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GIORGIO CATENA, ENZO FUNARI, MAURO LENZI

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TELERILEVAMENTO

Application of remote sensing to the eutrophic problems of Orbetello's lagoon (Italy)

GIORGIO CATENA (*), ENZO FUNARI (**), MAURO LENZI (***)

SUMMARY. – *The Orbetello lagoon has periodically suffered from huge eutrophication phenomena. Such phenomena are due to the insufficient exchange between internal waters and sea water. The conformation of the lagoon and its shallow waters, the presence of huge masses of benthic algae, the geometry of the canals, which are even closed by gratings to prevent high-quality fish from flowing out, make these exchanges difficult. In order to detect in real time the water exchanges between the lagoon and the sea, an IR camera was used. The camera allows the plumes of water masses which get into or out of the lagoon to be detected. The remote sensing survey has allowed to spot the areas in which the lagoon suffers the most and where adequate management measures would permit to obtain remarkable improvements in the lagoon water quality.*

1. Introduction

Orbetello's lagoon, located in southern Tuscany (Italy's Western coast), has a surface of about 2,600 hectares and an average depth of 1m. The lagoon is of great ecological interest for its peculiar characteristics among the brackish wetlands still existing in Italy. The WWF, for instance, has established an important protected area there for avifauna. In the last thirty years, the human activities in the area have strongly grown: four intensive aquaculture farms, producing about 200 tonnes of fish per year, discharge their waste waters into the lagoon. Even though the number of residents is rather stable, during tourist periods the population increases about ten times, and reaches over one million people.

(*) Remote Sensing Unit, Istituto Superiore di Sanità, Viale Regina Elena 299, 00161 Rome, Italy, Tel. +39-06-49902295, Fax +39-06-49387083, E-mail: catena@iss.it

(**) Head of the Environmental Medicine Department, Istituto Superiore di Sanità, Viale Regina Elena 299, 00161 Rome, Italy, e-mail: funari@iss.it

(***) Laboratory of Lagoon Ecology and Aquaculture, O.P.L. srl, Orbetello (GR), Italy, e-mail: lealab2@hotmail.com

Because of the nutrient accumulation in the sediments, the lagoon is characterised by a diffuse chronic hypertrophy that now looks rather independent from land emissions (Caprioli et al. 1989). Since the end of the 1970's, the excess of nutrients has led to the phenomena of macroalgal and at times phytoplankton blooms. These algal masses are almost continuously produced during the year and reach densities even higher than 20 kg/m^2. Opportunistic macroalgae, such as *Gracilaria verrucosa*, *Chaetomorpha linum, Ulva rigida* and *Cladophora vagabunda*, which are typical of eutrophic and hypertrophic waters, have followed one another in the dominance of submerged vegetation. The degradation of this material which consumes huge amounts of oxygen gives rise to conditions of diffused anoxia. In these conditions, massive fish kills are a frequent consequence.

This difficult environment has caused dramatic changes in the quality and quantity of fish stock and a drastic reduction in algal biodiversity. Furthermore, these conditions alter the quality of the shores nearby, thus posing a threat to the important tourist activities in the area. Finally, the lagoon filling-up process is strongly accelerated (Lenzi 1992).

Some management measures have been promoted in order to counteract these phenomena and safeguard the economic activities based on lagoon resources. On the basis of the results of a survey (Bucci et al. 1988) focused on water exchange between the lagoon and the nearby water bodies, some powerful pumps have been installed at the mouth of two lagoon canals (at present the Fibbia and Nassa canals, Fig. 1) which continually emit water into the lagoon: the water flows out from the third canal, the Ansedonia canal. These pumps improve water exchange in critical periods, especially during the summer when the absence of wind and weak tidal excursions favour stagnation. When the pumps work at full blast, the average water level of the lagoon increases by about 0.3-0.4m, thus equalling autumn and winter levels, and a current generates towards the outlet which is no longer affected by tides. In view to favouring the flows of water masses within the lagoon, three 2.5 – 3m deep short canals have been dug on the lagoon floor along the same axis of the canals connecting the lagoon with the sea (Fig. 1). The canal connecting Orbetello's residential area with Mount Argentario has been dug to ease the movements of boats between the residential area and the Navigabile canal, which is currently dammed and used as a marina, and flows to the sea near the Nassa canal.

Water forced circulation has partially mitigated the phenomenon of the massive fermentation of the algal mass. Nevertheless, because of the conformation and shallow waters, many areas in the lagoon are still characterised by water stagnation and oxygen depletion as, for instance, thermography in Fig. 2 shows. Such thermography is taken from the position indicated by an X in Fig. 1. In the thermography the surfacing macroalgae are given in light grey and show the limit of stagnating water.

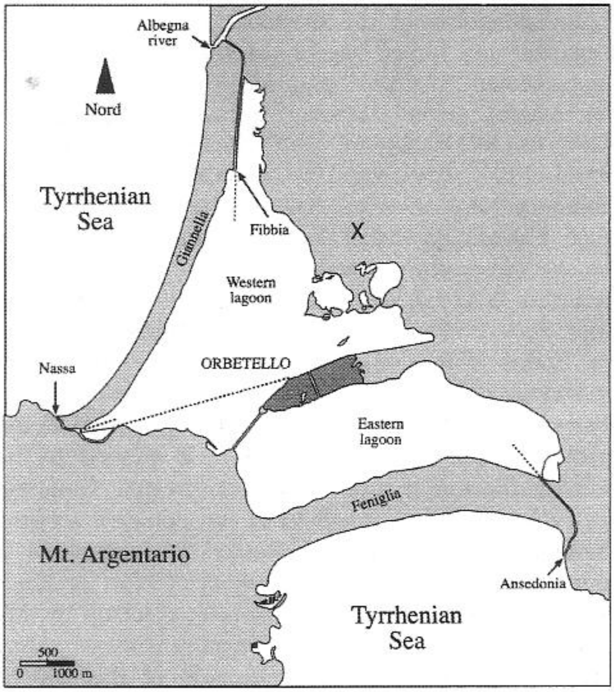

FIG. 1

Orbetello's Lagoon (Southern Tuscany, Italy). It is possible to see the three canals that connect the lagoon to the sea and the dam which connects Orbetello's residential area with Mount Argentario. The dotted lines show the traces of the canals dug on the lagoon floor. The X indicates the position from which the thermography shown in Fig. 2 has been taken.

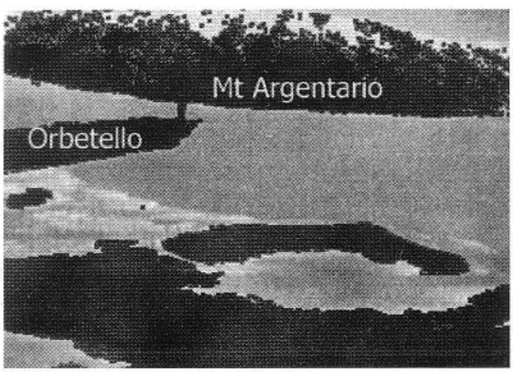

FIG. 2

Thermography taken from the position indicated with X in Fig. 1. The semi-submerged macroalgae shown in light grey, signal the limit of stagnating waters.

A better understanding of the dynamics of the water masses both in conditions of natural and forced sea fluxes would be particularly useful to optimise the management measures. In order to show and assess the movement of water masses, remote sensing techniques largely used to study various problems on the quality of water bodies will possibly be utilised (Pattiaratchi et al. 1994, Anderson 1995, Barale 1996).

Such techniques have already been used successfully in the lagoon to study macroalgal blooms, by using both satellite (Travaglia and Lorenzini 1985) and the MIVIS multi-spectral air-borne sensor (Alberotanza et al. 1999). The literature (Catena and Palla 1980, LeDrew and Franklin 1985, Ferrier and Anderson 1996) shows that the assessment of surface temperatures in water bodies allows to visualise the movement of currents and presence of emissions and to know in general their surface circulation. Ferrier and Anderson (1996) state that among the various channels present in a multi-spectral sensor, the thermal one has proved to be the most useful in visualising the tide-induced water movements. Compared to traditional research methods, remote sensing has the potential to provide greater spatial and temporal coverage and additional environmental information. Moreover, the possibility to have synoptic shots of most of the lagoon near the outlets of the above-mentioned canals is a precious method to know their area of influence.

Since satellite data cannot be used because of the low resolution of the currently available thermal channels and the impossibility of over-flights at the same time with tidal phenomena, a helicopter-flown IR camera was used. Such camera checked the tidal impact on the flows of water masses present in the lagoon and measured their size.

2. The area under investigation

The lagoon (Fig. 1) is divided in two basins, the western one (~15 km²) and the eastern one (~12 km²), by the isthmus on which Orbetello's residential area is located and a dam which connects this area with the Mount Argentario; Feniglia and Giannella are two sandy dunes (locally called *tomboli*) which separate the lagoon from the sea. The western basin is connected to the sea by the Nassa canal and to the Albegna River by the Fibbia canal, whereas the eastern basin is connected to the sea by the Ansedonia canal. The canals (Table 1) are long and twisty, but not too wide. Fishing structures are present at the canal mouths. Such structures are constituted by barriers made up with metal gratings to allow fry in and prevent bigger fish from flowing out. These characteristics and the shallow waters in the canals cause the exchanges with the sea to be limited. The eastern basin experiences greater eutrophication problems. Also the exchanges between the two basins are limited by the dam and the small canal existing within Orbetello's residential area is too narrow to allow effective exchanges.

Table 1
Dimensions of the canals

Canal	Length (metres)	Mean width (metres)	Depth (metres)
Ansedonia	1840	20	1.5 ÷ 2
Fibbia	3500	18	~ 1.5
Nassa	700	30	1.5 ÷ 2

This survey consisted in flying on the lagoon and sea outlets of the three existing connection canals, both when free exchange took place and the pumps were working. In the first case, the over-flights have been carried out twice on every canal with high and low tide, whereas in the second case the over-flights have been carried out once on the lagoon outlet of the canals and twice, with high and low tide, on the sea outlet of the outgoing canal (Ansedonia). The objective was to highlight the existing plumes in order to track the size of the lagoon-sea water exchanges and to point out the presence of possible areas having a minimum or totally lacking exchange. In summertime the lagoon waters are isohaline or, after intense evaporation, hyperhaline. In this case, sea water plumes, which flow in with the high tide, float on the water within the lagoon and are therefore perfectly visible in thermal images.

3. The Instrument Used

For the study, an AVIO TVS 610 portable IR camera has been used. Such camera works in the 8-14μm wavelength interval, has a thermal sensitivity of 0.1°C at room temperature, and a geometric resolution (Instantaneous Field of View, IFOV) of 1.4 mrad. This means that it can describe an object bigger than 14×14cm from 100 m. The detector is made up of a two-dimensional matrix of microbolometres (320×240 elements) and thus doesn't necessitate to cool down. The system has a maximum 4-hour autonomy, a video output, the possibility to record thermal images on to a PCMCIA card and a serial interface. The equipment weighing about 3 kg, has an 5″ built-in liquid crystal display and a series of useful functions: automatic adjustment to room temperature, possibility to record alphanumeric and vocal comments on the image, possibility to visualise minimum and maximum temperatures, and to measure the temperature in three spots chosen at will, and so on. A chromatic scale present on the original image allows to immediately assess the differences in temperature present. The dynamic range of the image is 12 bit, equalling 4096 levels, and allows to re-process the image as much as the operator wants, once it has been retrieved, as if it were the image of a scene being filmed at that very moment. The frame frequency of 1/30 per second allows to clearly visualise moving objects or to carry through aerial images without having a blurry effect on them.

The flights, which were carried out at an altitude of 500m (1700ft) have been carried through in June (when natural exchange occurs) and July (when forced exchange occurs) 1999, from a Bell 407 helicopter, placed at the operators' disposal by the Tuscany Region. The flights were made at a low altitude, in order to have a better geometric resolution, because of the small foreseenable difference in the temperatures between the internal and external waters. The time when the flights were carried out and the time and tide levels are indicated in Table 2. In Table 3 the wind speed and direction present during the flight are indicated (average hourly values-according to the Agenzia Regionale per lo Sviluppo e l'Innovazione Agricolo-forestale (ARSIA - Regional Agency for Agricultural-Forestal Development and Innovation).

Table 2
Tide conditions during the flights

Day of flight	Time of occurrence and height of the tide (in metres)		Time of flight
29-06-1999	16.08	0.04	15.00 ÷ 15.40
30-06-1999	10.03	0.23	9.45 ÷ 10.35
17-07-1999	7.20	0.08	7.40 ÷ 8.20
17-07-1999	12.25	0.21	16.20 ÷ 16.40

Table 3
Wind conditions during the flights (ARSIA)

Day and time of flight		Wind direction and speed, average hourly values (m/s)	
29-06-1999	15	NO	4.4
30-06-1999	9	NO	4.2
30-06-1999	10	NO	4.4
17-07-1999	7	NE	2.8
17-07-1999	8	NO	0.8
17-07-1999	16	NE	2.5

A software, PE, has allowed to transform the proprietary binary format (*.iri), with which thermal images are stored onto a PCMCIA card, into bitmap format. The former, in fact, cannot be rendered by common graphic programmes.

4. Results and Discussion

The small tidal excursions existing in the area (shown in Table 4) can move the waters within the lagoon, but the geometry of the canals, their filling-up, the flat and shallow morphology of the bottom and the huge quantity of macroalgae make the phenomenon irrelevant a few hundred meters from the canals' oulets into the lagoon, as the following thermal images show.

Table 4
Minimum and maximum tidal excursions for each month of the years 1997, 1999 and 2000, in centimetres

	1997		1999		2000	
	min	*max*	*min*	*max*	*min*	*max*
January	5	35	4	33	5	34
February	7	35	4	32	5	33
March	6	33	4	31	5	30
April	4	32	3	30	2	29
May	3	30	5	32	3	31
June	4	33	6	34	7	32
July	5	34	5	33	8	34
August	7	34	5	33	7	35
September	7	32	3	30	4	31
October	5	31	3	31	1	30
November	4	31	4	33	1	31
December	4	33	7	34	3	33

The photograph in Fig. 3 shows the mouth of the Ansedonia canal (A) into the lagoon, the small lateral canal where the pumps can be positioned (arrow) and the settling basin of the waters coming from two of the four big fish farming plants present in the lagoon (B). On the canal outlet, the barrage gratings are visible. In the foreground, it is possible to notice the algae present on the lagoon floor. In Fig. 4, the thermography of the same area with high tide is shown. Such thermography is taken from another position to show the entire plume of emission: because of the small thermal difference between the incoming water and the water in the lagoon – about 1.5°C – the contrast in this and the other thermographies shown has been accentuated with an image-processing software in order to make the phenomenon more visible. The letter D indicates the plume of emission: according to measures carried out on the basis of the thermographies, sea water penetrates only for 700m. This value suits well the value of 600m reported in the ENEA survey (Bucci et al. 1988): the pointed form of the plume is actually due to the canal on the floor which favours the penetration of water into the lagoon; the letter B indicates the big settling basin of the waters coming from the neighbouring fish farming plants, whereas the small plume marked with C, is due to the above-mentioned small lateral canal. The big white spots within the settling basin are due to macroalgal masses. During the over-flights, as shown by tables 2 and 3, the wind was blowing from NW. Such direction is indicated by the arrow in the thermography: it is to be noticed how the plumes, particularly the plume indicated by C, are pushed towards the coast by the wind.

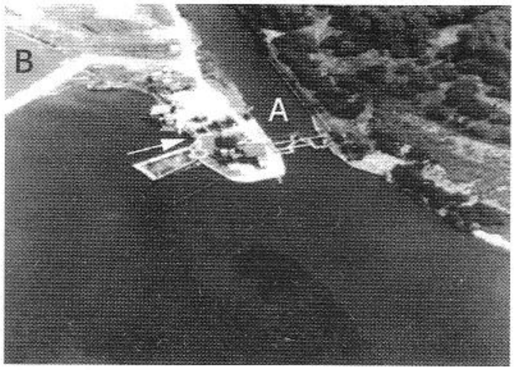

FIG. 3

In the figure, it is possible to see the lagoon outlet of the Ansedonia canal (A), the small lateral canal where the pumps can be positioned (arrow), and the settling basin (B) of the waters coming from two of the four big fish farming plants present in the lagoon.

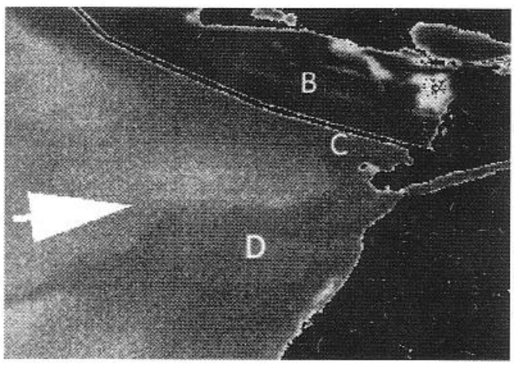

FIG. 4

Thermography taken from the outlet of the Ansedonia canal, in conditions of high tide, from a position from which the entire plume of emission can be seen. The letter D shows the plume; its pointed form is due to the canal on the lagoon floor which favours sea water penetration. B indicates the wide settling basin of the discharge coming from the fish farming plants, whereas the small plume, C, is due to the installation for the pumps along the lateral canal. The big white spots in B are due to algal masses. When the thermography was taken, the wind was blowing from NW, its direction is indicated by the arrow: note that the plumes, in particular that indicated with C, are pushed towards the coast.

The picture in Fig. 5 shows the lagoon outlet of the Nassa canal: in the foreground the Nassa canal and a wide semi-closed basin which is used as a semi-intensive fish farming plant are visible. In the background, it is possible to see the final part of the canal with the fishing structures and a fish farming plant. The waste waters of such plant are directly discharged into the canal. On the right in the figure, huge macroalgal masses are evident in conditions of low tide.

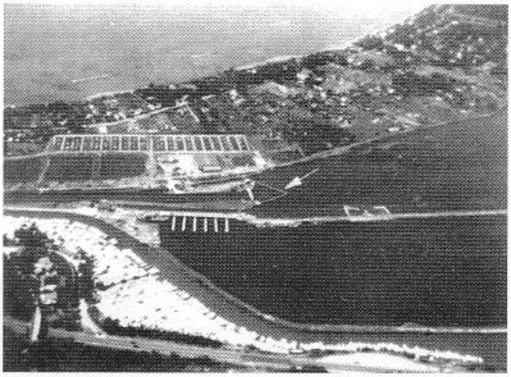

FIG. 5

The lagoon outlet of the Nassa canal can be seen. In the foreground the Navigabile canal and a wide semi-closed basin used to farm fry are shown. In the background, the final part of the canal with the fishing structures (arrow) and a fish farming plant are shown. The waste waters of such plant are directly emitted into the canal. On the right of the figure, big quantities of surfacing macroalgae are visible.

The thermography in Fig. 6 taken from the sea with high tide shows the internal outlet of the Nassa canal. The plume expands for about 1600m, thus confirming the data reported by the ENEA (Bucci et al. 1998). The lighter areas mainly near the two shores due to surfacing and/or semi-submerged algae are to be noticed.

The thermography in Fig. 7 has been taken almost on the same axis of the Fibbia canal, near its outlet into the Albegna River with high tide: in the foreground the Albegna River can be seen a few metres from its mouth (which is on the right of the figure). The white arrow indicates the limit reached by sea water (shown in a dark shade of grey), while it goes up-stream because of the tide: therefore also with high tide, fresh water and not sea water enters the lagoon. When the water of the river is particularly turbid, some sluice-gates are closed to prevent big quantities of suspended solids from entering the lagoon, because they would accelerate its filling-up.

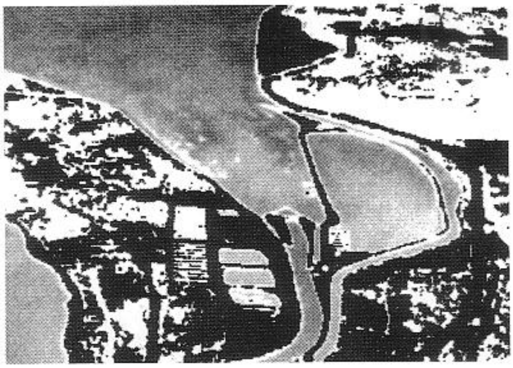

FIG. 6

This image shows the internal outlet of the Nassa canal, taken from the sea with the high tide. The areas where surfacing macroalgae are present, which are given in light grey, are visible.

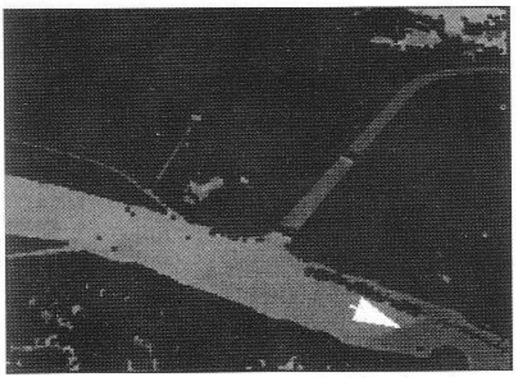

FIG. 7

The thermography has been taken almost along the same axis as the Fibbia canal, at its outlet into the Albegna River, in conditions of high tide. The Albegna River is in the foreground and its mouth is a few metres away on the right. The white arrow indicates the limit reached by sea water which goes up-stream.

In acknowledgement of the modest impact of the tides on internal water exchanges, Fig. 8 shows a thermography in which it is possible to see the sea outlet of the Ansedonia canal. Such outlet is indicated by an arrow and is in condition of low tide: the modest plume deviated by the NW wind towards the left side of the figure is visible.

The thermal images have revealed that when natural water exchange occurs in conditions of high tide, the lagoon receives water from the three canals that connect it with the sea and then releases it with low tide.

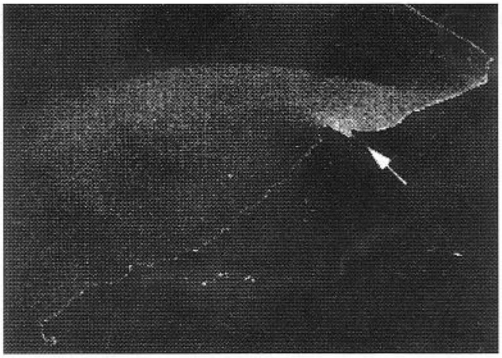

FIG. 8

The modest impact of tides on internal water exchange is confirmed by this thermography. It shows the sea outlet of the Ansedonia canal (arrow) in conditions of low tide. The modest plume is pushed by NW wind towards the left side of the figure.

The size of the discharge into the sea has been assessed when forced water exchange takes place (pumps in function): the thermography in Fig. 9 is relative to the sea outlet of the Ansedonia canal (shown by an arrow) and shows how the plume flows straight into the sea – for over 800m – and affects a vast area of it. It has also been possible to check how the tidal condition has a little impact on the plume size, when the pumps are working. A study by the ENEA (AAVV 1996) has pinpointed that the speed of water masses during forced sea flux periods is of the order of millimetres per second and the time necessary for the internal lagoon water exchange ranges from one to two months.

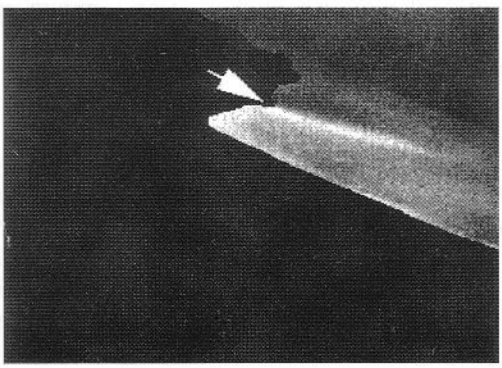

FIG. 9

The sea outlet of the Ansedonia canal (arrow) with the pumps working is shown in this thermography. The image shows that the plume enters straight into the sea for over 800m, and affects a vast area of it.

At the moment when the images were taken, i.e. when the forced sea fluxes occurred, the lagoon was experiencing a microalgal bloom (red tide), the nature of which has not been detected: the following thermographies show the situation in the two basins. The thermography in Fig. 10 taken from above Orbetello's residential area towards the Giannella *tombolo* which can be seen in the upper part of the image, shows how the bloom mainly affects the area towards the hinterland, leaving most of the western basin almost undamaged.

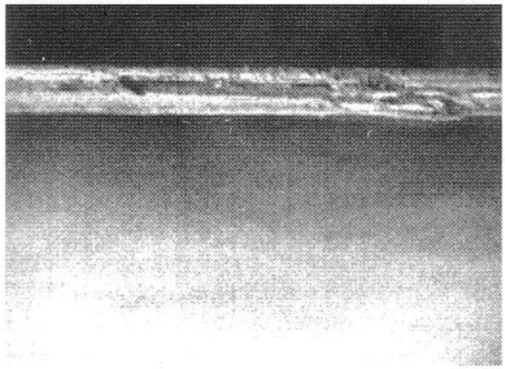

Fig. 10

Thermography taken in the presence of microalgal blooms. The thermography has been taken from Orbetello's residential area, towards the Giannella *tombolo* (top of the image). The image shows that the bloom affects mainly the area towards the hinterland, thus leaving most of the western basin untouched.

The thermography in Fig. 11, taken as well from above Orbetello's residential area but looking towards the internal mouth of the Ansedonia canal, shown by an arrow, shows how most of the eastern basin is affected by the bloom and only a small area near the Feniglia *tombolo* is not affected by it. The thermography in Fig. 12 shows the same area taken from a closer position; also in this image, the canal's outlet is indicated by an arrow. It is possible to see a build-up of macroalgae along the coast near Orbetello's residential area (bottom). This is due to wind and in the central part of the basin, the microalgal bloom (red tide) is fully developing.

The images relative to the bloom confirm the data found by the ENEA, according to which the Eastern basin is that which has a higher productivity and thus is more prone to dystrophic crises (Naviglio and Pratesi 1991).

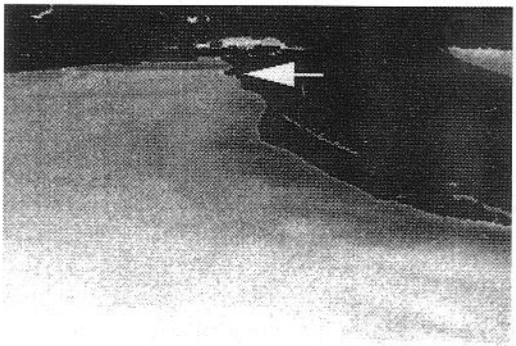

FIG. 11

This thermography too has been taken from Orbetello's residential area, but looking towards the internal outlet of the Ansedonia canal (arrow). Its assessment reveals that most of the eastern basin is affected by the bloom and only a small area towards the Feniglia *tombolo* stays undamaged.

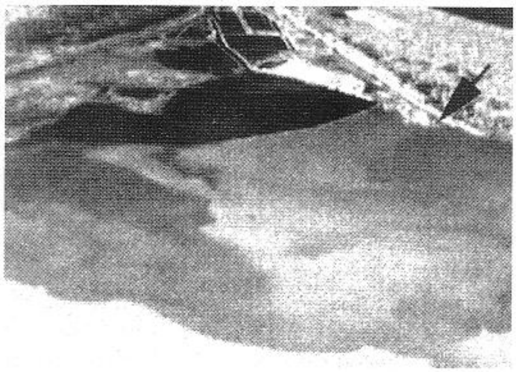

FIG. 12

This thermography taken from a closer position in the same area as that of Fig. 11 shows that along the coast near Orbetello's residential area there is a macroalgal build-up due to wind action (bottom of the figure) and that in the central part of the basin the microalgal bloom is fully developing.

5. Conclusions

The remote sensing investigation carried through on the area of the Orbetello Lagoon allows to draw the following conclusions:

1. water exchange occurring in a natural way, due to tides through the three existing canals is limited to circumscribed areas, near the mouths of the canals themselves.

In these conditions, the Orbetello lagoon doesn't have the possibility to substantially exchange waters with the exterior and therefore eutrophic phenomena and their consequences are favoured.

2. When forced water exchange takes place, the currently working pumps produce a current which moves from the western lagoon to the eastern one. However, the conformation of the lagoon excludes a vast part of it from this exchange. Despite the contribution of the pumps, significant though it may be, the lagoon water exchange is not sufficient as a whole to reduce eutrophication phenomena. The vast part that do not takes advantage of the exchange, suffers from the above-mentioned phenomena.

3. This survey allows to detect the limits of the management measures implemented so far and shows the areas where further improvement measures are required. These measures can concern:

- the installation of other pumps in the areas suffering the most which have been spotted by this survey;
- an improvement of water exchanges due to the canals, by bettering the characteristics and maintenance of the gratings of the fish farming structures and keeping the canals themselves clean;
- a rationalisation of the discharges of the fish farming plants within the lagoon.

The use of remote sensing has proved a useful tool in the study and management of one of the most interesting areas on the Italian territory from the naturalistic, productive and tourist point of view.

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