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Environmental Impact Study of Projects Affecting the Quality of Marine Ecosystems*

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According to the EEC Directive 85/337, an Environmental Impact Assessment (E.I.A.) procedure must be implemented to evaluate the effect of major projects on the environment. Several environmental activities are required by the E.I.A. procedure during various phases of the life cycle of the project, including construction, start up, operation and decommissioning. The Environmental Impact Study (E.I.S.) is a basic component of the E.I.A. procedure delivered by the engineering Company to the competent Authority for approval. Besides providing information needed for E.I.A., the E.I.S. also represents a tool for supporting decision as it defines project criteria, identifies mitigation measures and monitoring design. Owing to the complexity of the interactions among biotic and abiotic components, the application of E.I.S. to the marine environment generally implies an interdisciplinary and integrated approach.

Two typologies of E.I.S. recently developed are discussed and compared, concerning the construction of three submarine tunnels crossing the Strait of Messina and building of a Liquid Natural Gas (LNG) terminal for the liquid methane re-gasification at a coastal site of the Gulf of Trieste (Panzano Bay), North Adriatic Sea.

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INTRODUCTION

The first project consists of crossing the Strait of Messina by three submarine tunnels, two for vehicular traffic and one for the railway, about 6 kilometers long and 15 meters in inside diameter. The tunnels will be kept at a depth of approximately 40 meters and anchored to the bottom by steel wires. It was recognized that the main potential hazards for the marine environment arise, respectively, from the obstacle of the structures to the migration of big pelagic fishes, the eventual modification of upwelling processes, and from the re-suspension, dispersion and settling of sediment, following dredging operations and affecting in particular water turbidity and benthic biocenoses, mainly phanerograms.

The second project involves the construction of a Liquid Natural Gas (LNG) terminal in the Gulf of Trieste. The liquid gas, mostly methane, will be transported by gas tankers at a temperature of –160 °C to the terminal and here submitted to re-gasification using seawater as warming fluid for the most part of the year.

The following potential hazards for the marine environment were envisaged:

– the dredging and subsequent dispersion of bottom sediments (more than 9 million cubic meters of sediment must be dredged to allow marine traffic);
– the consequent turbidity induced along with the re-dissolution of nutrients and toxics from suspended particulate and sediment pore water;
– the inflow of colder seawater used for re-gasification as well as residual biocides used as antifouling agents.

The bay is already affected by the inflow from the two mouths of the Isonzo River, by the Timavo River and by urban wastes. Furthermore, the bay is very shallow, with the depth less than 15 meters, while clay and mud are the prevailing sedimentological components. The sites requiring particular protection are the fish and mollusk farming plants located along the eastern side of the Trieste Gulf and an area characterized by a phanerogam community lying near the western coastline and exploited intensively by fishing.

According to the E.I.S. procedure, in both cases the main aims of the study were the following:

– description of the environmental situation for all the biotic and abiotic components that might become affected by works;
– assessment of the effects of alternative interventions;
– identification of the most compatible and adequate solutions;
– design of a monitoring programme.

METHODOLOGY

The following techniques were employed in the course of environmental impact studies:

– conventional surveys at fixed hydrological stations;
– continuous surveys from a sailing vessel;
– experiments of nutrient, metal and hydrocarbon release from suspended sediment;
– numerical models:
  - 2-D (*x,y*) vertically integrated hydrodynamic model;
  - 2-D (*x,z*) dynamic-dispersive model simulating the upwelling behaviour in the Messina Strait;
  - 2-D (*x,y*) model simulating the dispersion of sediment, nutrients and pollutants released during dredging operations (Messina Strait and Panzano Bay);
  - 3-D model simulating the dispersion of effluents from the LNG plant of the Panzano Bay.

Survey at Hydrological Stations

The analytical methods used are listed in Table I. Other, mainly biological, parameters which were surveyed (phyto- and zooplankton, phyto- and zoobenthos and bacteria) are not discussed in this paper.

Continuous Survey from Sailing Vessel

Seawater was pumped on board from different depths and analyzed by »*in continuo*« techniques.[6]

Experiments of Release from Suspended Sediment

Various sediment fractions, sampled by a »Vibracore« in the dredging area of the Panzano Bay from the interface to a depth of 7 meters, were suspended and mixed in the laboratory with natural seawater sampled offshore. After half an hour of stirring, the suspension was centrifuged and nutrients, heavy metals and hydrocarbons were determined in the aqueous phase.

Preliminary tests were performed to find out the most adequate stirring time and concentration of suspended sediment. The release of nutrients and pollutants does not substantially increase after 0.5 hour of stirring, while the release per unit mass of sediment increases with the dilution of suspended solids. On the other hand, elements released at a very low concentration of suspended solids can fall under the detection limit.

It was demonstrated that tests performed at the level of about 1 g SS/l can be deemed representative of the spilling conditions following dredging

TABLE I

Analytical methods

Parameter	Method
Temperature, salinity, dissolved oxygen, pH, Eh, depth	Multiparametric idronaut Mod. 401 CTDO probe (vertical profiles and on board determination on a pumped water line)
Nutrients (in laboratory)	Colorimetric determination after Strickland and Parsons[1] and Grasshoff[2]
Nutrients (*in continuo*)	Automatic analysis by Systea-integral autoanalyzers
Chlorophyll a (in laboratory)	Spectrofluorimetric determination after acetone extraction (Standard Methods APHA-AWWA-WEF)[3]
Natural fluorescence	*In situ* Sea Tech fluorometer
Heavy metals	Anodic stripping voltammetry AS-DDP on rotating graphite electrode TFME
Mercury	Cold vapor AAS with pre-concentration on gold
Suspended solids	Particle counting with coulter counter multisizer II[4]
Hydrocarbons	High resolution gas chromatography / mass spectrometry + flame ionization detector after *n*-hexane extraction and concentration by rotating evaporator
Primary productivity	^{14}C method after on deck incubation[5]
Radiance	Multiparametric PAR-PNF 300 probe
Current (*in continuo*)	Doppler acoustic profiler

operations. Nevertheless, from a scientific viewpoint, the very complex processes of adsorption, desorption, chelation, *etc.* taking place during spilling and involving solid sediment components (organic and inorganic), pore water and seawater as well as the equilibria between different chemical species must be investigated more accurately.

Mathematical Models

The analysis of hydrodynamic, dispersive and trophic processes has been carried out by numerical models. The effects of the three submarine tunnels on the current pattern and upwelling phenomena in the Messina

Strait have been studied using the PHOENIX model, a widely used system of computer codes for the numerical simulation of zero, one, two and three dimensional fluid flow and heat or mass transfer.[7–9] For this specific application, the model has been used in the vertical 2-D configuration (x,z) and has been extended from the southern opening of the Messina Strait up to the area north of the sill. Curvilinear co-ordinates have been used for a better representation of the tunnels and of the large sea bottom variability, and the actual vertical density and current profiles have been applied at the two open boundaries. Simulations have been carried out for spring and neap tidal conditions, with and without the tunnels, and the results have been compared to evaluate the modification of the current regime induced by the tunnels. The model was previously calibrated against experimental current data. Phoenix has been used also for the analysis of 3-D dispersion of the effluents from the gasification plant in the gulf of Trieste. In this application, the fully 3-D configuration of the model and a curvilinear grid have been employed to represent the large sea bottom variations due to dredging in the area of the LNG marine terminal. Dispersion analysis has been carried out for different current conditions representative of the local current regime and the extension of the area potentially affected by significant temperature variations has been assessed.

Considering the shallow water depth and the barotropic nature of the gulf of Trieste, tidal and wind driven currents have been hindcasted by a 2-D, vertically integrated hydrodynamic model HYDROH.[10,11] The model simulates tidal and wind driven currents and sea surface elevation in a barotropic basin. The momentum and continuity equations are integrated on a regular grid by a time explicit, finite difference scheme with sea surface level as open boundary conditions and surface wind and atmospheric pressure as forcing terms. The time evolution of the vertically averaged current components and of sea surface elevation at the grid nodes have been calculated.

For the analysis of the circulation in the Panzano Bay, two nested models have been set up: a low resolution model with a mesh size of 375×250 m, extended over the whole gulf of Trieste, and a more detailed one, having a mesh size of 85×85 m, limited to the bay where the locating of the LNG marine terminal was planned. The low resolution model was used for the assessment of the open boundary conditions for the detailed model of the bay.

For the analysis of sediment dispersion during dredging operations, a numerical model has been developed that simulates sediment transport, dispersion, sedimentation and re-suspension by the current and waves, redissolution of nutrients and pollutants from the particulate, their dilution and decay and trophic processes. The non-stationary mass conservation equations (Eq. 1) for sediment, nutrients, phytoplankton and pollutants are integrated on a regular grid using a finite difference scheme and the 4th order Runge Kutta algorithm for time integration.

The basic equation is

$$\frac{\partial(HC_i)}{\partial t} = \frac{\partial(HV_x C_i)}{\partial x} - \frac{\partial(HV_y C_i)}{\partial y} + \frac{\partial}{\partial x}\left(HK_x \frac{\partial C_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(HK_y \frac{\partial C_i}{\partial y}\right) + \\ + S_i + B_i + D_i H \quad (1)$$

where C_i is the vertically averaged concentration of the following components:

C_1 = sediment
C_2 = phytoplankton
C_3 = nitrogen
C_4 = phosphate
C_5 = zooplankton
C_6 = detritus
C_7 = BOD
C_8 = dissolved oxygen
C_9 = conservative and non conservative pollutants
H = water depth
V_x,V_y = current components
K_x,K_y = diffusion coefficients
S_i = source
B_i = nutrients or toxics release rate
D_i = decay rate or biochemical trasformation rate

In the case of trophic parameters, D_i assumes the typical analytical formulation of trophic models, including photosynthesis, respiration, grazing *etc*. (see, for instance, Ref. 12 and many other codes available). At the open boundaries, radiative conditions are applied for outflow conditions and a constant concentration value is assigned for inflow conditions. Integration is carried out in the approximation of negligible effects of sediment concentration on the hydrodynamics, and pre-definite current fields are used, generally obtained by hydrodynamic models. Other inputs are light intensity, sea water temperature, river and outfall discharges, sediment size and the natural concentration in the water of relevant parameters. The model computes the concentrations of suspended sediment, nutrients, phytoplankton and pollutants, the sedimentation rate and light attenuation at sea bottom. The simulation of sediment dispersion during dredging operations has been carried out for different hydrodynamic conditions (tide, Bora, Libeccio and Scirocco induced circulation) and for different dredging systems.

RESULTS AND DISCUSSION

The Messina Strait Tunnels Project

The Messina Strait is a dyachroneus system since the tidal cycles of the Tyrrhenian and Ionian Seas have an opposite phase and currents flooding alternatively through the sill reach velocities higher than 6 knots (see Figure 1). The study area was surveyed both by continuous surveys of suitable tracers from a sailing vessel along the route indicated in Figure 2 and by 24-hour surveys at some significant stations. Each continuous survey was performed in about 3 hours around the peak of the maximum or minimum tidal level, in order to seize the quasi-stationary situations following the dynamic phases of the growing and ebbing tides, respectively. Figure 3 shows an example of surface distribution of temperature surveyed in July during a phase of syzygy. The whole area south of the Messina Strait is characterized

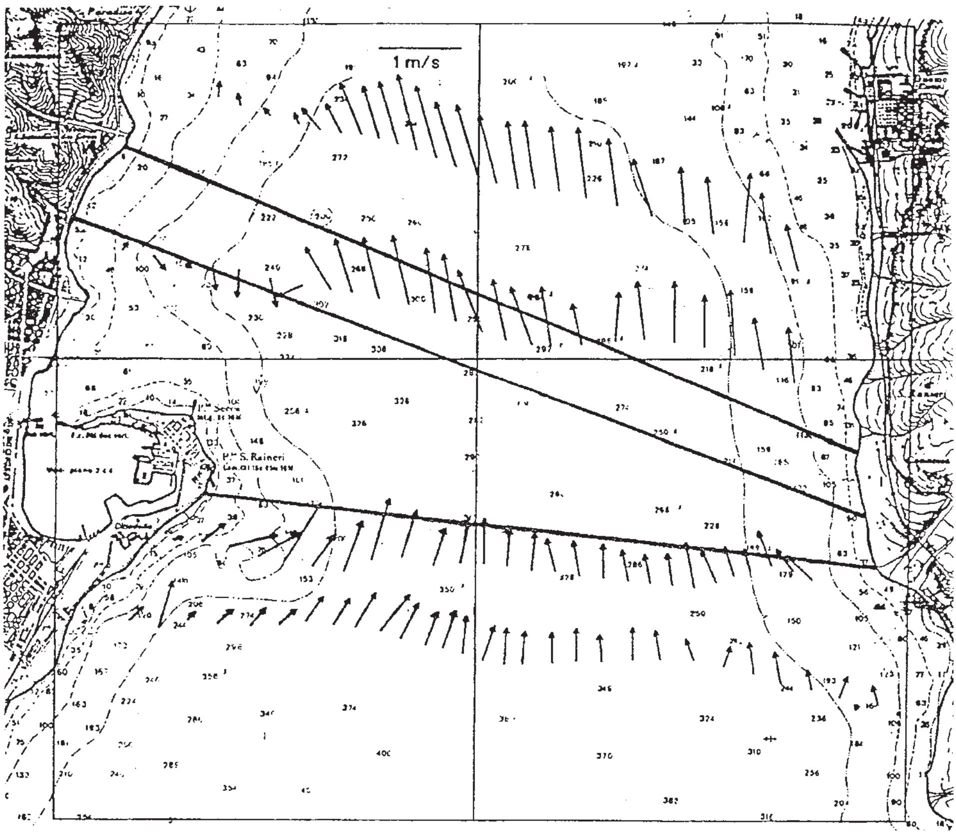


Figure 1. Lay-out of the tunnels and an example of bottom current field surveyed by a Doppler acoustic profiler (Messina Strait).

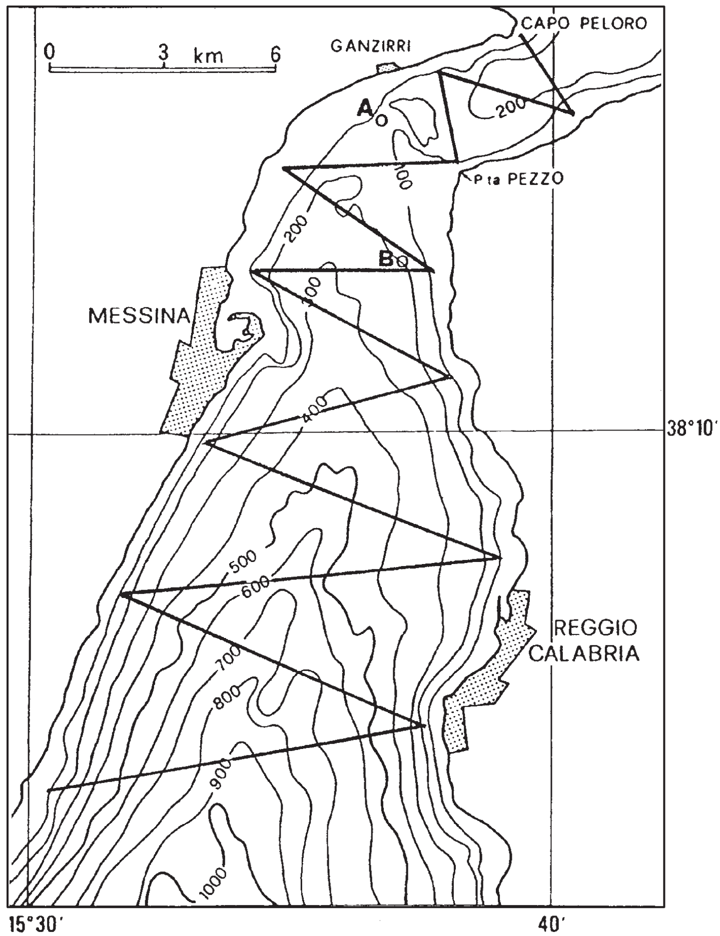


Figure 2. Route of continous survey and stations (A, B) of a 24-hour survey.

by upwelling, more evident along the coastal areas. During ebb tide, the warmer, nutrient-poor tyrrhenian water flows like a surface river and its centerline trajectory lies along the middle area of the basin. The tyrrhenian water flows back 6 hours later during the successive high tide phase. A similar behaviour was recorded for salinity, fluorescence (FTU), nitrate and primary productivity (see Figure 4). An increase of primary productivity about ten times higher than in tyrrhenian water was found in upwelling areas. Figure 5 shows the correlation recorded between primary productivity and density surveyed in syzygy from July 15th to 19th, 1992. The observed differences are explainable owing to the different time of residence of upwelled waters in the euphotic layer at the moment of sampling. In any case, the correlation is statistically significant and the stimulation of the plank-

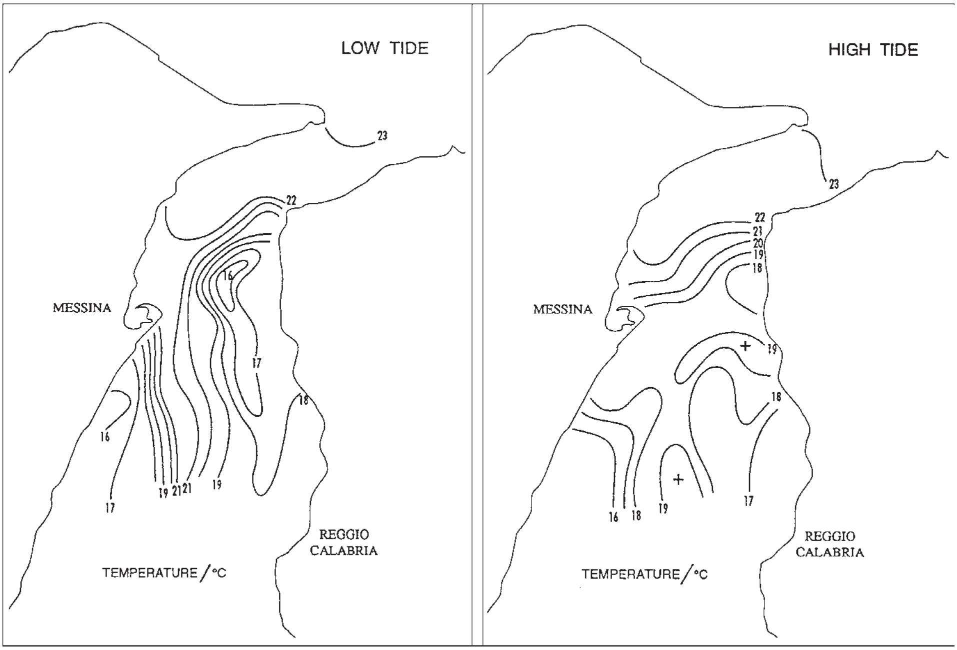
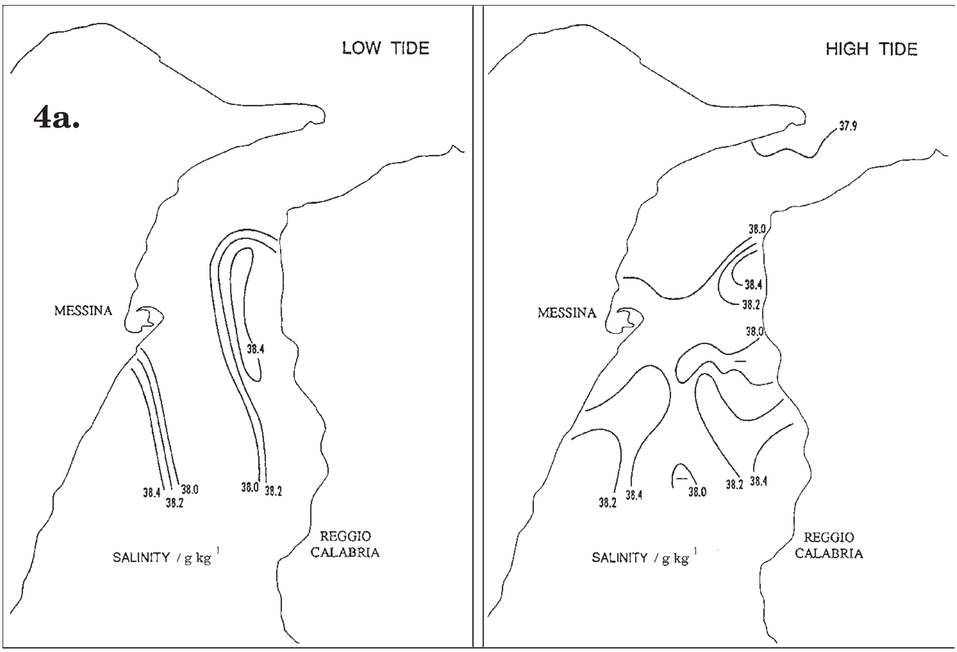


Figure 3. Effect of diurnal variability of syzygial tide on the surface distribution of temperature.



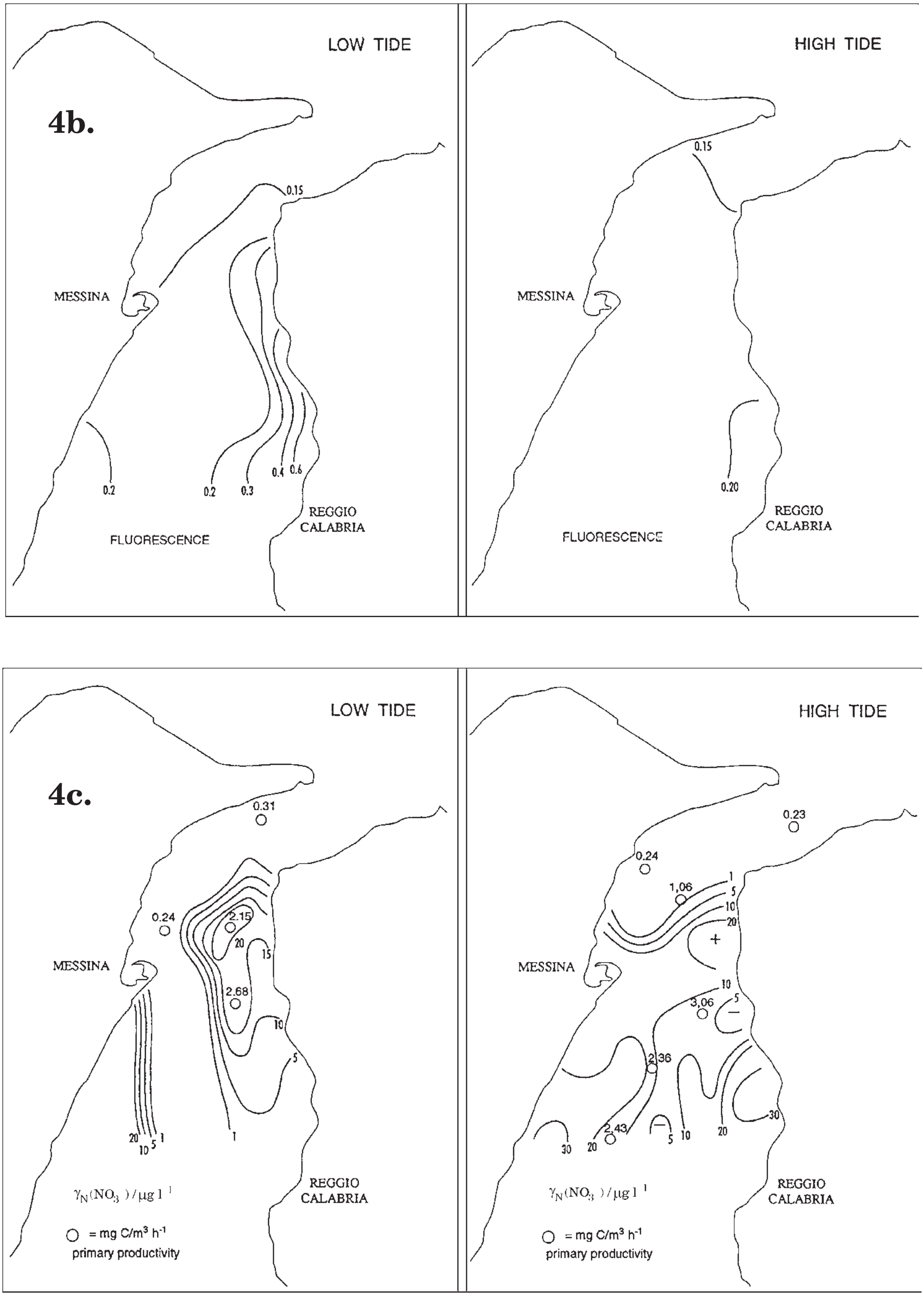


Figure 4. Effect of diurnal variability of syzygial tide on the surface distribution of salinity (a), fluorescence (b), nitrate and primary productivity (c).

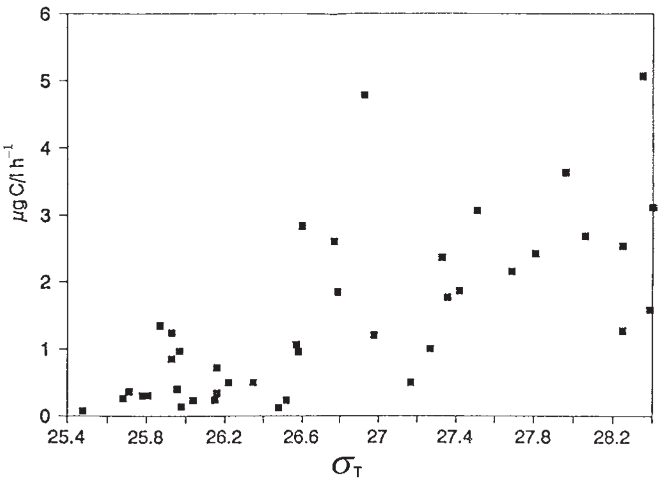


Figure 5. Correlation between water density σ_T and primary productivity.

tonic growth is likely to contribute considerably to the fish abundance in the area. Figure 6 shows the effect of the transition from syzygy to quadrature. In quadrature, the lowering of the tidal current velocity reduces strongly

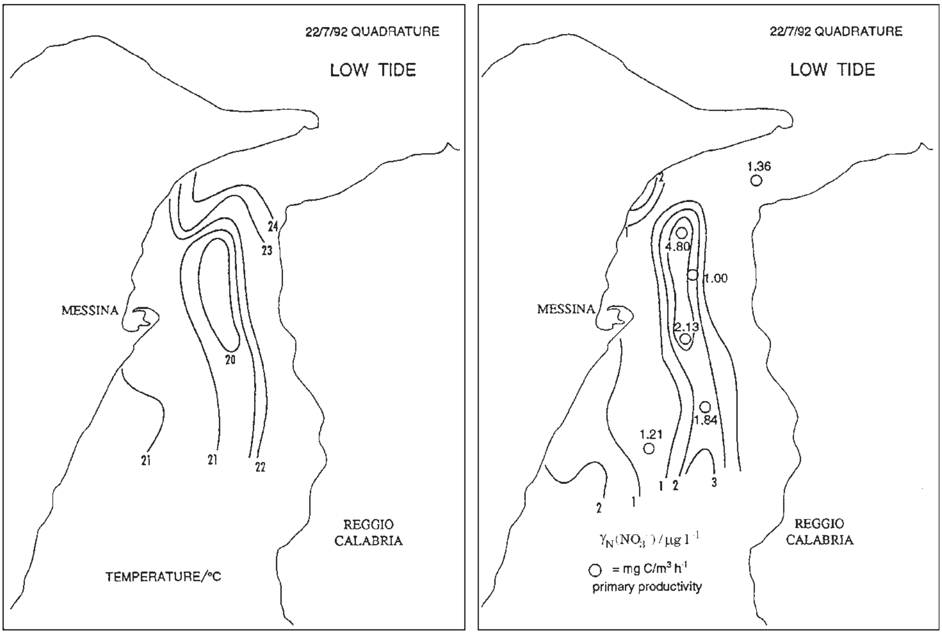


Figure 6. Example of surface distribution of temperature, nitrate and primary productivity in quadrature, low tide.

the upwelling. A small fraction of deep water is still present at the surface along the central area of the Strait, where primary productivity still remains higher, probably due to the increase in residence time. The phenomenological features were discussed by Cescon *et al.*[13] Gathered data were utilized to calibrate the (x,z) dynamic-dispersive model. The experimental and simulated thermal behaviours are compared in Figure 7.

The model was then used to simulate the modification to the current field induced by the presence of the tunnels. An increase of velocity is foreseen under and above the tunnels, as indicated by the example reported in Figure 8. Figure 9 represents the temperature distribution simulated along the central axis of the strait during the pre-operative phase and after the construction of the tunnels. The effect on upwelling is negligible.

The diffusion of suspended sediment following dredging operations near the 6 landing heads of the tunnels was simulated by the two-dimensional (x,y) dynamic-dispersive model. The model also simulates the thickness of

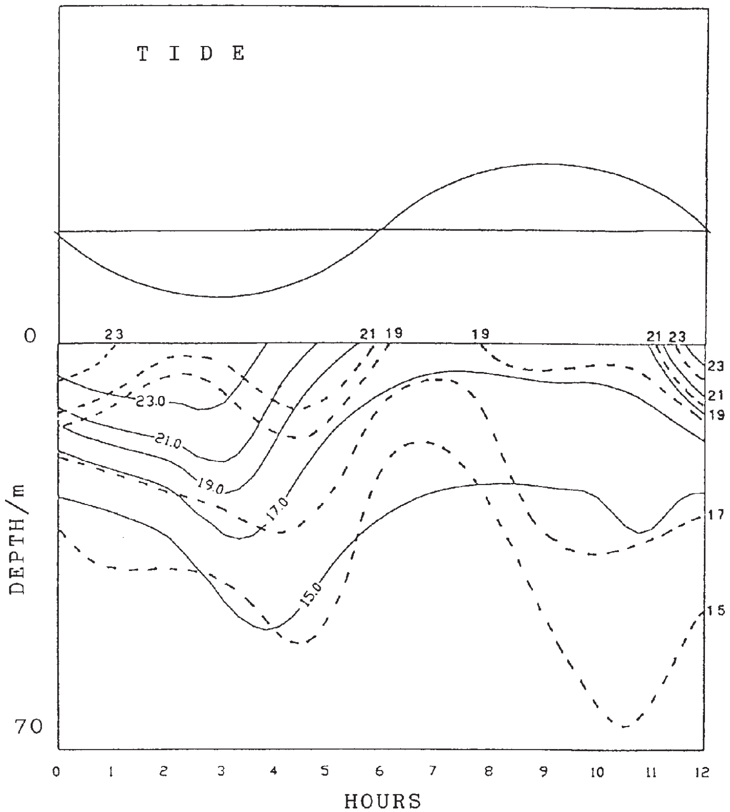


Figure 7. Comparison between experimental (dashed line) and simulated (full line) behaviour of temperature at the sill of the Messina Strait in syzygy.

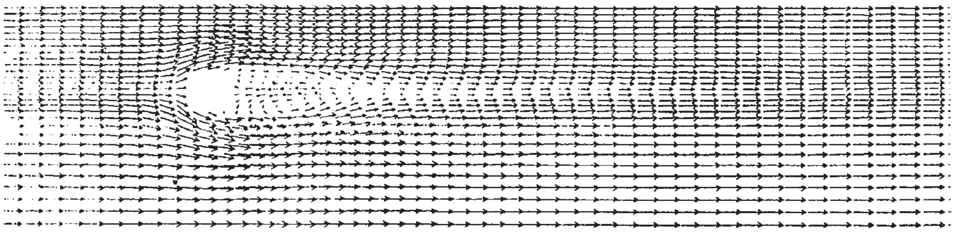
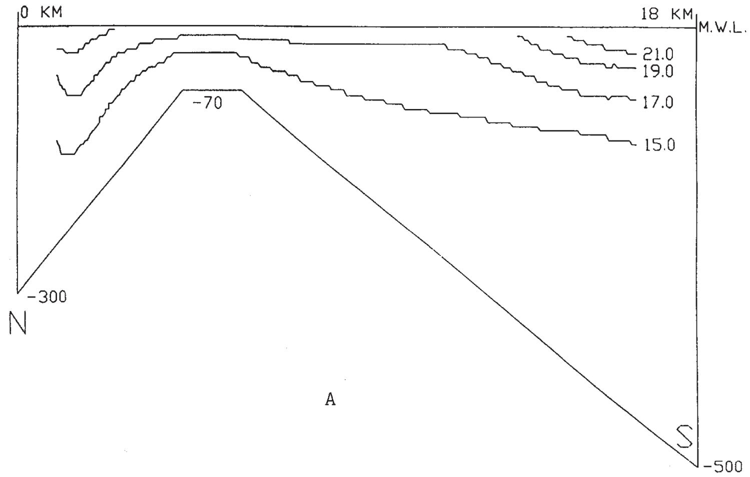


Figure 8. Example of velocity vectors around a tunnel simulated by hydrodynamic model.



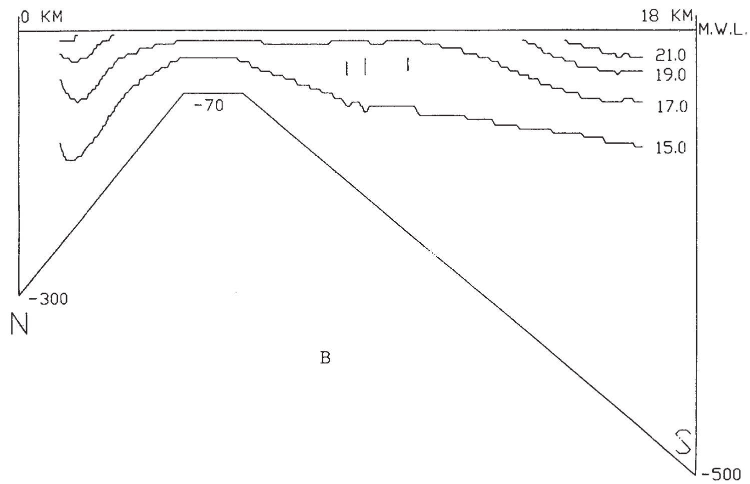


Figure 9. Simulated distribution of isotherms without (A) and with (B) the tunnels at the sill during a phase of maximum S-N current.

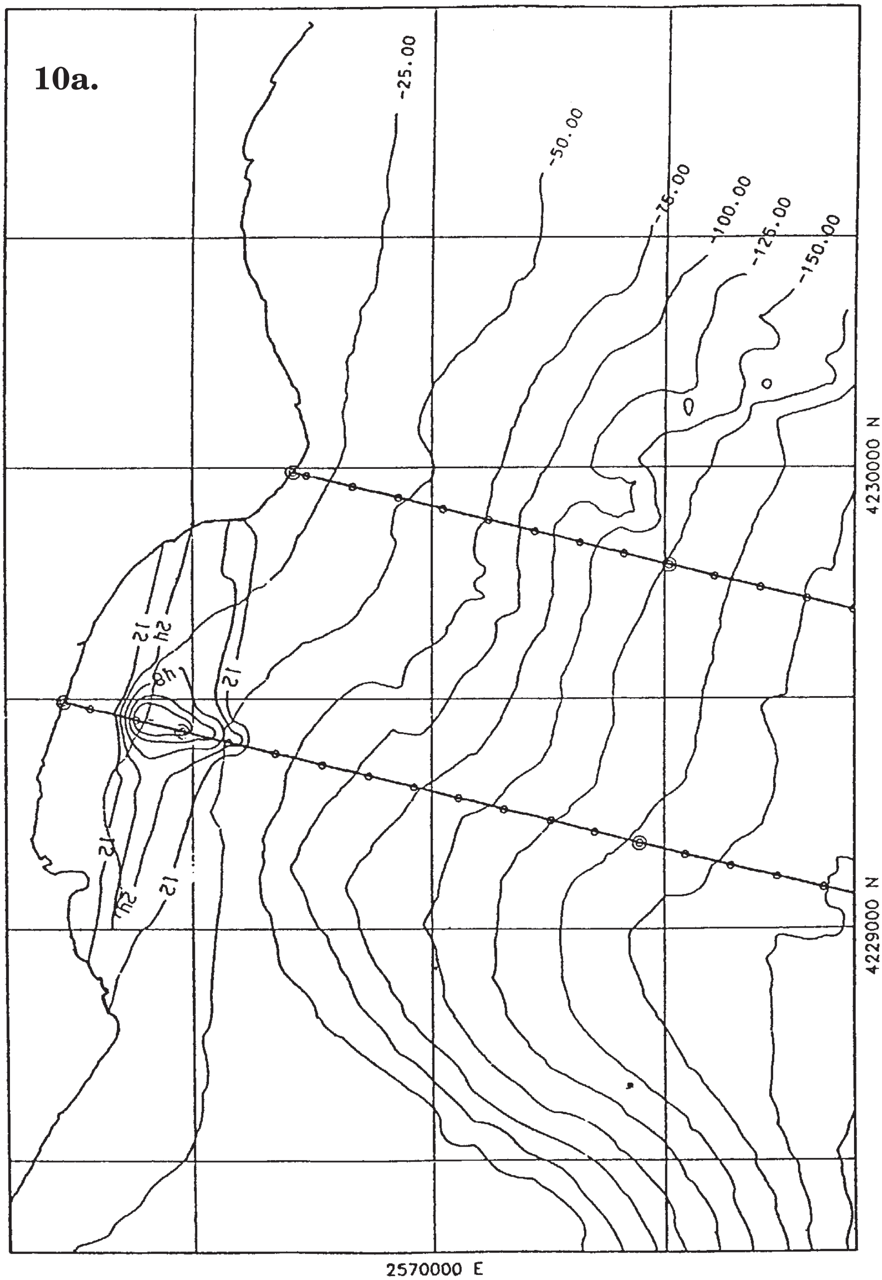
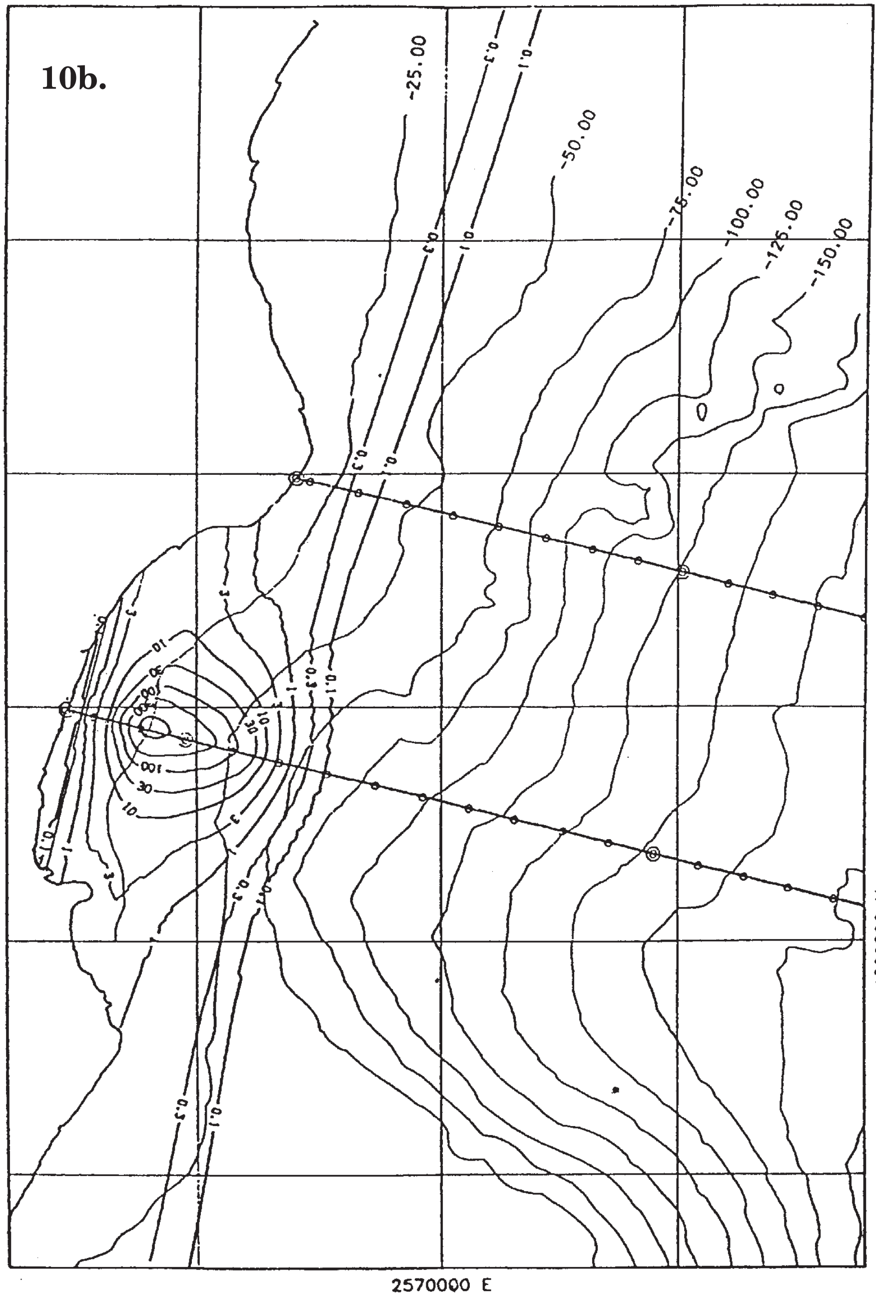
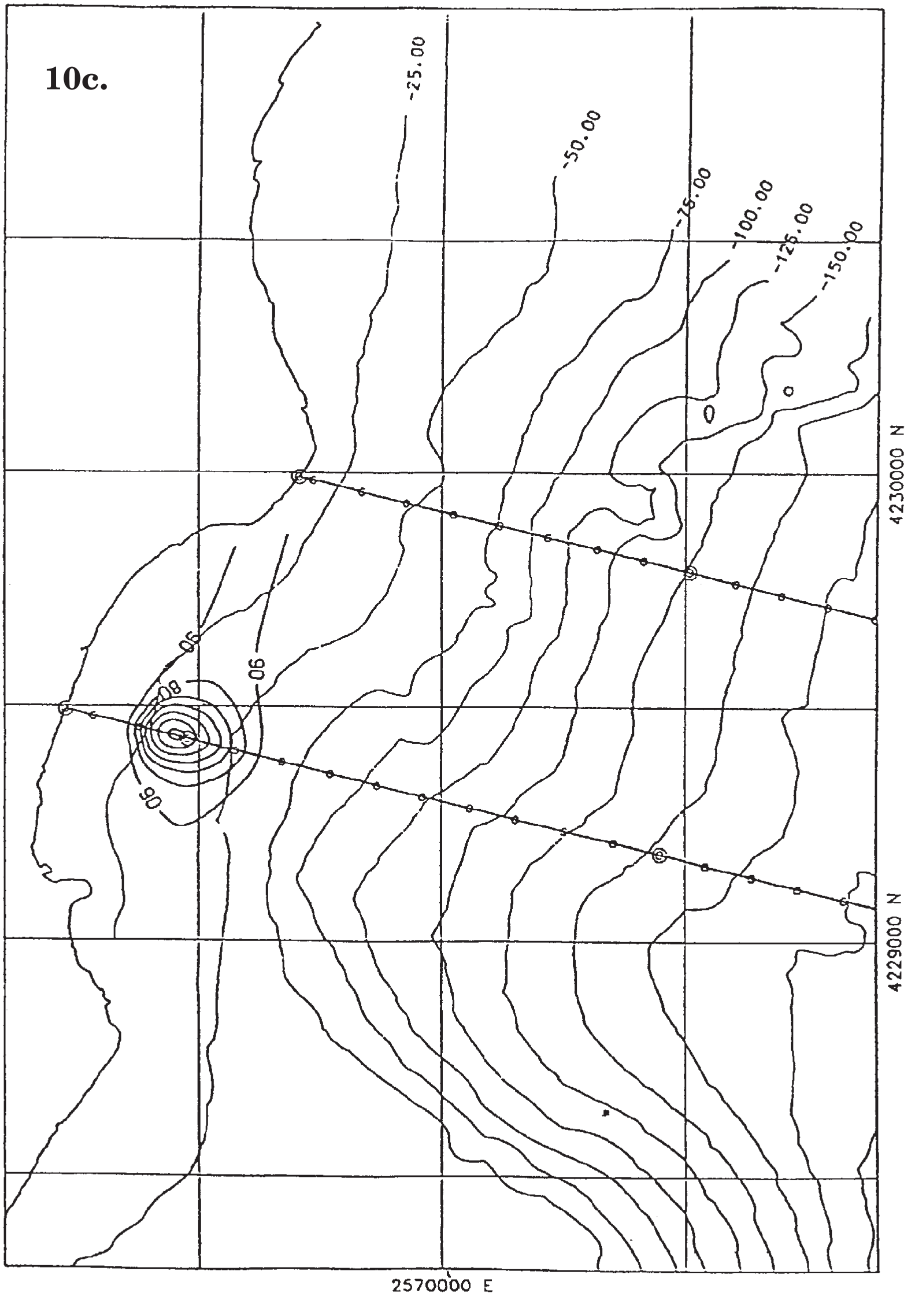


Figure 10. Examples of model simulation of dredging effects in the Messina Strait: (a) isochrones of the total time / hours with suspended solids concentration higher than 1 ml/m^3; (b) total sediment deposition / mm; (c) per cent light attenuation I/I_{nat} at the bottom.



the sediment settled and accumulated at the bottom, the time spent by the system at a concentration of suspended particulate higher than a fixed



value and the ratio between the average light intensity at the bottom and the corresponding natural values (see Figure 10).

Using the classical equation for the photosynthetic rate:

$$P = P_{\mathrm{MAX}} \frac{e}{kZ}\left[\exp(I_z / I_o)\exp(-k_z) - \exp(I_z / I_o)\right] \quad (2)$$

where $I_z = I_o \exp(-k_z)$

$k = \alpha + \beta[\mathrm{SS}] + \gamma \mathrm{F}$

I_o = incident light intensity

I_z = light intensity at depth Z

k = light extinction coefficient / m^{-1}

α = extinction coefficient of seawater in the absence of suspended solids (SS) and plankton (F) = 0.045 m^{-1}

β = suspended solid extinction coefficient = 0.072 m^{-1} per ml SS m^{-3}

γ = phytoplankton extinction coefficient = 1.2 m^{-1} per mg C l^{-1}

P = photosynthetic rate per unit biomass,

it was demostrated that the reduction of primary productivity is negligible. Indeed, a primary productivity reduction of 11.4% was estimated for an average value of 0.1 ml SS/m^3 and a 44% reduction for 1 ml SS/m^3. Values of suspended solids higher than 1 ml/m^3 are foreseen to occur in maximally 24 hours in an area smaller than 100 meters in width. Such very favourable conditions are mainly due to the high grain size of the sediment (from sand to gravel) implying a very short settling time for re-deposition at the bottom.

Quite different conditions may be found in areas where mudd and clay prevail, as in the case of the LNG terminal location.

The LNG Terminal of the Trieste Gulf

The Panzano Bay is presently affected by the inflow of several water courses and wastes (see Figure 11). Consequently turbidity, nutrients, chlorophyll, primary productivity, hydrocarbons, heavy metals and bacteria concentrations increase sharply in inshore area along with a reduction of salinity in the upper layer (see Figure 12) and a depletion of dissolved oxygen in the bottom layer. Table II summarizes the results obtained by sediment re-

TABLE II

Average release of nutrients, heavy metals and hydrocarbons / (μg/g SS) determined at the approximate level of 1 g suspended solids/liter

N_{TOT}	P_{TOT}	Pb	Cd	Hg	Σ Aliphatic H	Σ Aromatic H
20.2	4.05	0.098	0.015	0.0018	0.058	0.007

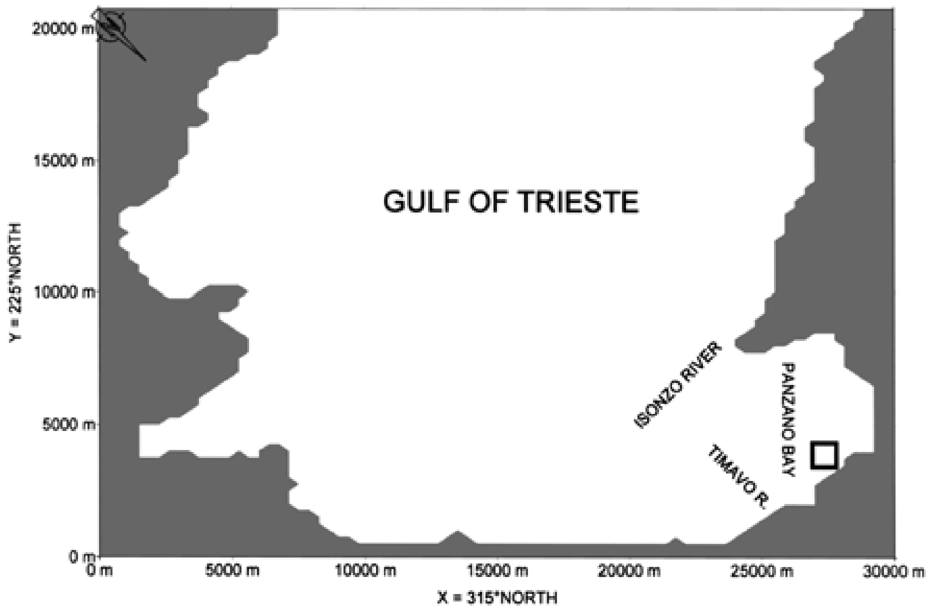
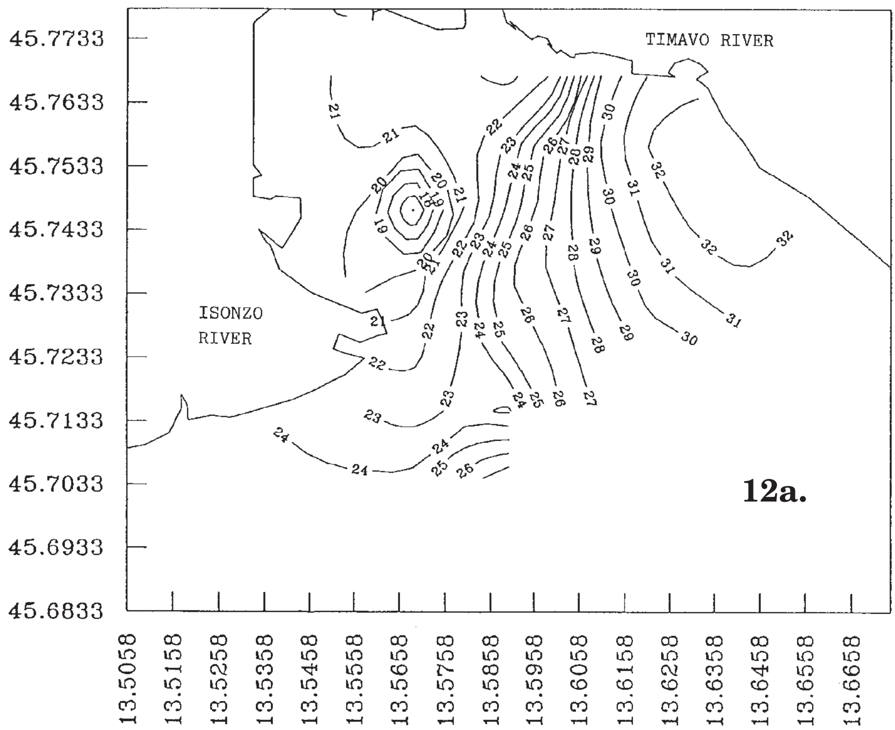


Figure 11. The project area (Panzano Bay). The square denotes the dredging area.



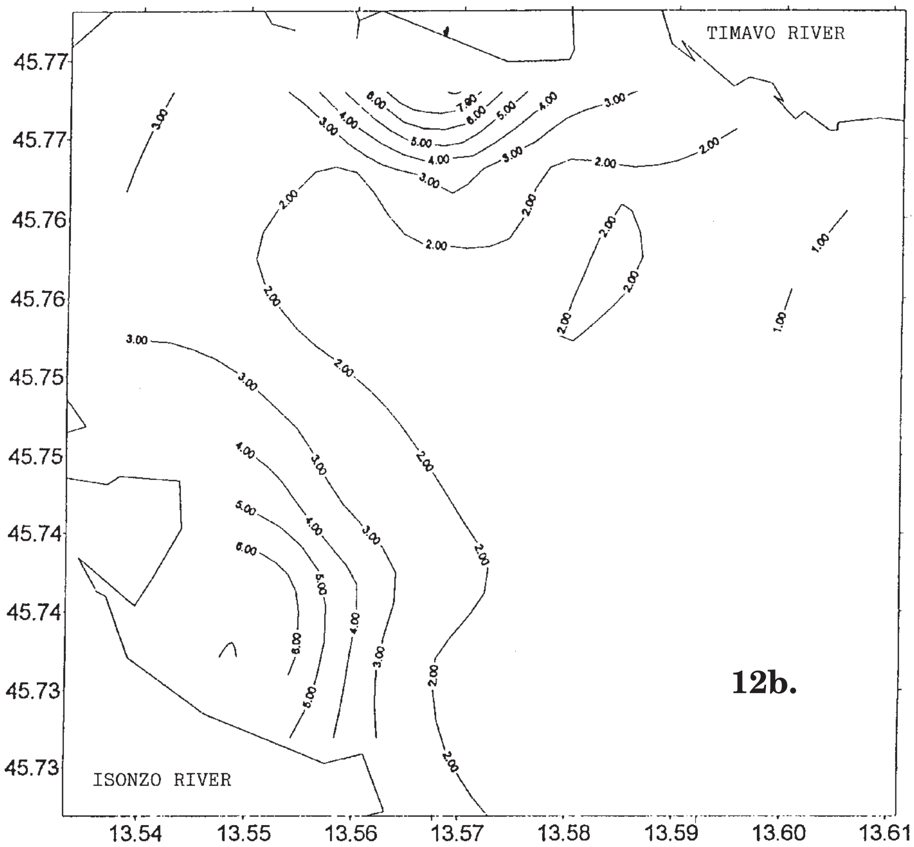
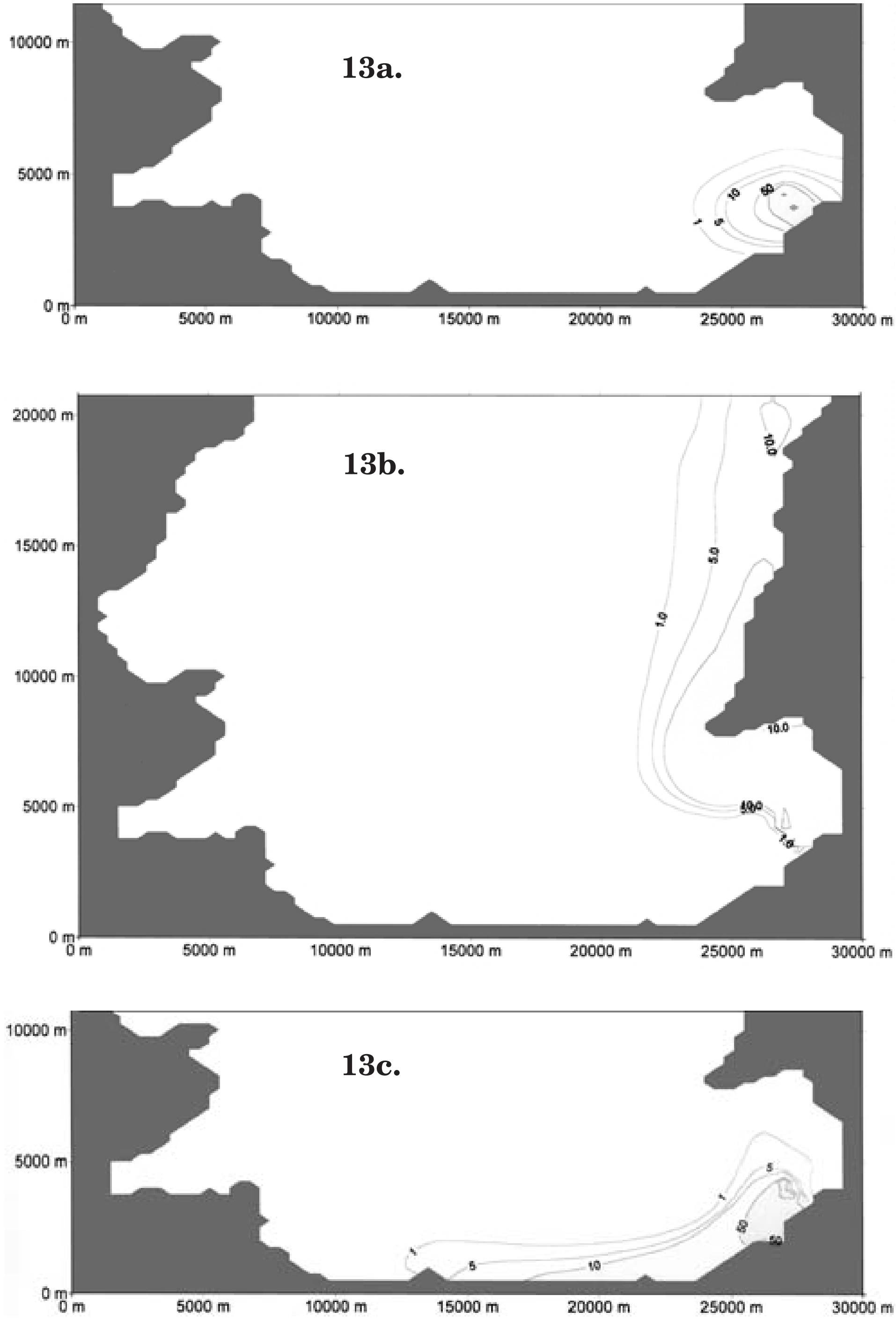


Figure 12. An example of salinity/g kg^{-1} (a) and chlorophyll/μg l^{-1} (b) surface distribution surveyed by continous analysis during a flood period.

lease experiments. For copper and zinc, on average, re-adsorption prevails over release.

The 2-D dynamic-dispersive and trophic model was used to simulate the areal distribution, vertically averaged, under different meteorological conditions of suspended solids (Figure 13), Secchi disk depth (Figure 14), nutrients (Figure 15) phytoplankton (Figure 16), heavy metals as well as the average light extinction at the bottom and the final thickness of the settled sediment (Figure 17).

Settling velocity of particles of different grain size, light extinction coefficient and its relationship with phytoplankton and suspended solid concentration (see Figure 18), boundary conditions (*i.e.* river flow rate and nutrient load) and natural background conditions used for model simulation were determined experimentally. The hydrodynamic sub-model was calibrated separately from current meter measurements.


13a.
10000 m
5000 m
0 m
0 m
5000 m
10000 m
15000 m
20000 m
25000 m
30000 m
1
5
10
50
13b.
20000 m
15000 m
10000 m
5000 m
0 m
0 m
5000 m
10000 m
15000 m
20000 m
25000 m
30000 m
10.0
5.0
1.0
10.0
1.0
13c.
10000 m
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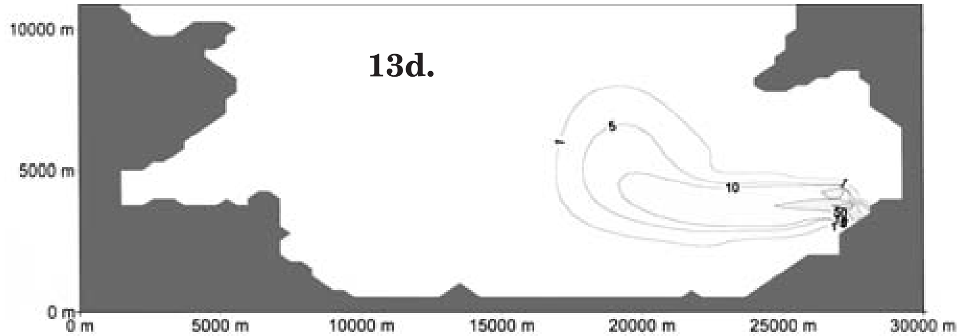


Figure 13. Simulated behaviour of the average suspended solid concentration / ml l^{-1} during dredging in the absence of wind (a) and with E-N-E (b), S-W (c) and S-E (d) blowing winds.

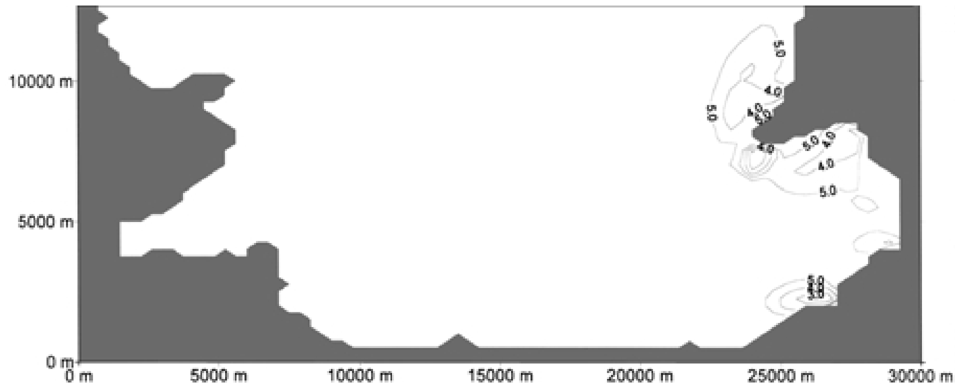


Figure 14. Simulated behaviour of Secchi disk / m distribution in the absence of wind during dredging.

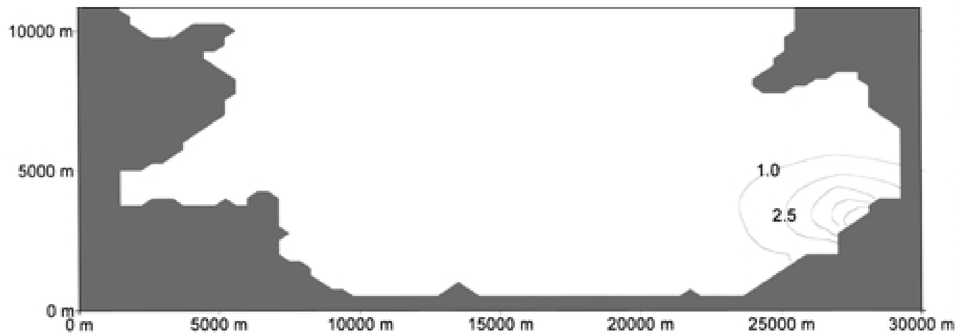


Figure 15. Simulated behaviour of phosphate distribution (γ_P (PO_4^{3-}) / g l^{-1}) during dredging in the absence of wind.

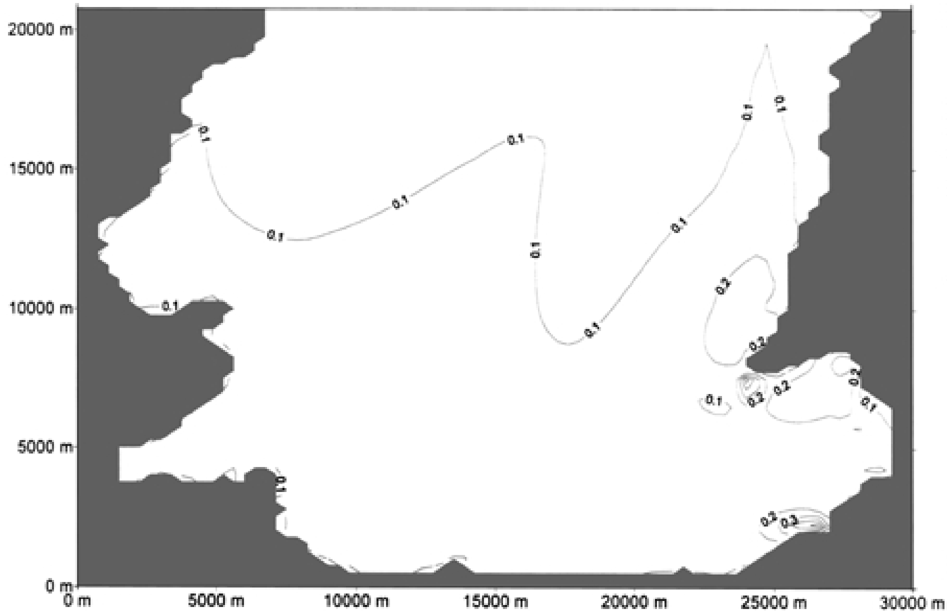


Figure 16. Simulated behaviour of phytoplankton (mg C/l) during dredging in the absence of wind.

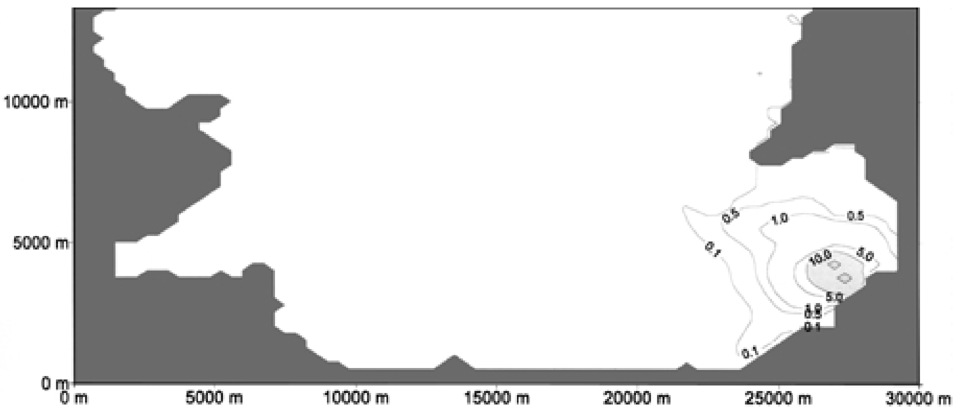


Figure 17. Simulated total deposition / cm at the end of the dredging with a mechanical dredge.

Figure 19 summarizes the present average distribution of heavy metals in seawater at some of the surveyed stations, together with the forecast increment due to sediment suspension and release. The relationship between

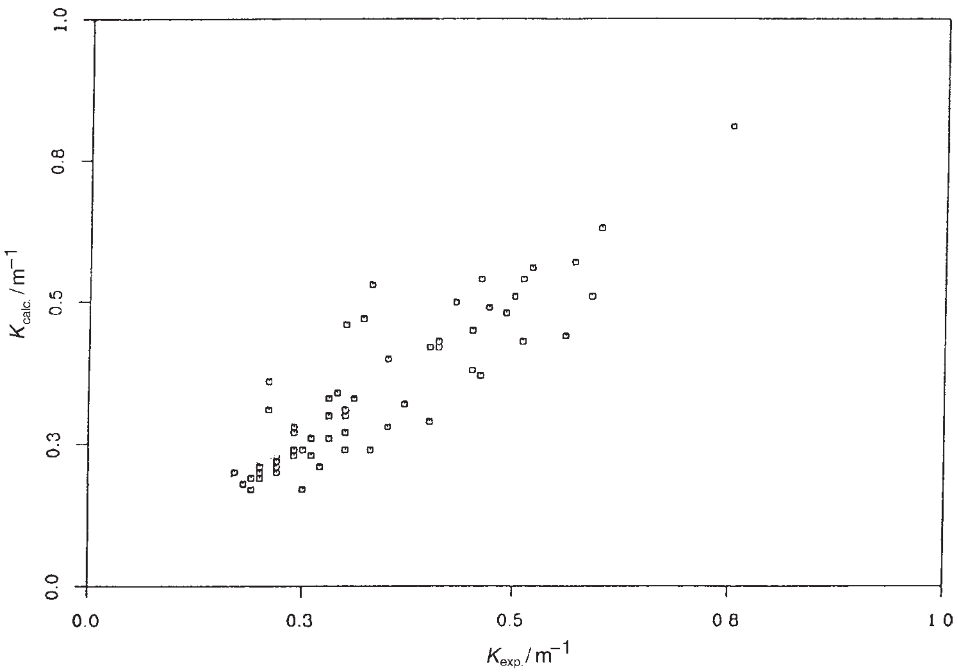


Figure 18. Comparison between theoretical and experimental light extinction coefficient (K / m^{-1}).

heavy metal concentration in water + particulate and mollusks can be drawn from an experiment previously carried out in a differently polluted area of the Venice lagoon using as target the fresh mythilus samples collected at the farming plants of Duino (see Figure 20). Using the correlation found and accounting for the model simulation results, an estimate can be obtained of the future contamination of mussels resulting from dredging operations (see Figure 21).

All the simulations shown refer to the use of a mechanical dredge. But it was proven that a hydraulic dredge is highly preferable, as it ensures a more adequate protection of critical areas. For instance, Figure 22 compares the average % light attenuation at the bottom simulated with mechanical and hydraulic dredges, respectively. Another mitigation measure is a work break in some (infrequent) instances of particular intensity or duration of ENE (Bora) and SW (Libeccio) winds.

Finally, Figure 23 shows the dispersive behaviour of seawater used for re-gasification: a ΔT lower than 1 °C and a 90% reduction of antifouling substances are forecast at a distance smaller than 1000 m from the inlet.

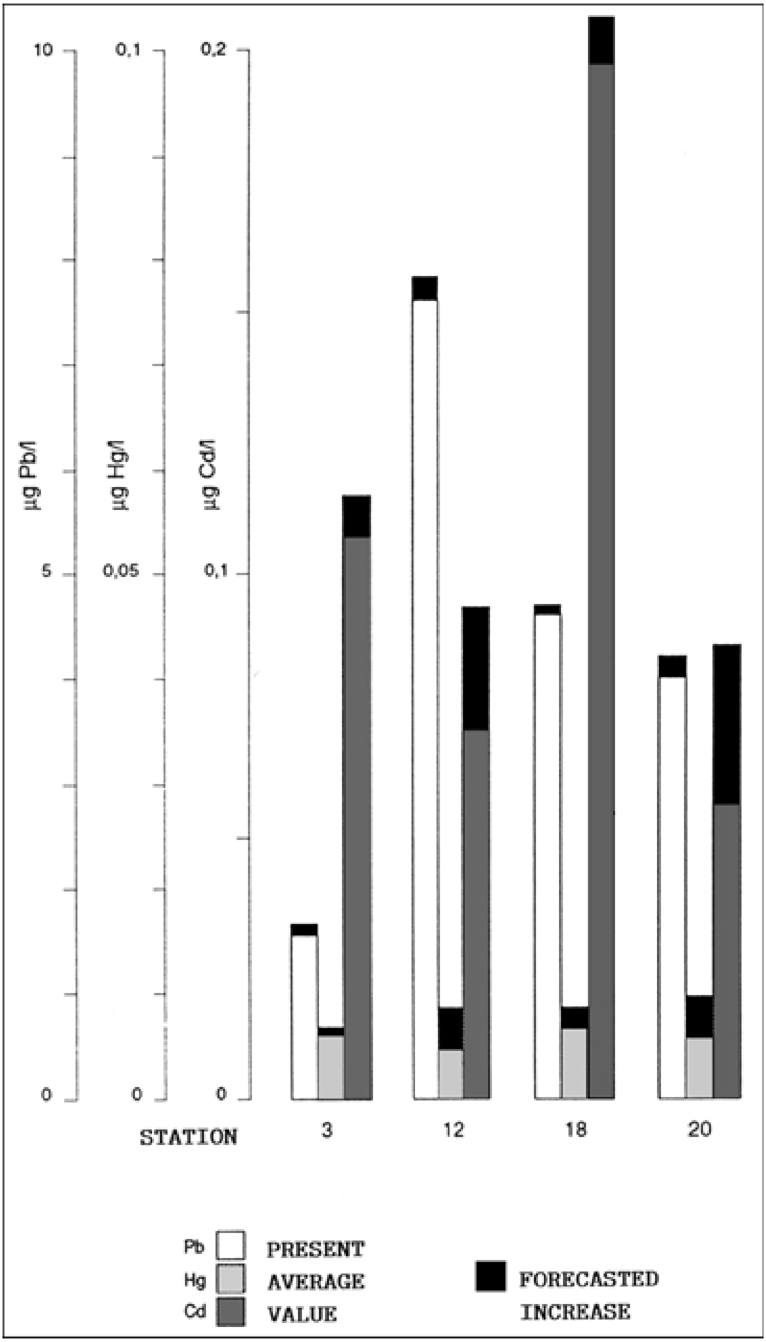


Figure 19. Present and forecast concentration of some heavy metals after dredging in some stations of the project area.

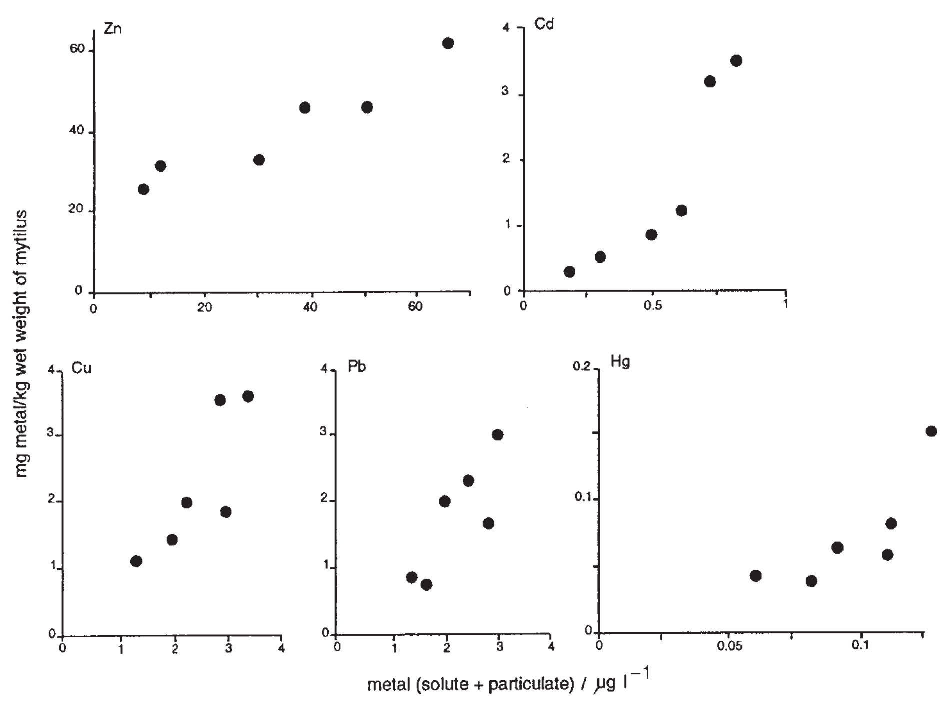


Figure 20. Correlation between the average heavy metal concentration in water + particulate and in mytilus after a 4-month bioaccumulation test.

An exaustive discussion on the use of such forecasting tools to support engineering decisions is beyond the scope of this presentation. However, attention is focused on this very challenging field of investigation, where standard methodology is not always available and the procedure must be assessed from time to time depending on the features of the problem.

CONCLUSIONS

From the engineering viewpoint, dredging of considerable volumes of pelitic sediments in shallow marine areas should be avoided whenever possible. Alternatively, dredging operations must be planned carefully and mitigation measures adopted on the basis of accurate model forecasting.

From the methodological viewpoint, the experimental activity and modeling should be planned taking into proper account the variability in both time and space of the forcing factors. For instance, previous investigations of the Messina strait were carried out disgregarding the diurnal and weekly

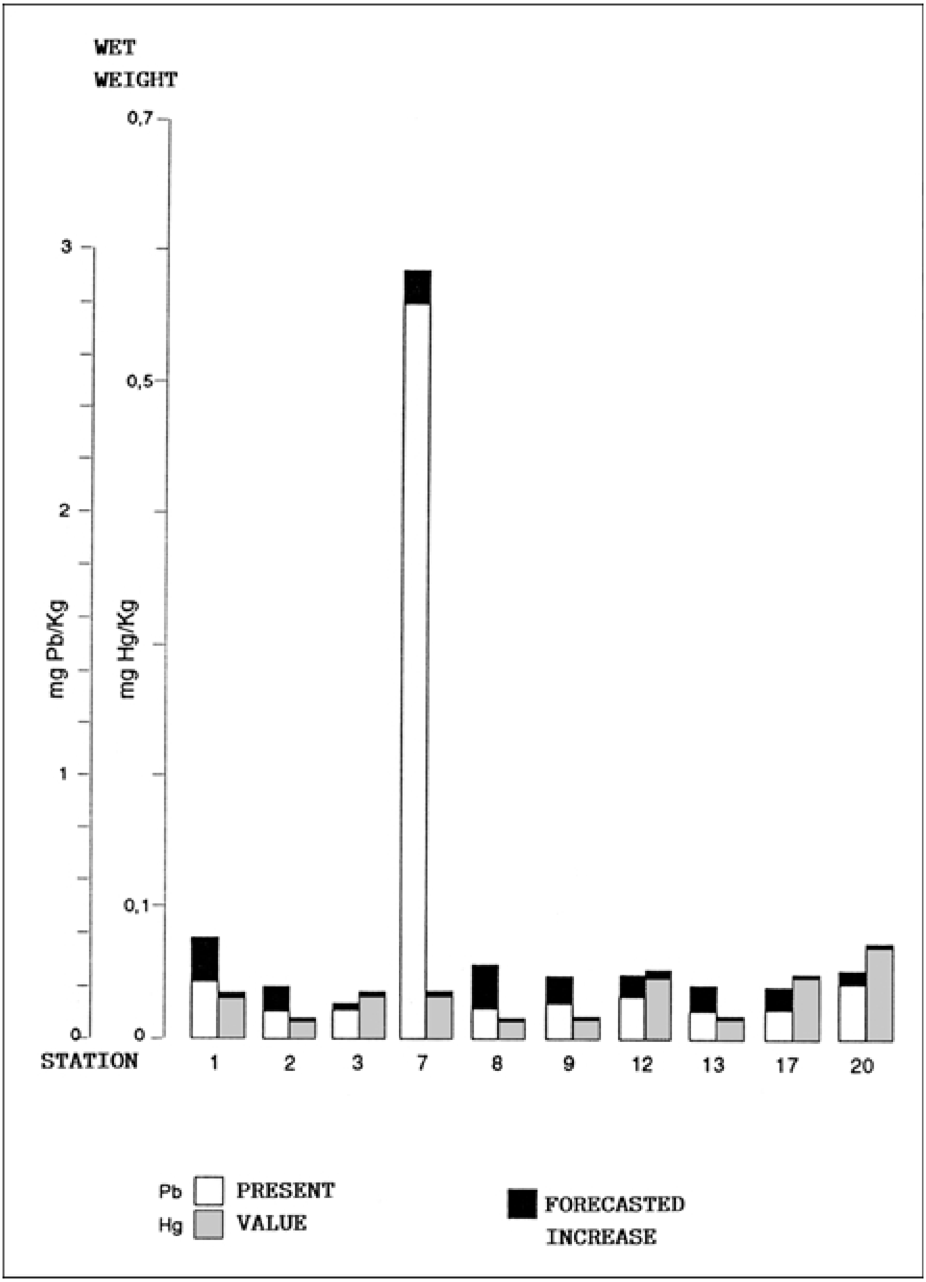


Figure 21. Present and forecast concentration of Pb and Hg in mytilus at various stations.

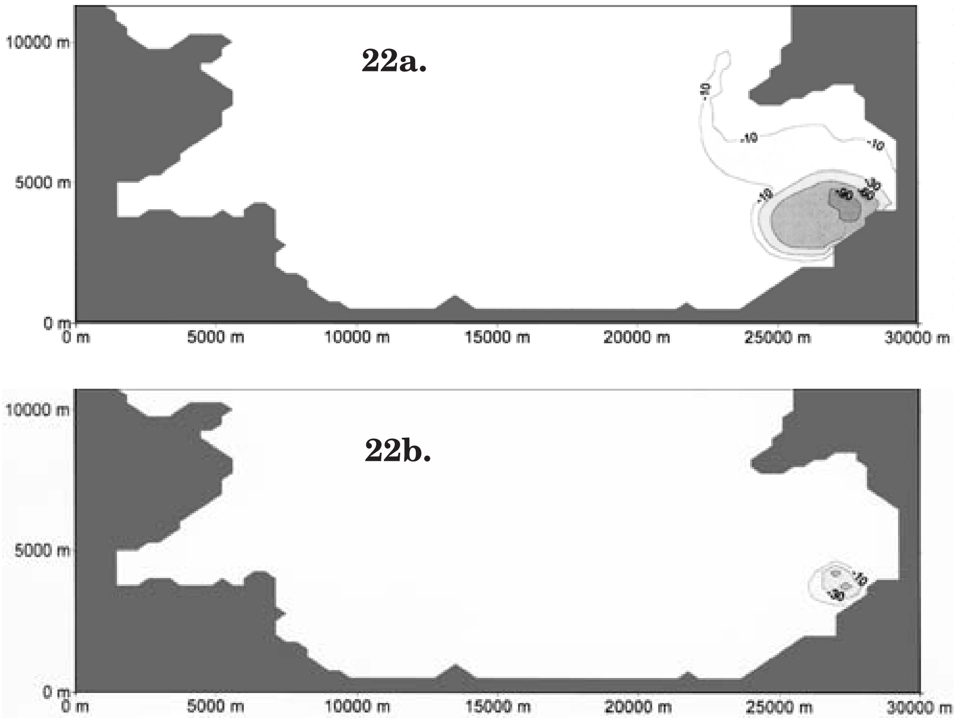
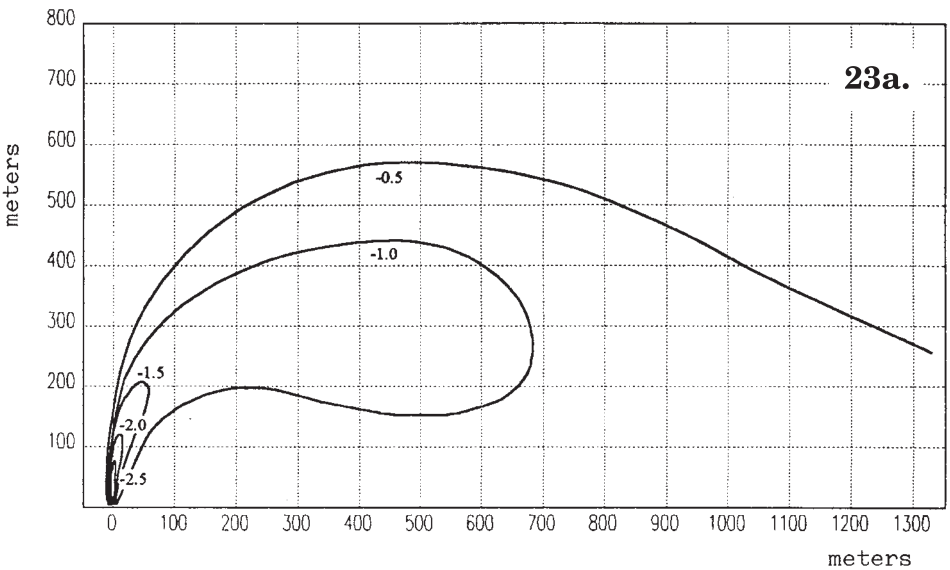


Figure 22. Comparison between the average per cent light attenuation at the bottom during dredging using mechanical (a) and hydraulic (b) dredges, respectively.



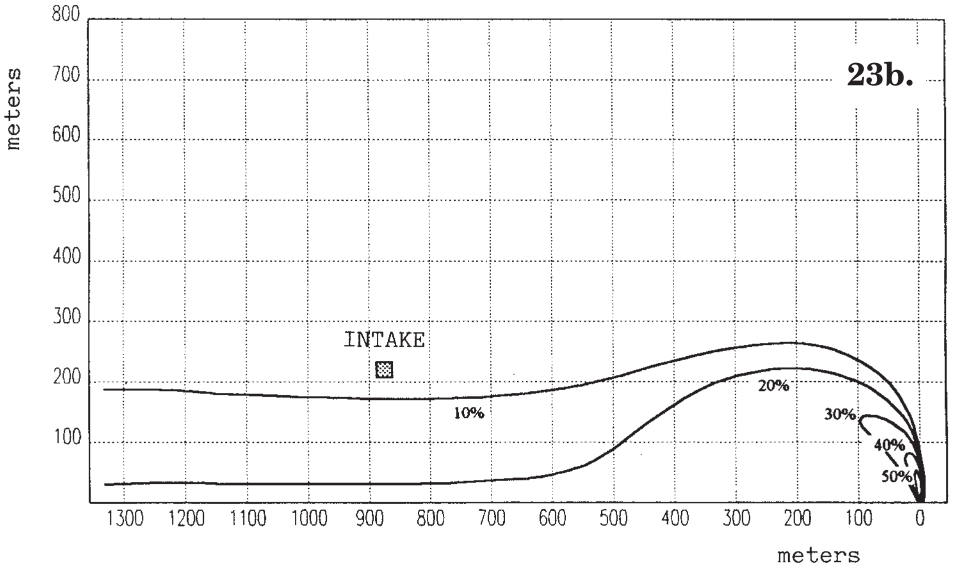


Figure 23. Dispersive behaviours of seawater used for re-gasification; ((a) = ΔT / °C, (b) = % ClO_2 used as antifouling agent) under different current conditions.

variability of the tidal cycle and upwelling was only detected at the sill. On the basis of the described investigation, the Thalassographic Institute of Messina is conducting a long-term monitoring programme of the Strait following similar methodology.

Finally, the presented EIS examples underline processes which require a more detailed knowledge of: the release of toxic substances and nutrients from suspended solids, after dredging; the contemporaneous and antagonistic effect of nutrient supply, light attenuation and the settling rate of particulate matter of different nature on primary productivity.

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SAŽETAK

Studije utjecaja na okoliš projekata koji utječu na kakvoću marinskih ekosustava

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Prema Direktivi EEC 85/337, procedura procjene utjecaja na okoliš (Environmental Impact Assessment - EIA) mora se primjenjivati kako bi se procijenio utjecaj velikih radova na okoliš. Procedura EIA predviđa nekoliko postupaka koji se primjenjuju tijekom pojedinih faza izvršenja radova, uključujući izgradnju, puštanje u pogon, rad i dekomisioniranje postrojenja. Studija utjecaja na okoliš (Environmental Impact Study - EIS) predstavlja temeljnu komponentu procedure EIA, a provodi je izvođač radova te je podnosi nadležnom upravnom tijelu na odobrenje. Osim što predstavlja izvor podataka za EIA, EIS također daje smjernice za donošenje mjerodavnih odluka, budući da definira parametre projekta, postupke otklanjanja eventualnog opterećenja okoliša, te planiranje monitoringa. Zbog kompleksnih interakcija biotičkih i abiotičkih komponenti u marinskom okolišu, primjena EIS općenito zahtijeva interdisciplinarni i integralni pristup rješavanju problema.

U radu se usporedjuju dva tipa nedavno razvijenih postupaka EIS, koji se odnose na projekt izgradnje tri podmorska tunela u području Messinskog tjesnaca, te izgradnju LNG-terminala (terminala za ukapljene plinove) na obali u području Tršćanskog zaljeva (zaljev Panzano) u Sjevernom Jadranu.