Toxic Contamination in Large Lakes

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CHAPTER 6

LAKE ORTA (N. ITALY): RECOVERY AFTER THE ADOPTION OF RESTORATION PLANS

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ABSTRACT

Heavy industrial pollution (copper and ammonium sulphate) from a rayon factory was responsible for the disappearance of almost all forms of life in the lake since the late twenties. The in-lake N-\textsubscript{NH}_4 oxidation produced a gradual N-\textsubscript{NO}_3 accumulation and a progressive strong decrease of pH down to values around 4. The copper concentration peaked at about 100 \textmu g/L in the mid sixties, when additional sources of heavy metals (Cu, Zn, Cr) i.e. several new metal plating factories were set up on the lake western shores. Toxicity tests with rainbow trout indicated that copper at the prevailing very low pH was the major cause of absence of pelagial fish in the lake.

In 1976 the new Italian water pollution law obliged the rayon factory to set up a large, new treatment plant for the recovery of copper and ammonium sulphate; at
the same time new plants for domestic and industrial effluents were planned and are now finished or under construction. This resulted in an immediate change in the lake water composition, particularly in the N-NH$_4$ concentration (now at about 2 mg N-NH$_4$/L) and in some signs of recovery in the biological community, e.g. blooms of Brachionus urceolaris and the settlement of a new population of Tubifex tubifex in the profundal zone.

A research program is now being conducted on the lake and its "paralimnion", in order to adequately survey the recovery process and to give useful suggestions for the adoption of possible direct measures. Liming of the South basin of the lake is being seriously taken into consideration and a proper scientific and technical program set up as a collaboration between the CNR-Istituto Italiano di Idrobiologia, Pallanza and the Regione Piemonte and the Provincia di Novara.

It is an honor to be here at this World Conference on Large Lakes and have the opportunity to show the case of Lake Orta, with particular reference to its recent striking recovery. We feel that the results obtained and the convergence of the chemical and biological situation of our lake with those lakes in the world, that similarly undergo acidification as a result of acid depositions, make the Lake Orta case one of very general interest.

INTRODUCTION

Lake Orta is the seventh largest Italian lake by volume (1.3 x 10$^9$ m$^3$ and depth (max: 143 m; mean: 71 m). It occupies the south-western part of the larger Lake Maggiore drainage basin. Its outlet, River Nigoglia (Figure 1) joins the River Strona, a tributary of the River Toce, which flows into Lake Maggiore.

Both Lake Orta and its drainage basin have a long, narrow shape extending in a N-S direction. The main sub-basins are located in the western part of the area, except for that of the River Pescone (18 km$^2$), and are formed by the contributing areas of the following streams (from North to South): rivers Bagnella, Acqualba, Pellino and Lagna (Figure 1).

Some characteristics of Lake Orta are given in Table 1. It is very important to note that the actual mean water residence time is 10.7 years. It has been calculated that after 10.7 years, 45 % of the original water is
Figure 1. Sketch map of Lake Orta and its drainage basin. The circle indicates the normal station for chemistry and plankton sampling; the triangle, the station for profundal benthos; the barred strip indicates the transect: Imolo-Punta Casario, along which the drift crosses are released for water current studies; the large arrow indicates the location of the main complex of plating factories.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Basin Area</td>
<td>116 km²</td>
</tr>
<tr>
<td>Mean Altitude of Drainage Basin</td>
<td>650 m a.s.l.</td>
</tr>
<tr>
<td>Mean Lake Level Altitude</td>
<td>290 m a.s.l.</td>
</tr>
<tr>
<td>Lake Area</td>
<td>18.136 km²</td>
</tr>
<tr>
<td>Lake Volume</td>
<td>1286 x 10^6 m³</td>
</tr>
<tr>
<td>Mean Depth</td>
<td>70.9 m</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>143 m</td>
</tr>
<tr>
<td>Water Inflow (precipitation)</td>
<td>1901 mm/yr</td>
</tr>
<tr>
<td>Mean Outflow Discharge</td>
<td>4.81 m³/s</td>
</tr>
<tr>
<td>Yearly Outflow Discharge</td>
<td>151.688 x 10^6 m³</td>
</tr>
<tr>
<td>Theoretical Detention Time</td>
<td>8.478 yrs</td>
</tr>
<tr>
<td>Theoretical Renewal Rate</td>
<td>0.118 /yr</td>
</tr>
<tr>
<td>Actual Renewal Rate</td>
<td>0.093 /yr</td>
</tr>
<tr>
<td>Mean Actual Water Residence Time</td>
<td>10.7 years</td>
</tr>
</tbody>
</table>

still present in the lake (Bonacina and Bonomi 1974). The lake basin, formed by ice erosion on a pre-existing river valley, is mostly formed of gneiss, micashists and granites. Because of the geology of the catchment basin the water of Lake Orta was originally poorly buffered, with total alkalinity ranging from 0.3 – 0.4 meq/L (Monti 1929).

The very pure waters of Lake Orta once supported a rich biological community: about 150 algal species (Glaj-Levra 1925) and an abundant population of copepods and, above all, of cladocerans (Pavesi 1379, Monti 1929) which are the favorite food items for zooplanktophagous fishes. Fish were also abundant: trout (Salmo lacustris), shad (Alosa finta lacustris), bleak (Alburnus alburnus alborella), perch (Perca fluviatilis), pike (Esox lucius) and eel (Anguilla anguilla) were the major catch. After 1901 Coregonus wartmanni (white fish) was successfully introduced in the lake and became one of the most important fishes from the economic point of view. In 1914-1916 Salvelinus alpinus (char) was also introduced (De Agostini 1925). In 1911 a Fisherman's Cooperative Association was founded with the aim, among others, of taking care of fish reproduction and restocking. The yield of fish in Lake Orta was very high: in 1927 an issue of the Proceedings of the Italian Ministry of Agriculture, Industry and Commerce reports the total yearly catch to be 65.4 tons, given as a normal production for the lake; that is a production of 36.2 kg/ha, almost twice that of Lake Maggiore (20.5 kg/ha; Baldi 1979), at that time.

Bearing in mind the lake volume of Lake Orta (Table 1) and its value as a holiday resort and a centre for
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water sports, it is readily concluded that its restoration and protection are high desirable.

THE CASE HISTORY

In November, 1926, a rayon factory (Gemberg, Figure 2b) was set up at the southern end of the lake (the outlet, River Nigoglia, leaves the lake at its northern end, Figure 1). The factory needed (and still does) a large quantity of pure soft water for washing and cooling purposes. The factory discharge is "enriched" with copper sulphate and ammonium sulphate, at a pH of about 10 and temperature of 18-22°C. Some iron salts were also discharged, due to a process of partial copper recovery. The mean daily discharge of the factory effluent was, and still is, 12,000 m³. This represents about 3% of the lake mean discharge.

At the end of 1927, water samples from the open lake were completely devoid of phyto- and zooplankton (Bachmann, in litteris). Two years later, practically all forms of life had disappeared, and the lake water was classified as sterile (Monti 1930). According to Monti, this extraordinary chain of events was attributable to the algicidal action of copper, which rapidly destroyed almost all the phytoplankton and consequently zooplankton and fish. The factory which caused this ecological disaster tried in many ways to deny its responsibility. The inhabitants were divided between fishermen deprived of their livelihood and the people who had found work in the factory. Eventually, all fishermen were employed by the factory and the controversy stopped. However, the problem of the lake remained.

The factory effluent contained, in varying quantities through the years, ammonium and copper sulphate (Table 2), plus other substances such as sodium carbonate and calcium oxide which are not relevant in this context. The decrease in the total inorganic nitrogen loading during the period 1975-1979 was due to a decline in the rayon market. As shown, in the late fifties, the total amount of copper reaching the lake increased greatly. This is attributed to the many small bathroom accessory plating factories which opened on the south-western shore near the mouth of the River Lagna (Figure 1 and 2d). They discharged heavy metals (Cu, Zn, Cr, Ni), anionic detergents and cyanide into the lake. The lowering of copper loadings in the period 1959 to 1967 L (Table 2) was due to the installation of a copper recovery plant in 1958.
Figure 2a. Aerial view of Isola S. Giulio (Central Basin).
Figure 2b. Aerial view of the Bemberg factory area located immediately to the south of Lake Orta.
Figure 2c. Aerial view of the Bemberg factory area with the factory lake water reservoirs used for rayon process water.
TABLE 2  ANNUAL TOTAL INORGANIC NITROGEN (TN$_{in}$) AND TOTAL COPPER LOADING FROM THE RAYON FACTORY TO THE LAKE (1927-1979)

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>TOTAL INORGANIC NITROGEN (TN$_{in}$) tons/yr</th>
<th>COPPER (tons/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1927-1946</td>
<td>up to 1,000</td>
<td>up to 40</td>
</tr>
<tr>
<td>1947-1958</td>
<td>1,000-2,000</td>
<td>40-80</td>
</tr>
<tr>
<td>1959-1967</td>
<td>2,000-3,000</td>
<td>4-5</td>
</tr>
<tr>
<td>1968-1974</td>
<td>about 3,000</td>
<td>about 4</td>
</tr>
<tr>
<td>1975-1979</td>
<td>about 2,000</td>
<td>about 3</td>
</tr>
</tbody>
</table>

$^1$ max.3,350 in 1970

For copper, the mean annual loading from these factories of was calculated to be 13 tonnes (Bonacina and Ruggiu 1973). As far as heavy metals are concerned, the available data are rather scanty. The mean concentrations at Station A (Figure 1) are: approximately 40 ug total Cu/L, 60 ug total Zn/L and 5 ug total Cr/L. About 85 ug Al/L were also found (the Al is likely leached from the lake sediments). The situation is made worse because of metal accumulation in the sediments (Corbella et al. 1958, Barbanti et al. 1972, Bonomi and Ruggiu 1974). Recently Provini and Gaggino (1985) calculated that the metal content of the lake sediments, particularly chromium, constitutes a "considerable" to "very high" ecological risk.

As a result of this heavy loading, nitrates (derived from in-lake ammonia oxidation) started to accumulate (Baldi 1949) and pH to decrease to about 4 while the buffer capacity of the lake tended to zero (Vollenweider 1963). Year by year the oxygen decreased due to nitrification processes. Finally, the large quantities of ammonia were no longer completely oxidized and started to accumulate in the lake waters, while the oxygen depletion in the hypolimnion increased (Bonacina 1970).

At the beginning of the seventies, the situation at the circulation period was as follows: mean concentration of ammonia nitrogen: 4.8 mg/L; nitrate nitrogen: 5.5 mg/L; copper: 50 ug/L; pH: 4.5; oxygen saturation: 60% (Barbanti et al. 1972). During the summer, due to its relatively high temperature, the factory effluent tended to stratify within the epilimnion. As a consequence, ammonia concentration increased to as high as 8 mg N/L in the first ten meters (some 1 mg/L of which is free ammonia), while pH ranged from 7-9 (Bonacina 1970, Barbanti et al. 1972, Bonacina and Bonomi 1974). In addition to this vertical
stratification, a horizontal south to north gradient was present from spring to autumn. This was due to the relative positions of the polluted inlet and outlet. Indeed, the epilimnic summer concentration of ammonia nitrogen was higher near the southern end of the lake (from south to north: 8.5 and 6.6 mg N/L) whereas epilimnic summer values of pH varied in the same direction from 8.9 to 8.4 (Bonacina and Bonomi 1974).

The biological situation had changed slightly since 1927. In fact, sudden algal and rotifers blooms started no later than August 1929 (Bachmaniella planctonica Chodat, nov. gen., nov. sp.; Baldi 1949). Afterwards there was a burst of Pedalia mira (= Hexarthra fennica) in September 1946 (Baldi 1949) and later on, in July 1971 (Barbanti et al. 1972) successively, there were blooms of Scenedesmus armatus (Nov.–Dec. 1960; Vollenweider 1963) Ankistrodesmus convolutus (Jul. 1969; Bonacina 1970), Brachionus urceolaris (Oct. 1983 and Jan. 1984; Bonacina, unpublished data). In the seventies, there were very few planktonic species inhabiting Lake Orta. There were two algal species: Oscillatoria limnetica (blue green) and Coccomyxa minor (green), plus some diatom species with very low density, one copepod species (Cyclops abyssorum) and some rotifer species (Brachionusurceolaris, B. calyciflorus, Keratella cochlearis). In the profundal of the lake there were no macrobenthonic species but a rich population of benthic ciliates flourished (Ruggiu 1969).

There were no fishes at all. In 1975 short-term field survival tests showed ionic copper to be the major acute toxic factor for adult specimen of the rainbow trout (Salmo gairdneri) (Calamari and Marchetti 1975). However, there are also chronic effects which must be borne in mind: investigations on Norwegian lakes have demonstrated a strong correlation between lowering of pH and progressive lack of fish fauna in low alkalinity waters (Muniz et al. 1984). Furthermore, it must be remembered that other metals are permanently present in the lake waters. Their toxicity to fish fauna and zooplankton is well known (Haux and Larsson 1984, Intersool and Winner 1982, Winner 1976 and 1984).
RECOVERY ACTION

For the successful restoration of Lake Orta there were three main problems which had to be solved:

1. stopping the continuous input of ammonia nitrogen,

2. treating the heavy metal wastes from the plating factories (Figure 2d), and

3. preventing the sewage from 35,000 inhabitants (tourists included) from reaching the lake.

The first problem has ceased to exist. The rayon factory, compelled by the Italian law on water pollution (approved in 1976 by the Italian Parliament) constructed a big treatment plant for the recovery of ammonia and copper salts. Operation started in late 1980. Consequently, the mean annual loading (Cu and TN$_{in}$) from the factory effluent since 1980 has been about 0.3 tons/yr and 30 tons/yr respectively.

The second problem is still awaiting solution. Although a treatment plant has been constructed (Figures 2f and 3) it has not yet started to work effectively. This is because it is an activated sludge plant, which receives both domestic sewage and effluents from the plating industries, which unfortunately are still characterized by peak metal concentrations that inhibit the proper operation of the plant. Table 3 reports the estimated heavy metal loadings from the plating industries.

The third problem will be solved shortly when both the new Omegna treatment plant (Figure 2e and 3) and the villages to be served are connected with the pipeline network.

SIGNS OF RECOVERY

Some significant effects have been produced on the lake waters by the recovery of ammonium sulphate from the factory effluent. Firstly, there has been a decrease in the total inorganic nitrogen (TN$_{in}$) concentration, in particular that of ammonia nitrogen. It has dropped from its early 1980 level of about 5 mg/L to about 2 mg/L. Secondly, there has been a marked decrease of
Figure 2d. Aerial view of area where most of the plating factories are located.
Figure 2e. Wastewater treatment plant for the town of Omegna (see P1 on Figure 3) which shall receive domestic (mainly) and industrial wastes.
Figure 2f. Wastewater treatment plant on the Lagna stream, receiving sewage from the nearest villages and industrial wastewater from the plating factories (see P2 on Figure 3).
summer-autumn epilimnic N-$NH_4^+$ concentration and pH values. The third effect is the abatement of the horizontal north to south N-$NH_4^+$ and pH lake-long gradient (Bonacina and Bonomi 1974).

The TN$_{in}$ load received by the lake today is less than 1% of the previous peak leads, resulting in the development of new vertical and horizontal stratifications. This causes lake water pH now to be in the 4-6 range year round and from surface to bottom. An inversion in the previous horizontal gradients seems
TABLE 3  PRESENT COPPER AND CHROMIUM LOADINGS
TO THE LAKE:
A: conveyed to the Lagna treatment plant
B: directly disposed of into the lake

<table>
<thead>
<tr>
<th>METAL</th>
<th>YEAR</th>
<th>A (tons/yr)</th>
<th>B (tons/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1983</td>
<td>about 4</td>
<td>about 1</td>
</tr>
<tr>
<td></td>
<td>1984</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Chromium</td>
<td>1983</td>
<td>9.1</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>1984</td>
<td>9.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>2.4</td>
<td>5.5</td>
</tr>
</tbody>
</table>

to be developing along the main axis. The nitrification of the residual mass of ammonium ion in the lake and the lack of the bicarbonate buffer system are responsible for the still very low pH values. In spite of the apparently rather low nitrification rate, calculated by some means of hypolimnic mass-balances (Bonacina and Ruggiu 1973, Gerletti and Provini 1978) and the low nitrifier counts (Gerletti and Provini 1978) the lake as a whole is showing at the moment the effects of efficient and marked nitrification. In this context it must be borne in mind that during the sixties the loading into the lake from the rayon factory was about 3,000 tons N-NH₄/yr. This resulted in a sharp increase in the N-NH₄ concentration (from 1 to 4 mg/L in 6 years) and a parallel decrease in the concentration of the lake water nitrate (Bonacina 1970). The limits of the nitrification potential of the lake system were apparently thus shown. The authors are of the opinion that the current N-NH₄ concentration and the comparatively insignificant N-NH₄ loading from the rayon factory will maintain a considerable capacity for nitrification and will result in a rapid decline of N-NH₄ in the lake waters, but in a slow decrease in nitrates. Consequently, the pH will tend to stay very low very several years.

Some immediate responses of the biota to the rapid chemical changes have already occurred. There are occasional blooms of some sporadic planktonic populations, more now than in the past, e.g. *Scenedesmus* sp., *Brachionus urceolaris*. Some typically littoral cladocerans (*Sydä cristallina*, *Chyadorus sphaericus*) may now be found in open waters. Recovery by the profundal zones of all three lake basins (Figure 1) through colonization by a macrobenthonic population of the tubificid *Tubifex tubifex* is becoming evident.
A possible recovery of the fish community has not yet been documented. It is anticipated that this community will probably suffer even further setbacks as a result of the extreme acidity, the somewhat high heavy metal concentrations and the current new epilimnic situation (low pH for the whole year). Recently the authors were unable to detect any fish mark with their echosound recorder when using this instrument in many areas of the lake, including the main inflowing stream inlets.

CURRENT RESEARCH

Hydrography of Lake Orta

The paramount morphological characteristic of Lake Orta is its subdivision into three different basins with a progressively increasing depth from south to north. From the hydrographic point of view it is different from the other deep Italian sudalpine lakes in that its effluent, River Nigoglia, outflows from the northern end of the lacustrine valley. The area for dumping copper and ammonia waste into the lake, responsible for the past large scale chemical pollution, is located at the opposite end (Figure 1).

In this geo-hydrographic context, the CNR-Istituto Italiano di Idrobiologia began a study on water movements in lake Orta, especially in its southern basin, with three different aims:

1. to investigate the possibility that the pollutants trapped in the lacustrine sediments close to the rayon factory discharge might be released and transported by water movements into other parts of the lake;

2. to analyze the diffusion of the present wastewater from the industrial factory into the lake;

3. to verify the possibility of using suitable techniques in order to speed up the recovery rate of the lake, for instance, liming of its southern basin, or part of it.

The first approach to the water movements of Lake Orta was carried out using current crosses released at five depths (0.5, 10, 20 and 30 m) along a fixed transect:
Imolo-Punta Casario (maximum depth 34 m; Figure 1). During each field experiment (five in 1985 and two so far, in 1986) the crosses were topographically positioned at intervals of approximately two hours. It was recognized that wind is the most important acting force, especially for water in the upper levels. In these strata the water velocity was, in some cases, more than 10 cm/s. The deeper the levels investigated, the less swift the water movements, so near the bottom the maximum speed was 3-4 cm/s. The roles of thermal stratification of the morphology of the lacustrine valley in determining the energetic and directional components of water currents were also recognized. Their maximum velocity was recorded during the spring 1986 when at the beginning of stratification, the work of the wind was distributed exclusively on the first strata, the only ones involved in the circulation of the lake. The general current pattern is therefore linked with the present anemological situation, but it is also affected by the former winds.

Generally speaking, the counterbalancing movements occur at the same depth, but along opposite shores. The most common hydrological situation in Lake Orta indicates an anti-clockwise circulation with currents flowing south or south-east along the western shore, counterbalanced by a northward movement along the eastern shore. However, the opposite situation has also been recorded, i.e. a clockwise circulation. Counter-balancing at different depths is also possible, generally with the more superficial strata flowing north and the deepest in the opposite direction.

The next step in the research program will deal with the process of diffusion of the industrial effluent into the lake. The effluent discharge rate is about 12,000 m$^3$/d with a temperature of 25-30°C. If the effluent does not contain some physical or chemical characteristic which is sufficiently conservative to permit a suitable measurement of turbulent diffusion, it will be necessary to use a tracer, i.e. fluoroescient dye.

Chemistry of Lake Orta

Though the atmospheric deposition in the watershed of Lake Orta is decidedly acidic (Table 4) and constitutes a hydrogen ion input on the lake surface (18.12 km$^2$), the water of the tributaries (draining altogether 97.6 km$^2$) are buffered (Table 4). The mean total alkalinity
TABLE 4  pH, CONDUCTIVITY AND MEAN CONCENTRATIONS OF ATMOSPHERIC DEPOSITIONS (A) AND INFLOWING WATERS (B); mean values for the years 1984-1985, compared with the lake chemistry at the overturn (C:1984; D:1985)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.9</td>
<td>7.5</td>
<td>4.4</td>
<td>3.9</td>
</tr>
<tr>
<td>Conductivity uS/cm</td>
<td>29</td>
<td>90</td>
<td>124</td>
<td>153</td>
</tr>
<tr>
<td>H⁺ ueq/L</td>
<td>39</td>
<td>0</td>
<td>44</td>
<td>126</td>
</tr>
<tr>
<td>NH₄⁺ ueq/L</td>
<td>58</td>
<td>25</td>
<td>284</td>
<td>164</td>
</tr>
<tr>
<td>Ca²⁺ ueq/L</td>
<td>29</td>
<td>303</td>
<td>315</td>
<td>324</td>
</tr>
<tr>
<td>Mg²⁺ ueq/L</td>
<td>6</td>
<td>117</td>
<td>123</td>
<td>123</td>
</tr>
<tr>
<td>HCO₃⁻ ueq/L</td>
<td>0</td>
<td>308</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SO₄²⁻ ueq/L</td>
<td>83</td>
<td>223</td>
<td>641</td>
<td>645</td>
</tr>
<tr>
<td>NO₃⁻ ueq/L</td>
<td>48</td>
<td>93</td>
<td>319</td>
<td>321</td>
</tr>
<tr>
<td>SUM cations¹ ueq/L</td>
<td>146</td>
<td>693</td>
<td>1031</td>
<td>1013</td>
</tr>
<tr>
<td>SUM anions² ueq/L</td>
<td>146</td>
<td>704</td>
<td>1036</td>
<td>1032</td>
</tr>
</tbody>
</table>

¹ includes Na⁺, K⁺  
² includes Cl⁻

is about 300 meq L⁻¹ and the pH generally above 7.0. Even during heavy rains, which are quite frequent in this area, no episode of acid input from the tributaries has been detected (Mosello, unpublished data). So, it is evident that the strong acidification of the lake water is due to in-lake processes.

Many in-lake reactions, mostly biologically mediated, produce or consume hydrogen ions (e.g. Stumm and Morgan 1981, Brewer and Goldman 1976, Schindler et al. 1985). In the case of Lake Orta, ammonia oxidation has been recognized since 1962 as a source of acidity (Vollenweider 1963 and 1965). This has also been recently confirmed on the basis of a chemical budget (Mosello et al. in press). The lake water showed a pH of 4.0-4.5 during the years 1984-1985, with minima of 3.8-3.9 occurring at the end of the stratification of 1984. Table 4 shows the mean pH and ionic concentration at the lake overturn. The surface water shows lower acidity and pH may reach values as high as 6.0 during summer. This is due to the influence of tributaries and biological processes of phytoplankton.

It is to be stressed that the present chemical condition of the lake is very different from its original state, before the beginning of ammonia pollution, as documented from earlier studies (Monti 1930, Baldi 1949) as mentioned in the introduction of this paper. The same conclusion may be obtained by
analogy with the chemistry of a lake located in the same region, Lake Mergozzo, hydrogeochemically very close to Lake Orta.

The relation between ammonia oxidation and pH decrease is shown in Figures 4a and 4b, respectively.

**Figure 4a.** Ammonium nitrogen in Lake Orta (1984-1985). (Values are means calculated for the 0-143m water column).

**Figure 4b.** pH values in Lake Orta (1984-1985). (Values are means calculated for the 0-143m water column).
The ammonia nitrogen decreased substantially from 1985, practically halving the values in the lake. This decrease is of great importance when it is also compared with the long-term variation of ammonia concentration (Figure 4). The more relevant pH decrease was from September 1984 to January 1985. Also, in this case the values are among the lowest measured in the lake. The oxygen concentration shows a decrease as well. This is in agreement with the decrease in ammonia concentration. During 1985 ammonia concentration, though again very high (2.0 - 2.4 mg N/L), showed a decrease much lower than the previous year (Figure 4). The variation of pH and oxygen concentrations during 1985 are consistent with that of ammonia, showing in the case of pH a moderate increase in comparison with the overturn value, and in the case of oxygen (Figure 4c), a lower decrease in 1985 than in 1984.

![Graph showing dissolved oxygen values](image)

Figure 4c. Dissolved Oxygen values in Lake Orta (1984-1985). (Values are means calculated for the 0-143m water column).

The slight increase in pH during 1985 is related to the alkalinity input from the watershed, as calculated from the chemical budget (Mosello unpublished). The lower ammonia oxidation rate during 1985 is probably due to the inhibitory effect of pH, which in the hypolimnion was around 4.0 year round.

The acidity of the lake waters permits a relatively high concentrations of heavy metals in solution which
are derived from the industrial activities in the watershed. At the 1985 overturn, the concentrations were 36 ug Cu/L, 80 ug Al/L and 55 ug Zn/L.

**Phytoplankton in Lake Orta**

It would be interesting, and rewarding, to give a full account of algal assemblages in Lake Orta from the time of the great pollution of 1926 to the present. It is a history of community collapse with great reduction in number of species, mass mortality of diatoms, recurrent ephemeral bursts of various species disconnected with the pristine communities, and no clear and established seasonal successions. As these events are beyond the scope of this discussion, reference is made to the papers of Vollenweider (1963) and Bonacina (1970), where the lake conditions of the past were extensively treated. Suffice it to say that by 1970 only two species, the blue-green *Oscillatoria limnetica* (then described as *Lynghya limnetica*) and the green *Coccomyxa minor* comprised the largest part of the phytoplankton throughout the year. By 1981, just after the wastewater treatment plant came into operation, some additional species were of importance (*Scenedesmus armatus*, *Microcystis aeruginosa*, *Achnantes minutissima*). A seasonal succession was evident.

Detailed observation on phytoplankton are currently under way, but still remain to be elaborated. However, after five years of treatment plant activity, things seem to be changing considerably and quickly. *C. minor* has further increased its importance, but the blue-greens have dwindled almost to nothing and, more important, a lot of small flagellate species belonging to several classes have appeared, together with some minute diatoms. It is tempting to conclude that the rapidly changing chemical conditions are flavoring the occurrence of opportunistic, pioneer species and to predict major changes in community structure in the future.

The authors believe that the peculiarities of Lake Orta offer a unique opportunity of gaining information on the ecology of phytoplankton, as the situation closely resembles a large-scale experiment. For this reason, the chemical and physical parameters are being monitored in the water column, along the plankton sampling and primary production measurement with the refinement of the oxygen technique. On the other hand, bioassay experiments are under way to test specific hypotheses on the effect of changing pH and nutrient
supply, and of the presence of heavy metals on the community metabolism and composition.

The authors also realize that practical suggestions for lake management will be a necessary outcome of their activity and their studies are largely planned with this end in mind.

Cycle and Toxicity of Copper in Lake Orta

Since the middle of the seventies, the Laboratory of Applied Hydrobiology of the Water Research Institute, in Brugherio (Milano), has investigated at different times, specific topics concerning Lake Orta: the acute toxicity of copper and ammonia (Calamari and Marchetti 1975), the nitrification processes (Gerletti and Provini 1978) and copper content in sediments (Provini and Gaggino 1985). At present, the copper cycle and its transport mechanisms are being investigated. The copper partitioning in dissolved and particulate phases has been investigated in order to assess the metal cycle in the lake, whose hydrochemical conditions have perceptibly changed during latest years (Mosello et al. in press). The soluble forms of copper, in the dissolved phase, are characterized after filtration on polycarbonate membrane (0.4 um). The fractions of the particulate phase are studied in the suspended particulate matter and the fresh sedimenting material which is caught monthly in two traps (30 and 140 m depth). The former is separated by centrifuging water samples (20 L) with a continuous flow system, then both are wet digested with nitric and hydrofluoric acids by heating in vessels (PTFE-lined).

The results show that copper, at the present conditions of pH 4.5 year round in the whole water column and of dissolved organic carbon (DOC) of 1 mg/L, is mostly (98%) as the ionic species in the dissolved phase. This has been confirmed by electrochemical analyses. The sedimentary fluxes of particulate matter range from 0.3 to 6.3 g/m².d in euphotic zone and from 0.5 to 10.1 g/m².d at the bottom, with minimum values during a large part of the year.

These results, together with those of further investigations that simulate changes of the environmental conditions, may be useful to elucidate the transport mechanisms copper and its behaviour in the lake. The results may also be used in a mathematical model.
Zooplankton in Lake Orta

After the catastrophic destruction of 1927 (Monti 1930) zooplankton of Lake Orta never returned to the previous normal condition of a balanced community. Like phytoplankton, zooplankton also underwent episodes of instantaneous blooms of various species (see also the section "case history"), but the bulk community was made up by a cyclopoid copepod, Cyclops abyssorum, still present with very few individuals (Vollenweider 1963, Banocina 1970). Today the zooplankton of Lake Orta is intensively studied. The main sampling point is Station A (Figure 3) where bimonthly samples are taken by means of a Clarke and Bumpus plankton sampler, and then examined and counted in order to update species composition and abundances. For these purposes, nets with differentiated meshes are used: in this way adult (bigger) and young (smaller) copepod and cladoceran forms as well as the small rotifers can be caught. In order to obtain specimen of rare species, samples are taken occasionally at various stations with much larger, although with the same mesh size, nets.

In 1985-1986 the most important species, from the numerical point of view, has been Brachionus urceolaris (Mueller) (Rotifera, Brachionidae) whose population can reach a density of 200,000 m\(^{-3}\) (Bonacina Jan. 1984 unpublished).

The Profundal Macrobenthos

In 1983, during one of the periodical surveys performed on the lake, a population of Tubifex tubifex Mueller (Oligochaeta; Tubificidae) was discovered in the profundal of Lake Orta. These worms are distributed all over the profundal of the three basins (from 20 to 143 m depth). In the bottom layers from the eu-littoral to about −20 m several (10) stonefly species are present, together with 2 chironomids: a Chironomus sp. and a Procladius sp..

During 1984, at a fixed station in the south basin (Station B, Figure 3) 12 replicate Ekman samples were taken at monthly intervals. The sorted material was divided into 5 compartments (eggs, embryos, young, mature and ovigerous individuals). The population displays a marked clumped distribution, typical of a new settler. The overall abundance values may be as high as 37,000 m\(^{-2}\).
The clutch size (eggs/cocoon) of this population is very high. Marked mid-summer mortality has been noted. An annual numerical balance for the 5 biological compartments shows that the "cost" of one ovigerous individual, in terms of mortality of the previous compartments, does not substantially differ from that estimated for other unpolluted lakes (Bonomi and Andreani 1978, Andreani et al. 1981, 1984).

EXPEDIENCY OF TAKING DIRECT MEASURES

The strong mineral acidity of the lake waters and the relatively high concentration of some heavy metals are the true bottleneck of the Lake Orta ecosystem at the moment. Ironically enough, the present pH situation is even worse because of the lake alkalinity from the rayon factory which, up to some years ago, had some beneficial effects on the epilimnic waters (e.g. increasing pH and precipitating Cu).

Therefore liming the lake appears to be a possible direct measure, naturally taking into account the feasibility and cost of such a scheme. This measure was already started some 25 years ago, but its cost (large lake volume) and a need for a non-stop intervention (continuous past heavy NH$_4$ loading, producing a continuous long term acidification) left the idea at a theoretical stage. Furthermore, in the past situation, when a wastewater treatment plant for domestic sewage was not even contemplated, an inorganic C addition (liming) and the P loading (untreated sewage) might have transformed the lake into a very productive system. The present situation looks drastically different. The actual acidity of the lake water and the potential proton production resulting from the nitrification of the residual ("historical") 2 mg N-NH$_4$/L may easily be calculated and the appropriate amount of carbonate required can then be computed and added to the lake waters. Chemical addition may be performed in several stages but need not be repeated over a very long period of time. Being aware of technical problems and of the high cost of liming the whole lake volume Bonacina and Bonomi (1984 and 1985) suggested limiting the liming to the southern basin, which has a much smaller volume.

A couple of years ago this proposed direct measure was still regarded by the local administrators as a "scientific curiosity", as the lake was in fact recovering anyway and at a very fast rate. Very recently (spring 1986) the local health authorities
realized that, due to the progressive pH decrease, the superficial waters were well below the pH range (6-9) allowed for public bathing. Consequently bathing was prohibited and liming became a direct measure to be seriously considered by the authorities themselves. At the moment the Regione Piemonto (one of the twenty administrative units in Italy) is willing to sponsor the project, possibly delegating the Province of Novara (local administration subdivision of Piemonte) to prepare the program. Both the scientific and technical aspects are to be set up in strict collaboration with the CNR-Istituto Italiano di Idrobiologia, Pallanza.

The scientific and technical program is being prepared. The technical aspects should be facilitated by contact with institutions or environmental agencies that have carried out and continue to carry out liming of acidified water on a large scale (e.g. Scandinavian countries). The local (south end) liming should produce, in a reasonably short time, the following striking effects:

1. neutralization of part of the lake and reconstitution of a "normal" alkaline reserve in this basin,

2. precipitation of heavy metals with a consequent strong decrease in toxicity for the present lake biota and for potential resettle,

3. enhancement of the nitrification of the residual ammonia (nitrification is now probably pH and inorganic carbon limited), and

4. reconstitution of a much richer animal community, including zooplankton and fish. Fish re-stocking will have to be strictly controlled by the Fishing Authorities (Province of Novara).

A continuous mild liming of the south basin — a future possibility — should also be effective in enhancing the nitrification of the N-NH$_4$ load from the rayon factory. Indeed, although in the present chemical situation the factory loading (30-40 tons N-NH$_4$/year) is negligible in comparison to the total ammonia mass in the lake (approximately 2,600 tons N-NH$_4$). In a future situation, when the residual N-NH$_4$ is totally oxidized to nitrate, the factory N-NH$_4$ loading is likely to have some local effects in the south basin.
The turbulent diffusion (drift, internal seiches and convective currents) should help in gradually bettering the chemical situation in the central and north basins of Lake Orta (Figure 1).

CONCLUDING REMARKS

Undoubtedly the case of Lake Orta is a unique example of how uncontrolled industrial pollution may throw a large deep lake into acute stress. Its dramatic environmental deterioration, both chemical and biological, was immediately detected by observers of the lake and three generations of limnologists, almost all of them from the CNR-Istituto Italiano di Idrobiologia in Pallanza. They have worked with the aim of not only surveying the situation of the lake but, more importantly, of pushing towards its restoration. We have been fortunate enough to be present at the start and follow its amelioration. The scenario demonstrates how, even in heavily polluted large lakes, the implementation of adequate treatment and recovery plants leads to an immediate improvement in the environmental situation.

A last stage in the "resurrection" of Lake Orta could be the adoption of some direct measures, e.g. liming of at least part of its waters. We are eager to participate in this enterprise and hope to be able to follow this final acceleration of its recovery.

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