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Geomorphological evolution and environmental reclamation of Fusaro Lagoon (Campania Province, southern Italy)

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Abstract

Analysis of morphological, geological and environmental characteristics of the Fusaro Lagoon has shown the present degraded condition of the lagoon and the perilagoon area. The lagoon developed during the mid-Holocene within a wide marine bay confined between the coastal volcanic structures of Mt. Cuma to the north and Torregaveta to the south in the western part of the Phlegrean Fields. Subsequently, the bay was gradually filled with pyroclastic materials from phlegrean eruptive vents and sediments carried by the rivers Volturno and Clanis, thus, creating an open lagoon. It then evolved into a partially closed lagoon due to the formation of a continuous littoral spit during the late Holocene, probably wider than the present-day one and surrounded by marshlands. Finally, the total closure of the lagoon took place in the Graeco-Roman period, following the stabilization of the dune ridge, and it assumed a shape similar to present-day one only towards the end of the 18th century.

Between the Roman period and 1941, three lagoon channels were opened in order to avoid the frequent environmental crises which continue to affect, although for different reasons, this salt-water basin. The basin has been exploited for more than 2000 years not only for mollusc culture and pisciculture, but also for the maceration of hemp and flax. In the 1980s, in order to reduce the effects of the environmental crises, dredging of the lagoon bottom has been carried out, altering the hydrogeological equilibrium and that of the ecosystem. Over the past 30 years, the supply of raw sewage of domestic, agricultural and industrial origin has ensured the presence of a high concentration of pollutants, including heavy metals.

On the basis of the data obtained and in order to restore this sensitive transitional environment, eco-compatible interventions are proposed which aim at morphological and hydrologic resettlement, abatement of pollutants on the bottom of the basin, reintroduction of endemic molluscs, together with monitoring the quality of sediments and both sea-lagoon waters and groundwater.

Keywords: Lagoons; Environmental geology; Holocene; Phlegrean Fields; Italy

1. Introduction

The Fusaro Lagoon (Fig. 1) lies within the municipal territory of Bacoli and it is situated in the northwestern part of the Phlegrean Fields. From the geomorphological point of view, this salt-water basin might be considered a seashore lake or a lagoon which, through three artificial channels, connects with the sea and is separated from it by a littoral spit bearing a dune ridge. From the Graeco-Roman period until mid-20th century, these channels have made possible the vivification of lagoon waters by the sea water, balancing at the same time the effect of freshwater effluents and limiting the temperature increase over the summer period.

The lagoon basin, having a great productive capacity, has been used over the centuries for mussel culture and pisciculture. However, today it is exploited only to a limited extent. The perilagoon area, the dune ridge and the beach, a total of 67 ha, are under protection by law as a landscape, archaeological site and hydrogeological unit.

Salt-water lagoons are considered among the most productive natural environments, especially those in temperate zones (Carrada and Fresi, 1988; Odum, 1988). However, at the same time, the waters and the bottom sediments suffer from natural contamination and man-induced pollution (Bhuvendralingam and Azmy, 1995; Ergun et al., 1995).

Analysis of the morphological characteristics, the dynamics of its morphological evolution, the correlations

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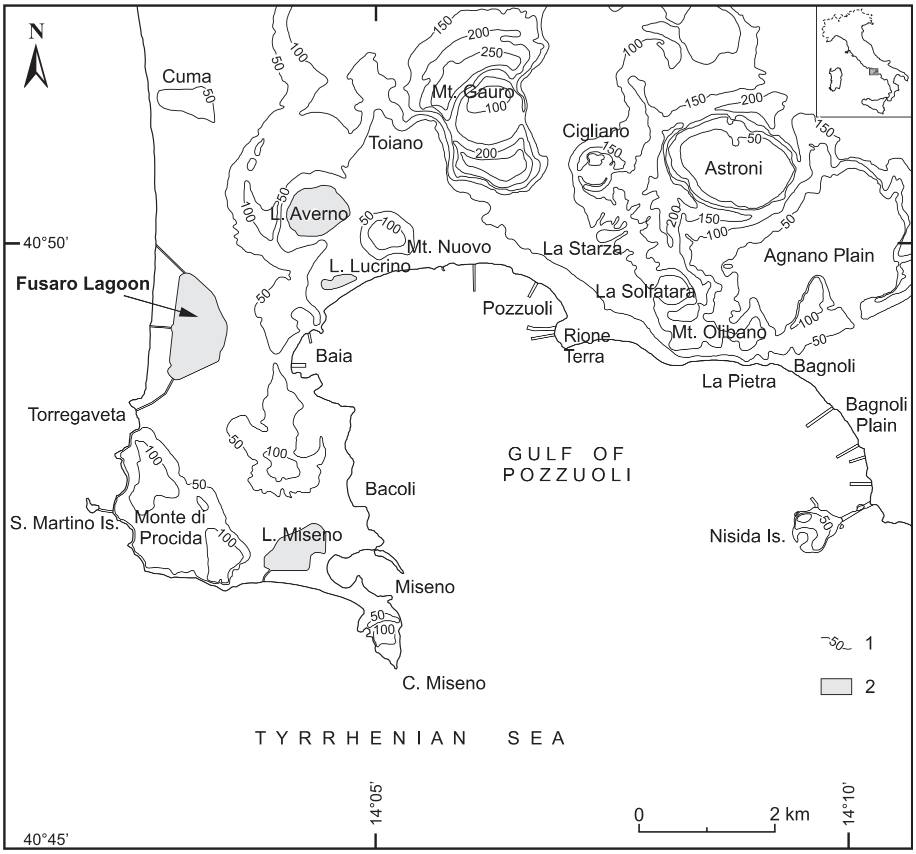

Fig. 1. Location of the Fusaro Lagoon in the western part of the Phlegrean Fields, southern Italy. (1) Altitude above sea level (m). (2) Lagoon.

between the geomorphic processes and various forms of pollution in the Fusaro Lagoon and their impact on the plant and animal species populating its waters suggest the necessity of proposing eco-compatible interventions for environmental restoration. These interventions should aim both at safeguarding the lagoon environment and restoring productive activity, putting into practice a programme for re-establishing the morphological characteristics, together with the flora and fauna which made this place unique in the past.

2. Geological and geomorphological framework

From the geological point of view, the Phlegrean Fields is a complex volcanic centre composed of numerous craters whose activity dates back to 200,000 years B.P. (De Vivo et al., 2001), with the first eruption probably in an underwater environment (Rosi and Sbrana, 1987). The eruptive activity of the Phlegrean Fields is divided into various cycles on the basis of radiometric age and stratigraphy of its products (Di Girolamo et al., 1984). One or more pyroclastic eruptions (Barberi et al., 1978; Luongo, 1986; Cioni et al., 1994; Deino et al., 1994) which occurred 39,000 years B.P. (De Vivo et al., 2001) led to deposition of the *Campanian Ignimbrite* or *Campanian Grey Tuff*, present in outcrops and beneath the Campania Plain. The explosive activity led to deposition of the *Neapolitan Yellow Tuff* which occurred 13,000 years B.P. and gave rise to monogenic volcanic structures during the period between 10,000 and 3600 years B.P. (Di Girolamo et al., 1984; Rosi and Sbrana, 1987).

The most important morphostructural element within the phlegrean area is a caldera with a diameter of about 230 km, formed following the eruption of the *Campanian Ignimbrite*. (Ortolani and Aprile, 1985). The formation of the caldera was followed by marine flooding, filling it with products from both intracalderic submarine activity (lava and pyroclastic material) and erosion of subaerially exposed remnants (De Pippo et al., 1984). The depression was rapidly filled by the deposition of pumilith and sediments (Colantoni et al., 1972; Pennetta et al., 1984). Furthermore, the submergence was characterised by the deposition of the *Neapolitan Yellow Tuff* followed by collapses which affected the central part of the caldera.

The present-day aspect of the Fusaro Lagoon is the result of a continuous change attributed to the mutual interaction between volcano-tectonic and bradyseismic phenomena, coastal dynamics, weathering and the increasing presence of man on the phlegrean territory (Parascandola, 1947; Luongo et al., 1988; Dvorak and Mastrolorenzo, 1991). All of these factors have contributed, in different ways and in different time spans, to the transformation of the emerged and submerged landscape (Cinque et al., 1997), burying under volcanic rocks and sediments important evidence from the prehistoric and Graeco-Roman periods (Amalfitano et al., 1990).

The Fusaro basin, known already in the Graeco-Roman period as *Acherusia Palus* (Maiuri, 1983), is a subtrapezoidal lagoon located about 15 km N of the Gulf of Naples. It is situated between Mt. Cuma and Torregaveta, behind a dune ridge, with its longer side facing the sea. It covers about 60.6 ha (~ 0.6 km^2) and has a perimeter of 4 km; it is about 1700 m long and has a maximum width of 800 m. In 1970, its mean depth was about -3 m, whereas the deepest point reached -6 m in the central part (Carrada, 1973). According the measurements obtained in a 1985 survey (Fig. 2a), the lagoon bottom morphology shows an almost centripetal trend of the isobathic lines, with a gradual increase in depth from the shores towards the depocentre. At present, there is a wide depression which is more than -10 m deep (Fig. 2b) caused by intense artificial dredging activity parallel to the western shore (Andolfo et al., 1993).

The lagoon, with a N–S orientation, is connected to the sea by three artificial channels (Fig. 3) cut through the dune ridges. The Foce Vecchia (old channel, Fig. 3a), dating back to Roman period, is located on the SSW shore of the lagoon and following a slightly curving course, debouching into the sea at the foot of the Torregaveta promontory. The Foce Nuova (new channel, Fig. 3b) dating back to Bourbon rule (1859), is located on the northern shore and follows a straight course to the NW before debouching into the sea. Finally, the Foce di Mezza Chiaia (central channel, Fig. 3c) crosses the central part of the former Royal Estate, following a straight course westward to the mouth and stretches into the sea for about 60 m.

The Fusaro Lagoon, like other present-day Adriatic and Tyrrhenian lagoon systems (Donadio, 1999; De Pippo et al., 2001a,b), has taken form within a shallow coastal waters located between two areas of high morphological relief, the volcanic structures of Mt. Cuma to the north and Torregaveta to the south. Subsequently, the accumulation in submerged areas and the progressive emersion of sediments emitted by phlegrean eruptive vents, together with the Volturno and Clanis rivers sediments redistributed by marine waves and currents, have enabled the genesis and the development of a wide littoral spit stabilized by a dune.

The evolution of the lagoon up to the Graeco-Roman period has been controlled by natural processes like

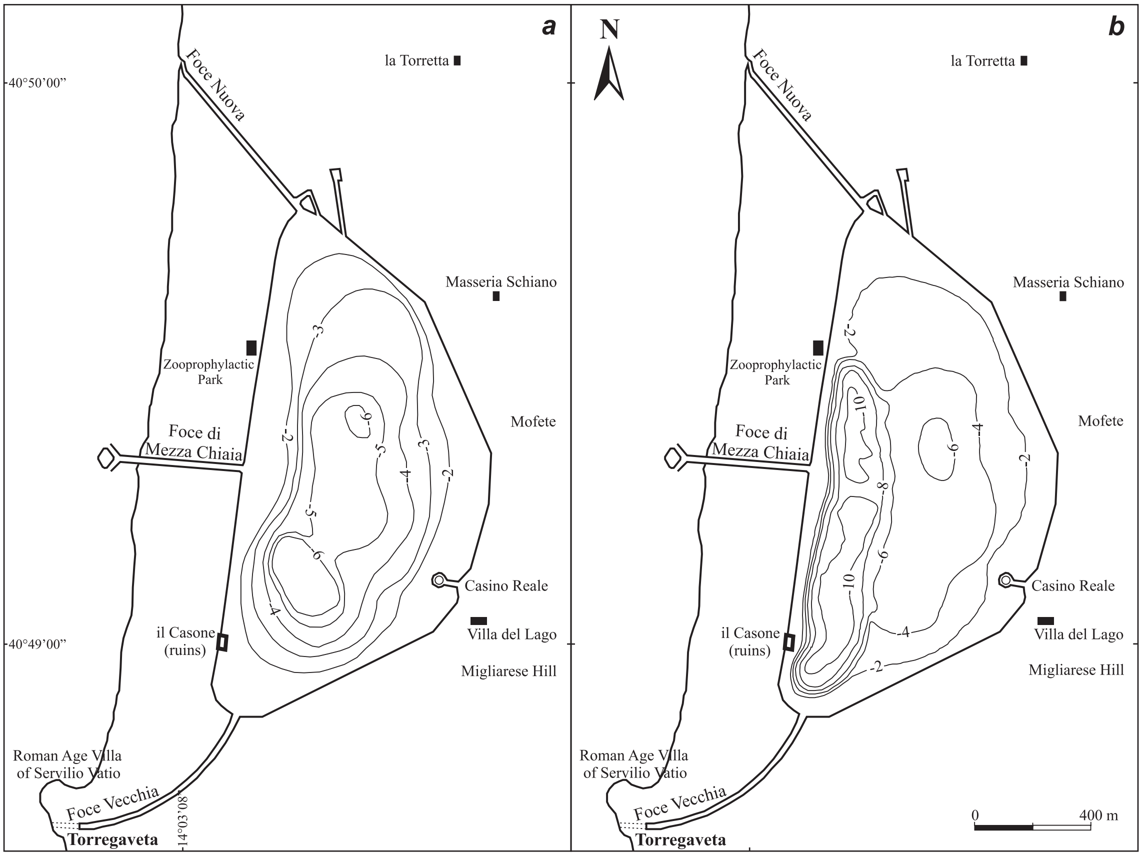

Fig. 2. Fusaro Lagoon bottom morphology (– m) registered in two different periods (Andolfo et al., 1993). (a) 1985 bathymetry in which a regular and centripetal trend of isobathic lines is observed, with a gradual deepening of the shores towards the lagoon depocentre (– 6 m). (b) 1988 bathymetry, after bottom dredging; the morphology is characterised by a wide, subrectangular depression more than – 10 m deep in front of the central and southern channels, lying parallel to the western shore, and by a sinuous trend of the – 2 and – 4 m isobathic lines within the eastern zone.

Fig. 3. The three artificial channels which connect the Fusaro Lagoon with the sea. (a) Foce Vecchia channel, constructed in the Roman period in the southern area cutting through a channel in the tuff. (b) Foce Borbonica or Nuova channel, located in the northern area and constructed in 1859. (c) Foce Centrale or di Mezza Chiaia channel, opened between the other two channels in 1941.

volcano-tectonic and bradyseismic phenomena, eustatic oscillations, coastal sedimentation and erosion. Subsequently, the evolution has been strongly influenced by human impact. During the Graeco-Roman period, the evolution of the lagoon was determined by its complete separation from the sea, creating a depression behind the dunes (coastal pond; sensu Brambati, 1988) following the formation of a littoral spit stabilized by the dune ridge. Between the Roman period and the present day, the following changes have taken place. First, it has been a partially open lagoon with one channel, after the opening of the Foce Vecchia to the SSW (Bourbon period), until 1859. Then, it became a partially open lagoon with two channels, after the opening of the Foce Nuova (or Foce Borbonica) channel to the N, between 1859 and 1941. Finally, the opening of the Foce di Mezza Chiaia (or Foce Centrale) channel in 1941 transformed the basin into the present lagoon with three channels.

The daily water exchange with the sea through these channels is about 12% of the total water volume of the lagoon, including the sea-level fluctuations due to tides (~ 40 cm range). There are three main streams feeding the lagoon: the stream that drains the Pantano Gaudiello swamp to the north, the thermal spring, Grotta dell'Acqua, located within the Roman ruins to the E, and Canale Mazzone, which used to drain the Acqua Morta swamp to the south. At present, the fresh water supply is considerably reduced by the artificial drainage net built during the 1970s and mainly represented by sewage discharge, which is a major source of pollution considering that it drains raw sewage. In recent years, the general condition of the waters and lagoon sediments has been worsened to the extent that the breeding of some fauna species of commercial value, such as mussels and fish, has almost completely disappeared as a result of pollution.

3. Geo-environmental and naturalistic aspects of perilagoon and lagoon area

In the Roman period, there were two forests in the area: the *Silva Gallinara* which extended from the north of Cuma to present-day Castelvolturno and the *Averno* forest. From the phytogeographical point of view, the Phlegrean Fields is considered within the temperate Mediterranean vegetation zone in spite of high rates of humidity. The vegetation in the area mainly consists of Mediterranean scrub and ilex trees.

The intense human presence in the Phlegrean Fields has partly altered the animal and plant communities. The vegetation is almost completely secondary and what remains from the ancient forests are only a few protected strips of Mediterranean scrub with ilex trees and other typical plant species (*Erica arborea*, *Myrtus communis*, *Pistacia lentiscus*), whereas, poplars, willows and reeds grow around the lakes.

The animal communities have also undergone variations over the years and at present, there are only small wild animals, in particular, numerous bird species. On the littoral spit and on the dunes in front of the lagoon, the grass species *Agropyron* has colonized the dry and salt-rich environment. Near the waterline, *Ammophila* has a very important role in intercepting sand grains to form dune ridges. Further inland, from the oldest dune ridge onwards, there are strips of Mediterranean scrub with *Cistus* and other bushes (Röiter et al., 1997).

In the lagoon, there are two different types of substratum (Peres and Picard, 1964): a mobile one on the bottom of the basin and in the channels, composed of sand covered by a layer of very fine organogenic mud, and a solid one in concrete used for the construction of the vertical aprons, for the protection of the banks and the channels, due to the lack of natural bedrock. The fauna of the Fusaro Lagoon is mainly composed of detritus feeder and filter feeder species, since salt-water environments are abundant in such material. The lagoon is mainly populated by polychaete annelids and amphipods which constitute the 95% of all zoobenthonic organisms living there, whereas the molluscs represent only the 5% of the total (Ferro and Russo, 1981). Among the amphipods, the *Microdeutopus gryllotalpa* found near Foce Nuova indicates an environment with high amounts of accumulated detritus, whereas among the polychaetes, the *Capitella capitata*, in high quantities, indicates an oxygen-poor environment with elevated organic pollution rates (Sordino et al., 1989). Organisms belonging to other taxa (Decapoda, Anisopoda, Isopoda and Echinodermata) are found in negligible quantities.

Marine species are quite rare, indicating little revitalisation of the lagoon by sea water due to the limited use of the channels. Although not quite abundant, the molluscs have a very important impact on the community in terms of biomass, both for the elevated specific weight of shells and for the presence of large adult individuals, such as *Cerastoderma glaucum* and *Mytilus galloprovincialis* bivalves.

The lagoon bottom sediments are heterogeneous. Within the central part, there are pelites; near the Foce di Mezza Chiaia, there are fine sands; whereas near Foce Vecchia, there are gravels. These substrates permit the survival of many types of suspension feeder and detritus feeder benthonic organisms (Andolfo et al., 1993). The mobile substratum is mainly colonized by bivalve molluscs and gastropods adapted to eutrophic environments with abundant detritus and by euryhaline species. Among the species populating the mobile substratum, the bivalve molluscs are those which suffer more the effects of summer dystrophic crisis during which they disappear almost completely. The solid substratum gate vertical banks is more exposed to tides and water turbulence. This substratum is populated by three different communities: Balanidae, Mytilidae and Serpulidae. These communities, with their calcareous shells covered by organogenic sludge, create a microenvironment in which the majority of benthonic species live.

The lagoon fauna consists of Opisthobranchia too, particularly abundant during spring and summer when reproductive activity reaches its peak. The existence of various species belonging to this subclass is important considering that the particular characteristics of the lagoon, such as the continuous variations of salinity, temperature and dissolved oxygen concentration, condition strongly their survival (Villani and Martinez, 1993).

4. Distribution of pollutants and contaminants in the lagoon

The Fusaro Lagoon has often been the object of attention for high levels of degradation and the general state of neglect which, over the years, serious and repeated dystrophic crises have caused (Sacchi and Renzoni, 1962; Carrada, 1973).

By the end of the 1960s the conditions in the lagoon were critical, especially during the summer period due to continuous sewage and rain water discharge from Torregaveta and Cappella urban centres (Centro Ittico Tarantino-Campano, 1967). Analyses of the lagoon water in 1967 showed that during the summer months, two major changes occurred: the dissolved O_2 fell to levels which did not permit the normal development of biotic communities, and the salinity increased to a level tolerated neither by fish nor by molluscs. The pH measured in the central part of the lagoon was 7.5–7.8, less than the sea water pH (8.2), which indicates an increase in hydrogen ions due to the presence of acidulants as a result of decomposition and putrefaction during the breakdown of organic matter under anaerobic conditions.

The dystrophic crisis in summer was counterbalanced by favourable conditions in spring, autumn and winter when the supply of fresh water increased (Carrada, 1973) and water temperature and salinity levels decreased and the benthonic vegetation recovered, creating a real seasonal cycle. Analyses of the lagoon water in 1985 showed high levels of salinity and temperature at high tide (De Maio et al., 1988), although the waters at the mouth of Foce Vecchia showed the effects of the fresh water from Volturno River (Moretti et al., 1985; Budillon and Moretti, 1994; De Maio et al., 1994).

Over the last 20 years, the lagoon has been the recipient of polluting domestic, agricultural and industrial discharges, to the point that it is now quite unusual to encounter the original ecological equilibrium of the lagoon. Furthermore, the continuous solid material supply had previously caused a reduction in depth of more than 1 m by the end of the 1960s (Leccese and Speziale, 1967).

The pelitic deposits, rich in decomposing organic matter, caused the reduction of dissolved oxygen in water and the formation of hydrogen sulphide. At present, at some stages of low tide, sewage discharged from the nearby main sewer of Cuma flows into the lagoon together with sea water through the northern channel. Furthermore, the industrial activity from 1960 to 1990 in the area has caused pollution by heavy metals such as Pb, Cd and Cu. The areas mainly affected by organic contamination are the southwestern shore and those near the Foce Vecchia and the Foce di Mezza Chiaia. This distribution may be attributed to stagnation as a result of the silting of channels, the shifting of bottom sludge to areas with variable flow and sea water pollution at the mouth of these channels.

Surveys to reveal the actual state of physical, chemical and microbiological contamination of the waters and sediments of the lagoon were carried out in October 2000 (Centro Ittico Tarantino-Campano 2000, Table 1) through surface water and sediment sampling (Fig. 4). In order to quantify the degree of contamination, levels of organic contamination agents (NH_3, nitrite, nitrate and phosphate) and heavy metals (Al, Cr_{III}, Cr_{VI}, Hg, Pb, Zn, Cd, As, Ag, Ni and Cu) have been examined together with the quantity of dissolved O_2.

The results of the analyses of bottom sediments show that southern and eastern parts of the lagoon bear high concentrations of pollutants. Sediments containing over 10 mg/kg of NH_3 are found in the central part, on a bottom varying around -2 and -8 m, along a NW–SE-oriented main axis, intersecting a NE–SW-oriented secondary axis. The dispersion of Al is at its maximum (over 10,000 mg/kg) within the southeastern perimeter and near the Foce Vecchia and the Foce di Mezza Chiaia, on a bottom with a mean depth between -2 and -4 m, and within the western depression up to -8 m. A circumscribed area with sediments containing over 30 mg/kg of Cr_{III} is limited to the northern part of the lagoon, in a depth varying from about -2 to -4 m. The distribution of Pb, Zn and Cu is similar to the one of Al; in other words, within the southeastern perimetrical area and near the Foce Vecchia, in the greater depths and partly within the western depression, although these zones are different in form and in surface area. The sediments containing over 3 mg/kg of Cd are distributed in a very small area in the northeastern part, up to -2 m depth and a second larger area in the southern of the lagoon, along a NE–SW oriented line, between -2 and -10 m and extending to Foce Vecchia. Relatively, high contents of Hg and Ni are present in very restricted areas, in the southeast between -2 and -4 m and in the central-south up to -6 m, respectively. Finally, within the analysed sediment samples, concentrations of Ag (< 0.5 mg/kg) and cyanides (< 50 mg/kg) have been found in negligible quantities.

In some surface water samples, the content of heavy metals such as Pb, Cd and Cu was above the limit set by law in 1999, whereas among the sediment samples the only ones exceeding these values were those for Hg, Cd, Pb and Cu (Table 1). The residence time in saltwater of the pollutants carried by surface runoff depends on the type of the element and its concentration: 100 years for 1×10^{-2} ppm of Al, 400 years for 3×10^{-3} ppm of Pb, 80,000 years for 3×10^{-5} ppm of Hg and, finally, 500,000 years for 11×10^{-5} ppm of Cd (Fergusson, 1982).

The microbiological analyses of the lagoon waters, carried out to identify two pathogenic bacteria indicating faecal contamination (*Escherichia coli*) and cholera infec-

Table 1
Chemical contamination values of the lagoon sediments carried out in October 2000

Sample (no.)	NH_3 (mg/kg)	Al (mg/kg)	Cr_{III} (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Cd (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	As (mg/kg)
Mean content of reference (Law 152/99)			20–50	0.5	45–80	200	1–2	40–60	45–75	15–20
1	4.0	12,871	17	5.5	34	41.2	1.7	39.5	< 10	8.1
2	12.3	10,569	18	2.5	35	42.3	1.8	28.2	< 10	11.1
3	2.2	7738	< 10	5.5	18	25.7	1.8	14.7	< 10	8.1
4	2.4	7783	< 10	< 0.5	19	28.8	1.9	17.2	< 10	7.1
5	3.9	18,759	18	< 0.5	35	57.7	3.5	40.2	18	13.5
6	1.8	8993	18	< 0.5	18	42.1	1.8	22.0	< 10	6.2
7	1.6	10,316	19	< 0.5	19	31.9	1.9	20.6	< 10	4.1
8	1.9	12,833	17	< 0.5	50	51.1	8.2	28.0	33	4.9
9	9.6	16,051	16	< 0.5	32	54.4	1.6	30.4	16	7.5
10	1.7	17,711	16	< 0.5	33	47.7	3.3	34.5	16	12.7
11	16.0	10,798	57	< 0.5	38	45.2	0.8	33.9	19	9.2
12	2.1	11,085	31	< 0.5	31	40.7	3.1	24.7	16	7.8
13	5.0	7718	36	< 0.5	18	25.5	1.8	23.7	18	5.5
14	2.0	2163	17	< 0.5	17	6.6	1.7	8.3	17	3.2
15	2.9	6955	33	< 0.5	33	37.5	1.6	22.9	16	7

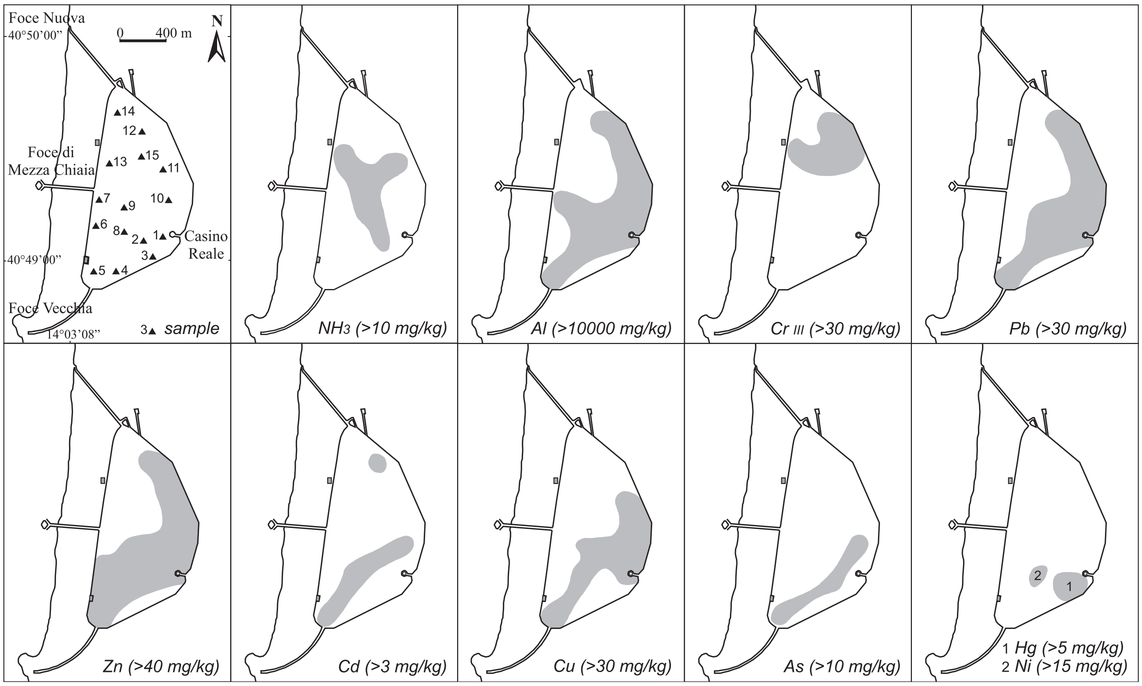

Fig. 4. Location and number of sampling points of the surface water, the bottom and the sediments, and distribution of some pollutants existing in the Fusaro Lagoon sediments in high concentration. Most of the pollutants (Al, Pb, Zn, Cd, Cu, As) are distributed on the lagoon bottom to the east and within the central-western depression caused by 1988 bottom dredging, and are directly influenced by winds blowing from the west, currents, the interaction with the rough bottom morphology and by partial obstruction of the channels. The presence of limited areas with high concentration of some pollutants (NH_3, Cr_{III}, Hg, Ni) is linked not only to the local flat morphology of the lagoon bed but also to the proximity of domestic, agricultural and industrial sources of pollution. The presence of As in the area might be connected to phlegrean volcanic genesis, too.

tion (*Vibrio cholerae*), show that the lagoon waters are not of high quality from a microbiological point of view, but that potential cholera infection was nonexistent.

5. Discussion and hypothesis of environmental recuperation

Between the beginning of the 16th century and the end of the 18th century, the form of the basin has changed from an initial subelliptical to subrectangular and finally to subtrapezoidal. Furthermore, it has undergone a gradual shrinking and a progressive anticlockwise rotation of its major axis. These variations have taken place together with the disappearence by filling or dredging of the three small basins to the north and south of Foce Vecchia, which were surrounded by marshlands prior to 1881. These transformations of the lagoon environment are thought to be linked to sediment, eroded from surrounding volcanic hills, under climatic conditions colder than at present (Little Ice Age, 1600–1850), in the absence of volcanic activity within the phlegrean area.

The influence of land accretion in the coastal swamps conducted between the end of the 19th century and the beginning of the 20th century together with the land reclamation during Bourbon rule, which contributed to the disappearance of Licola Lake behind the dunes to the north of Mt. Cuma, should also be taken into consideration when analysing the morphological evolution. In spite of the human impact over the past century, the shape of the Fusaro Lagoon, unchanged since 1780, indicates a certain stability in the evolution dynamics of the environment.

The opening of the three lagoon channels between the Roman period and 1941, the last two undertaken to restrain the frequent environmental crises which continue to affect the basin, has conferred a high level of trophism to this transitional environment, where tolerant populations poor in species but rich in number are present. However, dredging the lagoon bottom during the 1980s in order to reduce the environmental crises has altered both the hydrogeological equilibrium and that of the ecosystem.

The introduction of raw sewage of domestic, agricultural and industrial origin to the waters of the lagoon over the past 30 years has caused a high concentration of pollutants in the bottom sediments including heavy metals. Water pollution by heavy metals may be linked to the same cause of contamination as the sediments, considered both as receivers and occasional sources of release of pollutants into the waters. The majority of these pollutants (Al, Pb, Zn, Cd, Cu, As) are distributed in the eastern part of the lagoon or within the central western depression created by the dredging of the bottom and partial filling. This distribution is thought to be controlled by winds blowing from the III and IV quadrants, the influence of tidal currents in the shallows, the interaction of these factors with bottom morphology and especially the partial obstruction of the southern (Foce Vecchia) and central (Foce di Mezza Chiaia) channels. The presence of marginal areas characterised by high concentration of some pollutants (NH_3, Cr_{III}, Hg, Ni) may be attributed not only to the almost flat bottom which facilitates accumulation, but also to the proximity of the pollution sources, in accordance with Fergusson (1982). The concentration and diffusion of As in this area might also be linked to phlegrean volcanic genesis.

The present-day trophic structure of the benthonic and nektonic communities is relatively simple and the main energy–nutrition source is represented by detritus, with the predominance of detritus feeders. Salt-water lagoons are among the most productive natural environments, both aquatic and terrestrial, at least concerning geographically temperate climate areas (Odum, 1988). Thanks to its high productivity, the Fusaro Lagoon has been exploited for centuries for cultivating oysters, mussels and fish.

An environmental remediation, related to the need of ensuring a multiple use of the lagoon, is proposed. This project needs to take into consideration the morphological aspects, the productive potentiality of the basin and a possible expansion of employment within the aquaculture sector. For the formulation of this proposal, analysis of the pollution of the lagoon waters, sediments and the main benthonic species is required. The population is typically euryhaline; in other words, it is highly adaptable to salinity variations. The salinity value oscillates all round the year, whereas chlorinity value is stable around 20‰. The concentration of the phosphates and nitrites, higher than those found in the stretch of the sea in front of the lagoon, indicates a pollution believed to be due to detergents and agricultural fertilizers. The temperature of the basin varies between a minimum of 6–7 °C in winter and a maximum of 27–28 °C in summer, since it is conditioned by a limited water mass (30,000,000 m^3) with a low mean depth. During the year, sudden variations of dissolved oxygen concentration are observed, to the point that it creates an unusual metabolic cycle with values around 400% in spring and less than 50% in summer. The minimum dissolved oxygen concentrations are linked to the dystrophic crisis, caused by changes in temperature and salinity, which are increased due to decomposition of less adaptable organisms.

Within the lagoon, an ecosystem based on an altered food chain has been created. In fact, due to the introduction of N and P into the environment derived from various activities in the surrounding area, a rapid proliferation of algae followed by hypoxia and anoxia with the consequent partial death of flora and fauna is observed. This suggests a low rate of water exchange in the lagoon. In order to restore the characteristics of the lagoon ecosystem, it will be necessary to improve water exchange with the sea through the reestablishing of efficient functioning of the three channels, now in a state of neglect and degradation at present.

The interventions to be made are mainly excavation of the channels beds, trying to limit the turbidity of the waters and executing periodic monitoring of physical, chemical and microbiological characteristics of the waters and bottom sediments of the lagoon (Dias and Peneda, 1986). Moreover, the lagoon is affected by biological pollution, as shown by the presence of organic matter particles in the state of bacteriogenic decomposition and industrial pollution. Furthermore, it has also undergone an alteration of hydrogeological equilibrium caused by an intense artificial dredging with the removal of inert material from the bottom, a partial deepening of the basin, the consequent collapse of the shores due to earth flow and damages to perimeter banks.

In order to obtain optimum productivity of the lagoon, the biological pollution of the waters and sediments must be considerably reduced, through elimination, reduction or treatment of wastewater discharge. In the latter case, it is necessary to effect a complete tertiary treatment for the abatement of pollutants and achieve a hygienic and sanitary control of the lagoon waters, the sewage, run-off waters and industrial discharges.

In the light of a possible environmental restoration, considering the morphological aspects and the high contents of heavy metals, other pollutants and organic matter present in the bottom sediments (De Pippo et al., in press), it is necessary to effect a gradual renaturalisation intervention based on an innovative methodology (Motta, 2000). In particular, dredging of the lagoon bed for a thickness of about 1 m is proposed. The removed sediments could be treated both by mechanical and chemical processes for the abatement of the pollutants with long residence time in salt water (Fergusson, 1982).

The separation of the gravel–sand–clay fractions and coarse polygenic inert matter derived from industrial activity could be achieved by sifting of the dredged materials. Subsequent sedimentation in tanks with the recovery of the molluscs and hydrocyclonation for the recovery of fine sands is also achievable (Merico et al., 2000). The remaining parts, exposed to chemical–toxicological analyses in order to determine the type and distribution of the pollutants (heavy metals, N, etc.), could be treated with specific combined processes, both chemical and of biodegradation, for the abatement of the toxicity and organic matter, in order to reduce the time span to restore environmental equilibrium (Trost, 1993; Marrale et al., 2000). At the end of the treatment, the sediments should be reintroduced on the lagoon bottom, possibly by putting an impermeable diaphragm at the base (Montgomery, 1997; Bell, 1998) so that it is possible to reconstruct a uniform morphology. Such intervention is necessary, even though it might be harmful to benthonic species. It is also essential the stabilization of the shores affected by landslide and the reconstruction of perimeter banks with eco-compatible techniques (wicker trellis fences, palisades).

The project should also aim to safeguard morphological aspects, and the flora and fauna through establishment of reserve areas, integrated areas under total protection or biological protection. With respect to environment, landscape, employment and regulations, the area that surrounds the salt-water basin could be converted into a park, regulating the entrance terms and visiting terms for the public, especially in particular seasonal periods.

The littoral and the sandy dune should also be safeguarded through the realization of a pathway, as an obligatory itinerary, constructed on timber piles and suspended on ropes, which will help the natural revitalization of the ancient grove of ilex trees and the Mediterranean scrub. By recuperating the flora and fauna, both the land surrounding the lagoon and the historical buildings could be used for tourist activities and for research.

6. Conclusions

In order to preserve lagoon environments, it is necessary to execute specific interventions rather than radical ones on the basis of continuous observations of the chemical, physical and microbiologic conditions of the waters and sediments, in relation to morphological aspects and evolution dynamics of the coastal landscape.

The salt water and perilagoon environment of Fusaro, under threat by human presence at present, is affected by high levels of biological and chemical pollution. The abandonment of activities such as the cultivation of fish and molluscs, which had been carried out for centuries in the lagoon waters, and the reduced efficiency of water exchange with the sea have been the major causes of periodic and disastrous dystrophic crises. In some surface water samples, the content of heavy metals as such was above the limit set by law in 1999, whereas among the sediment samples, the only ones exceeding these values were those for Hg, Cd, Pb and Cu. The persistence of high concentration heavy metals (Al, Pb, Hg, Cd and Cu) in the bottom sediments, carried into the lagoon by surface runoff and anthropogenic discharges varies between 100 and 500,000 years.

In spite of the high levels of pollution and the general state of neglect, the Fusaro Lagoon still preserves its peculiar geomorphological aspects and important floral and faunal communities, which is an essential condition for the realization of the interventions to fully rejuvenate productive activities and to prevent degradation of an environment of national value to a stage in which it becomes irreversible.

In order to allow complete recovery of the natural environment, restoration and safeguarding of the lagoon and perilagoon areas are considered, which should reduce the causes of systematic dystrophic crisis and should decrease the level of pollutants. Although the Fusaro Lagoon is a small basin, sediment capping (Keller, 1996) and/or impermeable plastic liners placed on top of the polluted sediments and held in place by an overlying layer (Montgomery, 1997) of quarry sand is not recommendable for local high impact.

Briefly, in accordance with Zitelli (1988), Baker and Herson (1994) and Montgomery (1997), the restoration project should have the following scheme:

1. functional restructuring and protection of the lagoon channels;
2. environmental restoration following eco-compatible techniques for the improvement of water circulation (light and gradual dredging of the lagoon and channels bottom) and the abatement of the pollutants in bottom sediments (superficial decortication of the bottom, sifting and hydrocyclonation of the sediments with the recovery of the endemic molluscs);
3. reintroduction to the lagoon of the treated sediments over an impermeable diaphragm and of the endemic molluscs recovered;
4. bioremediation through introduction of vegetated buffer (Mediterranean scrub) and vegetated treatment systems along the lagoon perimeter;
5. introduction of hygienic and sanitary controls of the lagoon waters and the stretch of the sea in front of it, the bottom sediments, the waters from the surrounding areas and the groundwater;
6. complete integration of the lagoon and the perilagoon areas within the present-day nature reserves and protected areas of the Phlegrean Fields.

Finally, these remediation actions should also aid the natural biodegradation of the residual pollutants of lagoon waters and sediments.

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