Recovery of an industrially acidified, ammonium and heavy metals polluted lake (Lake Orta, N. Italy), due to the adoption of treatment plants

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With 3 figures and 3 tables in the text

Introduction

At the World Conference on Large Lakes — Focus on Toxics (Mackinac Island, Michigan, U.S.A., May 18—21, 1986) one of us gave an invited paper on the Lake Orta case, the recent abatement of its main pollutant and the plans for a direct intervention on its acid waters (Bonacina et al. in press). This is just one sign of the international interest in the pollution of this large, warmmonomictic lake in the Italian subalpine lake district. Of the 40 odd limnological papers produced on this lake, this is the fifth given at an S.I.L. Congress (the others being: Tonelli 1961, Ruggiu 1969, Bonacina, Bonomi & Ruggiu 1975, Guilizzoni & Lami this volume). This “old” (1926) pollution situation has developed in such a way that nowadays the chemistry and biology of the lake are strongly convergent with those typical of water bodies acidified by acid deposition. This also gives this case a more general aspect and permits us to profit from the experience made on this type of lake in other countries.

This paper, apart from describing the history of Lake Orta pollution and its limnological consequences, aims to point out the effects of the adoption of treatment plants at the sites of major pollution sources and a plan for the liming of the lake waters. Liming should produce, in a reasonably short time, the following striking effects:
1. neutralization of the lake and reconstitution of a “normal” alkaline reserve;
2. precipitation of heavy metals with a consequent strong decrease in toxicity for the present lake biota and for potential re-settlers;
3. enhancement of the nitrification of the residual ammonia (nitrification is now probably pH and inorganic carbon limited);
4. reconstitution of a much richer animal community, including zooplankton and fish.

Lake Orta is located in Northern Italy, north-west of Milan. It is a glacial lake, with an area of 18 km², a volume of 1,249 \( \cdot 10^6 \) m³, a maximum depth of 143 m and a drainage basin of 116 km². Its effluent, which outflows from the northern end of the lake, is a tributary of the larger Lake Maggiore. Lake Orta is heavily polluted by the effluents discharged since 1926 by a rayon factory located at its southern end.

Our information about the natural chemical conditions of the lake is rather scanty: we know that pH ranged between 7.1 and 7.3 in the first 50 m layer and between 6.9 and 7.1 at the depth of 100 m (Volkenweider 1963). In 1926 an alkalinity value of 0.3 meq \( \cdot 1^{-1} \) was recorded (Baldi 1949).

During a period of about fifty years, the rayon factory discharged into the lake increasing quantities of copper and ammonium (Table 1). While copper, according to Monti (1930), killed all of the phytoplankton organisms, indirectly causing the death of zooplankters and fish, the ammonium in-lake oxidation produced firstly the lowering of the alkalinity and pH; the latter shifted from 6.5 in 1948 (Baldi 1949) to 5.2 in 1960 (Volkenweider 1963), 4.8 in 1969 (Bonacina 1970) and 3.9 in 1985 (Fig. 1) (all values refer to the circulation period).

As for the ammonium, it was completely oxidized till about the fifties, causing an increase of nitrate concentration (Fig. 1); then it started accumulating in the lacustrine water, reaching a maximum of 0.4 meq \( \cdot 1^{-1} \) in the early seventies (Bonacina, Bonomi & Ruggiu 1973, Bonacina & Bonomi 1974). For the whole period 1970—1980 ammonium and nitrate concentrations stayed in the range 0.3—0.4 meq \( \cdot 1^{-1} \) (Fig. 1).
Table 1. Copper (Cu) and total inorganic nitrogen (TIN) loadings disposed into the lake. The noticeable reduction of the copper loading between 1957–1958 is due to the adoption of a copper recovery plant by the rayon factory. In the same way, TIN loading was tremendously lowered in the eighties.

<table>
<thead>
<tr>
<th>Period</th>
<th>Loading (t · a⁻¹)</th>
<th>Cu</th>
<th>TIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1926–1947</td>
<td>ca. 30</td>
<td></td>
<td>ca. 1000</td>
</tr>
<tr>
<td>1958–1974</td>
<td>3.7 – 9.5</td>
<td>1950 – 3350</td>
<td></td>
</tr>
<tr>
<td>1975–1979</td>
<td>2.8 – 3.1</td>
<td>2000 – 2400</td>
<td></td>
</tr>
<tr>
<td>1980–1981</td>
<td>0.8</td>
<td>1400 – 900</td>
<td></td>
</tr>
<tr>
<td>from 1982 on</td>
<td>0.3</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

At the end of 1981 a huge treatment plant, required by the Italian law on water pollution control and constructed by the rayon factory, drastically reduced the ammonium loading to a value of 30 t N – NH₄ · a⁻¹, which, together with the other N loads, means a total of 100 t N · a⁻¹. As a consequence, the ammonium in-lake concentration was halved in three years; the lowering of nitrate concentrations is much slower, as the in-lake production of this ion remains high (Fig. 1).

The biological situation

Zooplankton

The zooplankton population of Lake Orta was a very normal one (Pavesi 1879 a and 1879 b, Monti 1930): seven species of cladocerans (four of them being Daphnia spp.) and five species of copepods were enumerated (Table 2) and they were very abundant, if Pavesi could write about them: “...extraordinarily abundant, so that the bottom of the net was filled with the usual gelatinous matter formed by the entomostracans” (Pavesi 1879 a). We know that rotifers were also abundant (Monti 1930) and that the lake was rich in algae, especially desmids and diatoms (Pabona 1880, Giaj-Levra 1925).

In 1929, three years after the rayon factory started working, no plankton at all was still living (Monti 1930), killed by the copper loading which was entering the lake. In the following years, a very unbalanced zooplankton community reappeared, composed of a scarce population of Cyclops abyssorum and of a few species of rotifers which occasionally bloomed (Baldi 1949, Vollenweider 1963, Bonacina 1970). Diaptomids and cladocerans were never detected from 1925 to 1984 (Bonacina unpublished) when Bosmina coregoni and Chydrorus sphaericus began to occur very sporadically. The analysis of cores taken in various parts of the lake (Bonacina, Bonomi & Monti 1986) gave a clear confirmation of the total absence of cladoceran remains from the late twenties on, a period easily recognizable from the increase in copper concentration, so demonstrating that cladocerans were in fact missing, at least in the open lake, and not merely too rare to be caught.

From April 1986, we began to sample plankton fortnightly instead of monthly. On September 23rd a small population of Daphnia obtusa was found (Fig. 2) which very rapidly increased in number up to a maximum of 2,655 ind · m⁻³ and is still (January 1987) present with lower densities (331 ind · m⁻³) including females, ovigerous females and males.

That in an acidified lake the zooplankton species diversity should become lower and lower is a commonplace fact (Dillon et al. 1984, Sprules 1975) and Lake Orta is not an exception in this regard. However, according to Haines (1981) “the acidic lakes in both
Fig. 1. Mean values, measured at the overturn, of pH, ammonium and nitrate concentrations in Lake Orta. The arrow indicates the starting up of the ammonium treatment plant.
Table 2. Lake Orta zooplankton composition before 1930.

<table>
<thead>
<tr>
<th>Cladocera</th>
<th>Copepoda</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Sida crystallina</em> (O. F. Müller)</td>
<td><em>Acanthocyclops viridis viridis</em> (Jurine)</td>
</tr>
<tr>
<td><em>Diaphanosoma brachyurum</em> Liév.</td>
<td><em>Cyclopidae</em></td>
</tr>
<tr>
<td>Daphniidae</td>
<td><em>Cyclops prealpinus</em> (Kiefer)</td>
</tr>
<tr>
<td><em>Daphnia pulex</em> (De Geer)</td>
<td><em>Macrocylops fuscus</em> (Jurine)</td>
</tr>
<tr>
<td><em>Daphnia hyalina</em> Leydig</td>
<td><em>Metacyclops minutus</em> (Clas)</td>
</tr>
<tr>
<td><em>Daphnia longispina</em> O. F. Müller</td>
<td><em>Diaptomidae</em></td>
</tr>
<tr>
<td>Bosminidae</td>
<td><em>Acanthodiaptomus denticornis</em> (Wierzejski)</td>
</tr>
<tr>
<td><em>Bosmina longirostris</em> (O. F. Müller)</td>
<td></td>
</tr>
<tr>
<td><em>Bosmina coregoni</em> var. <em>longicornis</em> (Schödler)</td>
<td></td>
</tr>
<tr>
<td>Leptodoridae</td>
<td></td>
</tr>
<tr>
<td><em>Leptodora kindti</em> (Focke)</td>
<td></td>
</tr>
</tbody>
</table>

Scandinavia and Canada are characterized by a dominance of bosminids and a scarcity of daphnids and rotifers”. In Lake Orta, on the contrary, the true dominant zooplankter, at least in the last two years, is the rotifer *Brachionus urceolaris*. Stenson & Oscarson (1985) make the assumptions that in acidified lakes the zooplankton community should be dominated by 1. large-bodied species, 2. copepods, 3. grasping species. These statements are partially contradicted in Lake Orta, in that *C. abyssorum* is represented by very few individuals. According to Hörnström et al. (1984), daphnids are found at pH values below 6 only in humic lakes, where food supply is large; on this subject, but remembering that pH in Lake Orta is about 4 throughout the year, it would appear that indeed the food supply (phytoplankton) is abundant.

Finally, the sudden appearance of *D. obtusa* is in agreement with the findings of Stenson (1985) in Lake Gårdsjön system, where the plankton is mainly composed of small bog species that can tolerate acid conditions. We must remember that the *D. obtusa* of Lake Orta is unusually large, which is in agreement with the statement of Stenson & Oscarson (1985) that acidic lakes should be dominated by large-bodied species. In fact,
the lack of predators (fish or insect larvae, namely Chaoborus) is known to favour larger species.

**Phytoplankton**

The fate of phytoplankton of Lake Orta closely paralleled that of zooplankton in that, for some decades following the initial collapse, numerous occasional observations by various authors reported ephemeral appearance and bursts of different species in very poor communities. A first systematic study by Vollenweider (1963) in 1959—1961 revealed that some peculiar colonization was beginning to occur, and showed a succession with Oocystis in spring, Lyngbya in summer and the ultraplankton in autumn. Substantial changes were shown by Bonacina (1970) in the years 1968—1969, when out of the 43 species described, only 18 corresponded to those reported by Vollenweider. Lyngbya limnetica (later recognized as Oscillatoria limnetica) was still very abundant and together with the green Coccomyxa minor composed in fact the bulk of the community. In 1981 monthly samples were taken; the most prominent species was again C. minor, and co-dominants were the blue-green Microcystis aeruginosa and O. limnetica, and the green alga Scenedesmus armatus. The investigations were intensified in 1985 and 1986. The details cannot be reported here, but the main trends emerging after the pollution abatement in 1981 can be summarized as follows: (1) the number of species is increasing, as well as the total numbers; hundreds of millions of cells l$^{-1}$ are by now a common occurrence; (2) most of the cells are small-sized, usually below 40—50 μm$^3$; (3) a number of very small, often flagellated and still not identifiable green species is appearing; for this reason the importance of ultraplankton, even as biomass, is increasing very much; (4) C. minor is by far the dominant identified species, with maximum development in late spring and at depth below 10 m; (5) the blue-greens seem to be declining in this stage: they almost vanished in 1985 and 1986, except a small growth of O. limnetica in the late summer of 1986; (6) although diatom species are recorded, their share in the total numbers or biomass is negligible in any time of the year; (7) on the whole, the present state of the phytoplankton in Lake Orta can be defined as a “chlorophycean plankton”, possibly of a type not yet described in the literature.

**Zoobenthos**

Many benthos samples were taken at times in different parts of the lake: Corbella et al. (1958), in the course of their paleolimnological work on the lake, took many dredge hauls in order to ascertain a possible bioturbation in their core stratifications; they noticed a complete absence of micro- and macrozoobenthos in all their profundal samples. The littoral and sublittoral benthos was investigated by Moretti (1954 a and 1954 b) with special emphasis on Trichoptera; the biocenosis was recognized as being very poor and monotonous, with no mollusks; however, he was able to identify some 10 trichopteran species, among which Mystacides azurea was dominant. In 1968—1969, Oioli (1969) took eulittoral (0—0.5 m depth) samples at 5 stations and gave quantitative figures for this community, in which the mollusks were still completely missing; he believed that the overall abundance was in accordance with that given by other authors for the littoral of oligotrophic lakes. He also pointed out the presence in all stations of the
naidid *Pristina idrensis* and of the chironomid *Endochironomus* sp. but the complete absence of Hemiptera, Megaloptera and Lepidoptera.

Profundal macrobenthos was still completely missing in 1969 (Bonomi unpublished); on the other hand, the settling of microbenthos was described for the first time by Ruggiu (1969), who estimated this community as abundant and dominated by ciliate Protozoa and Rotifera. However, some macroinvertebrates were found in the areas corresponding to the submerged deltas of some inflowing streams (Bonacina & Bonomi unpublished). For instance, in January—February 1971 chironomids, oligochaetes and amphipods were sampled in such areas at 3–17 m depth interval; during July of the same year the same areas were sampled at greater depths, revealing that a similar community was present in the depth interval 18–62 m. Other areas, however, which were far from the main inflows, supplied dredge hauls completely devoid of macrobenthos. Recently we have been able to give paleolimnological evidence, for periods prior to the beginning of the industrial pollution, of the presence of a tubificid (probably *Spiroperma ferox*) in the profundal of Lake Orta (Bonacina, Bonomi & Monti 1986). We were indeed able to identify the cocoons of this species, which preserve very well in the sediments over a fairly long period of time, and document their disappearance at sediment layers corresponding to the increase of sedimentary copper and to the sharp decline of cladoceran remains (Bonacina, Bonomi & Monti 1986). This may be considered a further demonstration of the past oligotrophic situation of the lake.

During the autumn of 1983 we obtained the first qualitative profundal benthos samples (central basin) containing *Tubifex tubifex*: after further checks we observed its presence in all the basins of the lake. Then we selected a fixed (buoy) sampling station in the south basin, at which we took twelve replicate samples at monthly intervals during 1984. *T. tubifex* abundance in 1984 (Fig. 3) underwent very wide numerical changes, mainly in the compartment of immature individuals: a population increase from January to June, a catastrophic decline in July, a subsequent increase in late summer and a final decline in September—November. The numerical fluctuations exceeded those displayed by this species in reservoirs. In these water bodies the biological community is of recent

![Graph showing abundance of *T. tubifex* and its eggs + embryos (inside the cocoons) in 1984.](image-url)
settlement and, at least in our regions, *T. tubifex* is very frequently the only component of profundal macrobenthos; therefore a comparison is reasonable.

The clutch size (eggs or embryos/cocoon) is larger than in previously studied *T. tubifex* populations. The numerical balance of the population supplies the following figures: of the 140,000 eggs m$^{-2}$ $\cdot$ a$^{-1}$, assuming a 63% (laboratory estimation) egg mortality, 51,000 m$^{-2}$ $\cdot$ a$^{-1}$ hatch out of the cocoons and undergo a subsequent 36.7% mortality in the young stage; therefore the mortality of mature and ovigerous individuals appears to be extremely low. However this is to be considered only indicative, as the error associated with population abundance estimate, due to a very clumped distribution, is high. The type of distribution and the wide numerical fluctuations seem to be appropriate to a population colonizing an adverse environment.

**Present chemical situation**

In February 1986, at the overturn (Table 3), the whole water column had a pH of 4.06, an ammonium concentration of 0.16 meq $\cdot$ l$^{-1}$, a nitrate concentration of 0.20 meq $\cdot$ l$^{-1}$. These values make it possible to calculate an actual acidity (derived from the hydrogen ions) of about $100 \cdot 10^6$ eq for the lake as a whole.

Even if the oxidation of 1 mole of ammonium stoichiometrically produces 2 moles of hydrogen ion, we calculated that in Lake Orta the ratio: oxidized NH$_2$ $/$ produced H$^+$, is 1/1.5; this ratio results from the in-lake oxido-reduction reactions, as discussed by Mosello et al. (in press). Applying this transformation factor to the ammonium mass present in the lake at the 1986 overturn, we may estimate a potential acidity of about $300 \cdot 10^6$ eq H$^+$ that may be produced by ammonium oxidation; potential plus actual acidity accounts to a total of $400 \cdot 10^6$ eq H$^+$ for the whole lake.

We calculated the chemical budget of the lake for 1984 (Mosello et al. in press) and 1985 (unpublished) taking into consideration the main inflowing streams (75% of the drainage basin), the precipitations, the rayon factory effluent and the lake outflow. We estimated bicarbonate loadings of 42 to $25 \cdot 10^6$ eq $\cdot$ a$^{-1}$ for 1984 and 1985 respectively, while the corresponding ammonium values were 4 and $5 \cdot 10^6$ eq $\cdot$ a$^{-1}$; the rain-conveyed H$^+$ load was 1.2 and 0.8 $\cdot 10^6$ eq $\cdot$ a$^{-1}$.

### Table 3. Mean chemical concentrations at winter overturn (February 1986).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Dissolved O$_2$</th>
<th>pH</th>
<th>NH$_4$</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>SO$_4$</th>
<th>NO$_3$</th>
<th>Cl</th>
<th>Σions*</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>mg $\cdot$ l$^{-1}$</td>
<td>5.15</td>
<td>7.7</td>
<td>4.06</td>
<td>158</td>
<td>369</td>
<td>123</td>
<td>226</td>
<td>26</td>
<td>645</td>
<td>294</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>μeq $\cdot$ l$^{-1}$</td>
<td>5.15</td>
<td>7.7</td>
<td>4.06</td>
<td>158</td>
<td>369</td>
<td>123</td>
<td>226</td>
<td>26</td>
<td>645</td>
<td>294</td>
<td>66</td>
</tr>
<tr>
<td>RP</td>
<td>μg P $\cdot$ l$^{-1}$</td>
<td>6</td>
<td>1</td>
<td>37</td>
<td>53</td>
<td>5</td>
<td>104</td>
<td>180</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>μg P $\cdot$ l$^{-1}$</td>
<td>6</td>
<td>1</td>
<td>37</td>
<td>53</td>
<td>5</td>
<td>104</td>
<td>180</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>mg Si $\cdot$ l$^{-1}$</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>

* H$^+$ calculated from pH, included
Taking into account an average outflow water discharge of 4.93 m$^3$ sec$^{-1}$ (MINISTERO LL.PP. 1980, LIBERA et al. in press), and assuming: (1) an absence of chemical stratification; (2) concentrations in outflowing waters equal to average lake concentrations; (3) bicarbonate loading completely neutralized by lake acidity, we may set up a simple numerical model that allows a prediction of lake water acidity (actual + potential).

The estimated net bicarbonate loading ($27.5 \cdot 10^6$ eq $\cdot$ a$^{-1}$) should bring the lake waters to neutrality in 8–10 years, but twice this time would be required to attain an alkalinity of 0.15 meq $\cdot$ l$^{-1}$, and an additional 8–10 year period would be necessary for a situation in which lake water alkalinity equals the bicarbonate mean concentration in the inflowing waters (0.29 meq $\cdot$ l$^{-1}$).

**Water movements**

A study of water movements is now under way in the southern basin of Lake Orta to verify the most favourable hydrological situation for liming, in order to speed up the recovery rate of the lake. It should be noted that the area of the first approach of the liming plan is envisaged at the end opposite to the outlet.

The measurement of water movements was carried out using current crosses released at different depths along some transects and topographically positioned.

It was recognized that wind is the most important acting force, especially for the water in the upper levels; the role of thermal stratification, as well as lacustrine valley morphology, in determining the energetic and directional components of water currents was also pointed out. The maximum current velocity was recorded during late spring when, at the beginning of stratification, the superficial strata alone are involved in the lake circulation. In winter the currents showed very low velocities on the whole water column.

Because of the lack of vertical gradients and considering the presence of only weak horizontal currents, winter and/or early spring can be considered the right time to carry out the Lake Orta liming.

**Liming**

Given the present chemical situation, we have seriously considered the expediency of liming the lake waters. This direct measure was also taken into consideration in the past, but the heavy and continuous ammonium loadings and the consequent, proton producing, in-lake nitrification, made the project hardly feasible. The situation is very different to-day and the calculated amount of CaCO$_3$ needed (25,000 metric tons) seems within the bounds of possibility. At the same time, as liming technology has progressed, we realize that transportation and spreading of this suitably powdered mineral material gives no problem to-day, even in the case of large and deep lakes. Last year we visited some Swedish colleagues at the Department of Zoology, University of Gothenburg, at the Swedish Environmental Research Institute, Gothenburg, at the Institute for Freshwater Research, Drottningholm and at the Swedish Environmental Protection Board, Solna. The contacts were very fruitful and confirmed the feasibility of a liming project.

In the meanwhile, investigations are being carried out on water currents, chemistry of lake and inflowing and outflowing waters, phyto- and zooplankton, primary production and macrobenthos, in order to obtain a picture of the pre-treatment situation. A plan for a partial liming has been prepared, considering a direct intervention on the southern part
of the lake (ca. 3/4 of lake volume); we are aware that partial liming is not a solution, especially because in our case there exists no real hydrographic segregation from the rest of the lake. Economic and not ecological considerations have dictated the limitation of the area to be limed. We are now pushing toward the definition of a plan for liming the rest of the lake, which hopefully will be performed during the winter of 1987—1988.

So far our Ministry for the Environment has funded the partial liming plan; the Regione Piemonte and the Provincia di Novara are the local administrations that will perform the liming operations. Our Institute in Pallanza will have to task monitoring the effects of this direct intervention.

The construction of two treatment plants (and connected pipeline networks), that convey and treat most of the remaining industrial wastes and urban sewage, complement the proposed liming within the framework of a general plan for the recovery of Lake Orta. On the basis of careful analyses of all relevant factors, we are confident that the lake should be transformed into a “quasi-normal”, P limited, moderately productive water body.

References


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