ivanov et al., 2002), which contradicts the general view that allocates methanogenesis to the oil-field of the Black Sea shelf. Most of the methane produced in the sediment and water column is subsequently oxidized, but a non-negligible part was found to reach the atmosphere (Amouroux et al., 2002; Ivanov et al., 2002).

**Present-day functioning of the Black Sea ecosystem: cautious optimism**

Contrary to our expectations, EROS data recorded in 1995 and 1997 revealed some positive signs of recovery at different levels of the Black Sea ecosystem. However, the persistence of some indicators of environmental pollution call for greater caution.

First of all, Danube phosphorus and nitrogen loads to the Black Sea have decreased by 50 and 25%, respectively, compared to the peak values of 1989 (Cociasu et al., 1997; Lancelot et al., 2002). Budget calculations, based on the in situ measurement of ammonia benthic fluxes, indicate that sediments during the summer now contribute as much as ammonia for coastal phytoplankton as Danube waters (Friedrich et al., 2002). Benthic phosphate recycling accounts for only a half of Danube inputs (Friedl et al., 1998; Friedrich et al., 2002).

As a consequence of nutrient-input reduction and of biogeochemical transformations in the Danube estuary, coastal diatoms were found to be limited by phosphate availability in the presence of sufficient silicate (Ragueneau et al., 2002). Phosphate availability, rather than carbon sources, was also suggested to regulate organic matter degradation by bacterio-plankton during summer (Becquevort et al., 2002), which explains the observed transient accumulations of organic matter in the marine system. In agreement, a model reconstruction of biological successions over the same period (Lancelot et al., 2002) shows that diatom growth in the coastal and open Black Sea has been regulated over the last decade by ambient...
phosphate in spring and nitrogen and phosphate in summer, with silicon levels remaining undepleted. This contrasts with the current concept of diatoms being better competitors for inorganic phosphorus and nitrogen when silicate is sufficient; the concept behind the general understanding of human-induced eutrophication.

Inorganic contaminants were now also found to reach concentrations similar to those recorded in the Mediterranean and Baltic Sea (Guieu & Martin, 2002), although historically high levels of contaminants were reported in the north-western Black Sea. In contrast to metal pollution, the Danube River has still been found to represent an important source of organic pollutants for the north-western Black Sea, especially for its northern mouth (Chilia branch) (Maldonado & Bayona, 2002). The concentration of petroleum hydrocarbons, organochlorine compounds and sewage-marker trialkylamines was two orders of magnitude higher in the Danube mouth than in the open sea (Maldonado & Bayona, 2002). The chemical composition of the organochlorine compounds revealed a recent use of pesticides in the riparian countries. Their recorded concentration level was one order of magnitude higher than those reported for the Mediterranean Sea.

Although some signs of improvement were noticed in the water column, it must be stressed that sedimentary deposits represent the pollutants that ultimately sink. As an example, a comparison of post-Chernobyl$^{137}$Cs input from the Danube to the $^{137}$Cs inventory in the adjacent Black Sea sediments showed that more than 70% of the radionuclide discharged by the river was deposited in the Danube–Black Sea mixing zone (Gulin et al., 2002). Moreover, intensive oil-drilling activities on the shelf have introduced large quantities of several inorganic trace elements, such as Ba, Cu and Zn, which are now accumulated on the shelf sediment (Secreriu & Secreriu, 2002).

At the ecosystem level, some planktonic and benthic species, previously considered to be extinct or very rare, are now very common again in the Black Sea. Similarly, a slight recovery of the mussel (Mytilus galloprovincialis) population was observed from 1995 to 1997 (Gomoiu unpubl. data). The Mnemiopsis biomass of summer 1995 (Weisse et al., 2002) was ten-fold lower than during the period 1989–1990, and the number of anchovy eggs and larvae has increased (Shiganova, 1997). Interestingly, Mnemiopsis records for 1995 were similar to those reported for 1991, 1992 and 1993 (Müldü et al., 1994), suggesting that the population has now reached an equilibrium. However, as pointed out by Weisse et al. (2002), interannual trends must be interpreted with caution, as no standard method currently exists to estimate the biomass of Mnemiopsis.

Incidentally, the reported improvements correspond with the socio-economical decline faced by eastern and central European countries since 1991. The link between the observed reduction of Danube nutrient loads to the Black Sea and the economical situation of Danubian countries is further supported by scenarios of the Danube River model constrained with economical indicators of 1994 (Garnier et al., 2002). This highlights the great sensitivity of the Black Sea ecosystem to human-induced changes in the Danube watershed. However, as revealed by the EROS results, other human activities, such as overfishing, introduction of exotic species and pollution, superimpose the effects of man-made eutrophication in a complex pattern whose controlling mechanisms are not fully understood. The future recovery of the economies of central and eastern European countries, without adequate concerted environmental policy among Danubian countries, might, therefore, once more have dramatic consequences for the coastal Black Sea environment. Addressing this question requires internationally integrated multidisciplinary research projects such as EROS, with the dedicated involvement of both scientists and environmental managers in order to improve the basis for government decision-making, as well as elevating scientific competence with respect to marine resources management and evaluating the effects of eutrophication.

Acknowledgements

The EROS-21 project has been funded by the Programmes Environment and Climate (contract No. ENV4-CT96-0286) and INCO-Copernicus (contract IC20-CT96-0065) of the European Commission. This is publication No. 173 of the ELOISE initiative.

References


Human activities and the coastal environment, north-western Black Sea


Estuarine, Coastal and Shelf Science 54, 337–354.


