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Hydraulic paths and estimation of the real residence time of the water in Lago Maggiore (N. Italy): application of massless markers transported in 3D motion fields

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ABSTRACT

This study, conducted using the TRIM_LM model, is a continuation of work on the movement of the water mass at different depths in Lago Maggiore, and thus on the estimation of the real residence time of the water in the lake. Three-dimensional CFD numerical simulations were extended to a 4-year period, focusing on the movements of 202 (two hundred and two) massless markers inserted at different points in Lago Maggiore and at the mouths of 11 of its tributaries, enabling us to establish more realistic water renewal times for Lago Maggiore. By crossing the data of the horizontal trajectories of the environmental markers with those of their vertical variations, we reconstructed their movements over the four years of the simulation programme. An analysis of the results shows that the water mass in the layers of the upper 100 m has residence times between a minimum of 1 y and a maximum of 4-5 y. The water from the tributaries has residence times between 250 and 1000 days, depending on the distance of the tributaries from the closing section of the lake. The water in the layers below 100 m has residence times that still cannot be quantified with precision, but that can certainly be estimated at a number of years in two figures. These times are strongly conditioned by the depth of the late winter mixing, which in the last 40 y has not exceeded 200 m.

Key words: hydraulic course, residence time, massless markers, lacustrine hydrodynamic.

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INTRODUCTION

This paper further develops the study of the transit of the water mass at different depths in Lago Maggiore, and consequently of the estimate of the real residence time of its water. The study was conducted by applying the TRIM_LM model, the formulation and general calculation conditions of which are described in detail in Castellano et al. (2008), Castellano et al. (2010), Ambrosetti et al. (2009) and Ambrosetti et al. (2010). Continuing with simulations through a further series of elaborations has enabled us to refine the response of the model and verify its usefulness through an increasingly accurate adherence to the laws and concepts of modern physical limnology. We have thus made considerable advances in our knowledge, thanks especially to the increased resolutive power of the integration grid and finer tuning in the calibration of the turbulence model.

Simulations focused on the movement of 202 massless markers (against the 72 of the previous study) inserted at different points in Lago Maggiore. Their paths were calculated every 120 seconds, in the framework of a CFD three-dimensional numerical simulation extending over a 4-year period, *i.e.* twice as long as the 2-year simulation whose results are described in Castellano et al. (2010). This enabled us to establish more realistic renewal times for the water of Lago Maggiore.

The application of the method of massless (*i.e.*, non-reactive) markers transported by 3D motion fields and calculated with CFD systems may be regarded as a "recent approach" to the topic of lake water residence time. In fact, documentary evidence in the current technical literature is not very abundant but without exception of significant interest (Duwe et al. 2003; Doos, and Engqvist 2007).

In this paper we will not comment on the results relating to the 3D distributions of parameters such as velocity and water temperature, as they are essentially the same as those already described in detail in Castellano et al. (2009). Our results confirm the substantial correctness of the calibration performed *in situ* on the measurements of water temperature and current velocity, documented in the bibliography (Barbanti, and Carollo 1965; Castellano et al. 2008). Our focus here is on the fate of the massless markers inserted into the lake at the t=0.0 instant of the whole cycle of simulations, for a 4-year cycle starting on 1 January 2000.

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MATERIALS AND METHODS

The daily meteorological and hydrological data measured at the Observatory of the I.S.E. in Pallanza and at the stations at the inflows and the outflow of the lake were inserted into the model. The discrete lake model was subdivided into computational cells with a horizontal size of 250×250 m, while depth-wise it was divided into 50 layers, closer together in the upper levels, to a total number of 877,500 cells. In Fig. 1 the "longitudinal direction" is indicated with Y, with its positive direction from S to N and its zero point at the lake's incile, the "transverse direction" with X, with its positive direction from W to E and its zero point at the mouth of the River Toce. The "vertical direction" has its altitude "0" at the deepest point of the lake (370 m) and increases from the bottom to the top (Castellano et al. 2010).

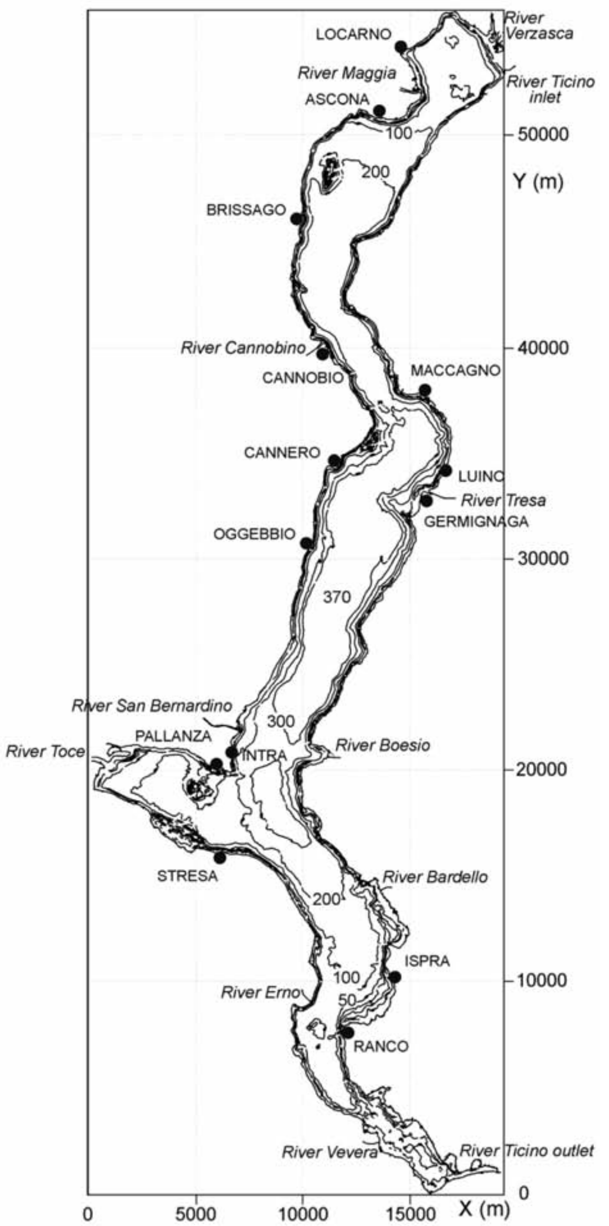

Fig. 1. Bathymetric map and integration grid of Lago Maggiore showing the inflows and the outflow (in italics).

As stated above, 202 markers were used in the study, subdivided into two groups. The first comprises the markers with a starting position inside the lake, subject to the lake's hydrodynamic conditions and referred to as "environmental markers". The second group comprises markers which at the t=0.0 instant were placed at the mouth of the main tributaries, and thus exposed to their current velocities; these are referred to as "tributary markers". Most of the environmental markers (about 90) were placed at different depths in the northernmost part of the lake, in the area in front of the mouth of the River Ticino, the main tributary. Their coordinates are therefore all close to X values=16,800 and Y values=55,000. Others were placed in the area between the River Maggia and Luino.

The rest of the environmental markers were placed in the lake at increasing depths more towards the south, but as far as possible towards the western shore. For each of the major tributaries, five markers were placed near each mouth, at depths between 0.5 and 9.0 m.

RESULTS

Summary of the routes of the environmental markers

By crossing the data of the horizontal and vertical trajectories of each environmental marker we reconstructed their movements over the four years of the simulation programme. The Figs from 2 to 11 shown below provide an example of some of their movements; Tabs 1 to 8 give their starting coordinates.

An analysis of the movements of the first 90 markers with a starting position in the northernmost area of the lake, in front of the mouth of the tributary River Ticino, shows that, in the 4 years of the simulation, 11 of them (Tab. 1) reached the lowest part of the lake or an area very close to the outflowing Ticino. These markers can therefore be considered as having definitively exited the lake.

As an example, Fig. 2 shows the horizontal and vertical trends of marker M30, with a starting position east of Locarno at a depth of 23 m. After initially moving towards the eastern shore of the lake, it gradually moved towards the western shore, continuing southwards until it reached the closing section after around 1000 days. As regards depth, it always stayed in the upper layers.

An examination of the fate of the remaining 79 markers, which were placed like the others in the most north-easterly part of the lake, reveals much more varied situations which may be summarized as follows:

a) Eleven markers (Tab. 2) – albeit with total routes of different length and direction – moved distances of between 40 and 50 km from their insertion point along the

Tab. 1. Starting coordinates and depths of the markers introduced in Locarno Basin: group of markers exiting the lake.

Marker	X (m)	Y (m)	Z (m)	Marker	X (m)	Y (m)	Z (m)
M_2	16625	55375	-0.5	M_32	16375	55375	-25.5
M_15	16875	55125	-9.0	M_33	16625	55125	-25.5
M_17	16625	55375	-11.0	M_49	16875	55375	-48.0
M_23	16625	55375	-16.5	M_55	16875	55125	-56.0
M_25	16625	55375	-20.5	M_58	16875	55125	-60.0
M_30	16875	55125	-23.0				

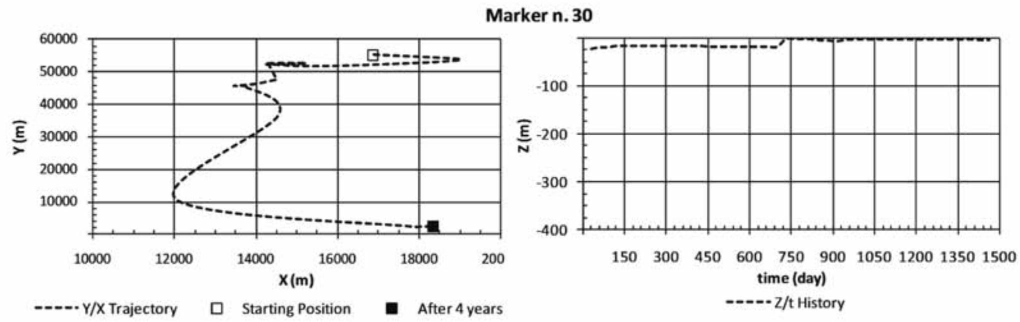

Fig. 2. Example of horizontal and vertical movements of marker M30.

Tab. 2. Starting coordinates and depths of the markers introduced in Locarno Basin: group of markers that moved between 40 and 50 km from the point of their insertion.

Marker	X (m)	Y (m)	Z (m)	Marker	X (m)	Y (m)	Z (m)
M_10	16875	55375	-7.0	M_28	16375	55375	-23.0
M_12	16875	55125	-7.0	M_53	16625	55125	-52.0
M_16	16875	55375	-11.0	M_60	16875	54875	-60.0
M_19	16875	55375	-13.5	M_65	16625	54875	-68.0
M_20	16625	55375	-13.5	M_72	16875	56425	-76.0
M_21	16875	55125	-13.5				

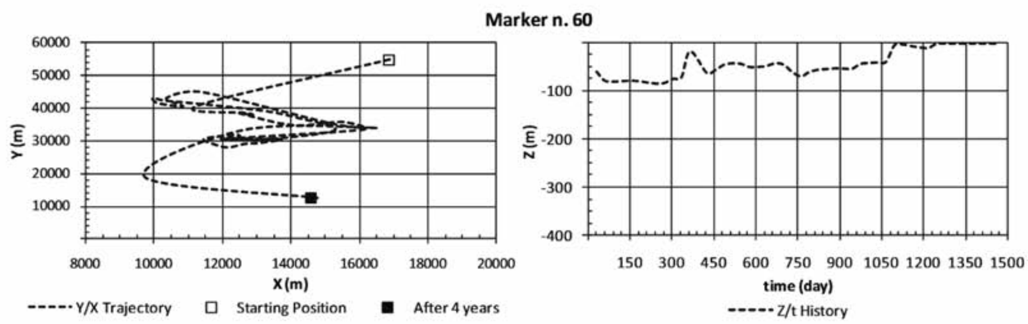

Fig. 3. Example of horizontal and vertical movements of marker M60.

ideal direction towards the outflow of the lake, while staying always within a maximum depth of 100 m.

The example given in Fig. 3 illustrates the route of marker M60, initially positioned to the east of Locarno at a depth of 60 m. After sinking at first to around 90 m, it returned to shallower depths and, following a tortuous route with frequent shifts from one shore to the other, at the end of the third year of simulation reached the Intra cross section. Returning to the surface, it continued its progress in a southerly direction, always following the western shore of the lake, until after approximately another 300 days it ended up in the Bay of Ispra.

b) Another 11 markers (Tab. 3) – albeit with total routes of different length and direction – moved between 30 and 40 km from the point of their insertion along the ideal direction towards the incile of the lake: their maximum depth never exceeded 100 m.

For this group the example given in Fig. 4 refers to the route of marker M86, which started from the area to the east of Locarno at a depth of 96 m. Initially it moved back and forwards between the two shores, more or less at the same depth, to rise after around 400 days to 30 m, when

Tab. 3. Starting coordinates and depths of the markers introduced in Locarno Basin: group of markers that moved between 30 and 40 km from the point of their insertion.

Marker	X (m)	Y (m)	Z (m)	Marker	X (m)	Y (m)	Z (m)
M_8	16625	55375	-5.0	M_64	16875	54875	-68
M_9	16875	55125	-5.0	M_66	16875	54625	-68
M_24	16875	55125	-16.5	M_70	16875	54875	-76
M_40	16875	55375	-37.5	M_86	16625	54625	-96
M_44	16625	55375	-40.5	M_88	16875	54625	-100.5
M_47	16625	55375	-44.0				

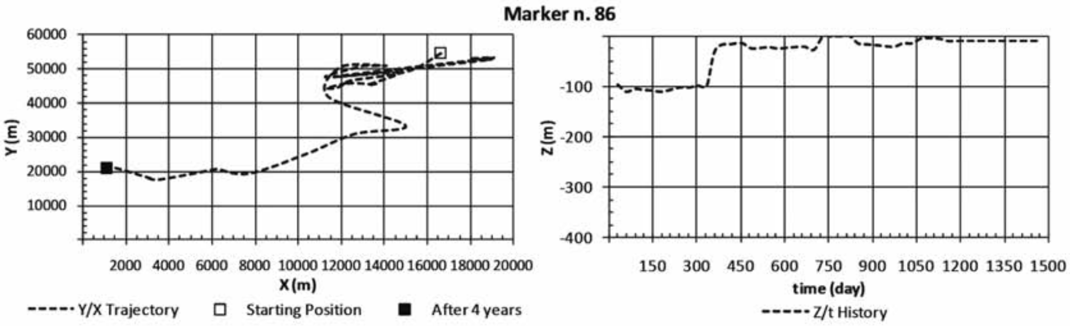

Fig. 4. Example of horizontal and vertical movements of marker M86.

Tab. 4. Starting coordinates and depths of the markers introduced in Locarno Basin: group of markers that moved between 25 and 30 km from the point of their insertion.

Marker	X (m)	Y (m)	Z (m)	Marker	X (m)	Y (m)	Z (m)
M_6	16875	55125	-1.5	M_31	16625	55375	-22.5
M_7	16875	55375	-5.0	M_38	16625	55375	-34.5
M_22	16875	55375	-16.5	M_59	16625	55125	-60.0
M_29	16625	55375	-23.0	M_78	16875	54625	-84.0

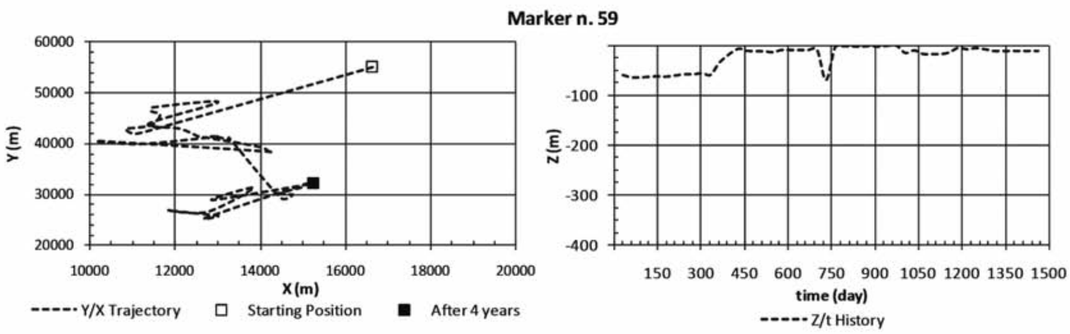

Fig. 5. Example of horizontal and vertical movements of marker M59.

still at the level of Brissago. Subsequently, staying at the surface and following the western shore of the lake, it reached the area of the Gulf of Pallanza after 1500 days and covering a distance of 40 km.

c) Eight other markers (Tab. 4) positioned in the area to the east of Locarno in front of the mouth of the River Ticino – albeit following total routes of different length and direction – reached distances of between 25 and 30 km from the starting point along the ideal line towards the outlet of the lake, remaining always at a depth of not more than 100.

d) In this case the example given in Fig. 5 refers to the route of marker M59, which was inserted into the lake at 60 m at a point to the east of Locarno. In the first year of the simulation it remained at a depth slightly greater than its initial depth, moving towards the western shore, and at the level of Cannobio it rose to the layers nearest the surface. Its route southwards then continued, with more than one side migration in the narrows between Cannobio and Maccagno, until at the level of Luino its progress ceased, after once again floating across the lake in the direction of Cannero. In 1500 days it moved little more than 25 km along the ideal line towards the outlet of the lake.

e) Five markers (Tab. 5) belonging to the group in-

Tab. 5. Starting coordinates and depths of the markers introduced in Locarno Basin: group of markers that moved very close to the incile of the lake but returned northwards.

Marker	X (m)	Y (m)	Z (m)	Marker	X (m)	Y (m)	Z (m)
M_42	16875	55125	-37.5	M_65	16625	54875	-68.0
M_48	16875	55125	-44.0	M_73	16875	54875	-80.0
M_63	16875	54625	-64.0				

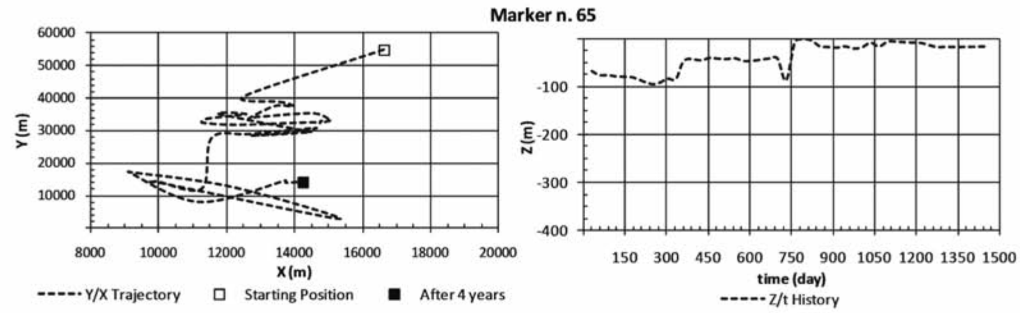

Fig. 6. Example of horizontal and vertical movements of marker M65.

Tab. 6. Starting coordinates of the markers introduced near Ascona.

Marker	X (m)	Y (m)	Z (m)
M_95	12125	50375	-112.0
M_106	12375	49875	-150.0
M_107	12125	49875	-150.0

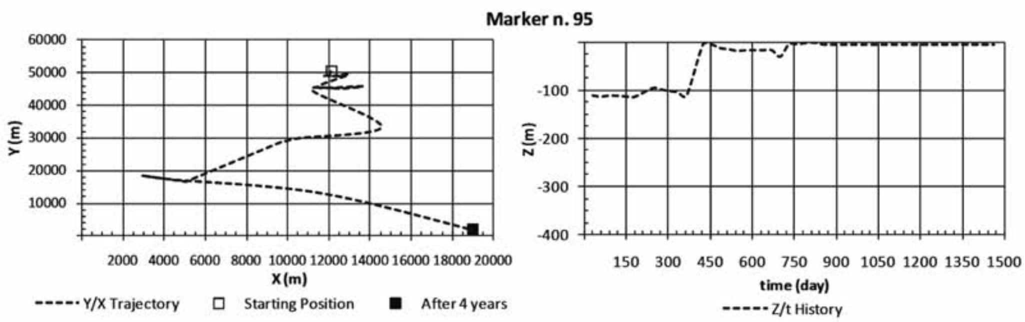

Fig. 7. Example of horizontal and vertical movements of marker M95.

serted at the point where the River Ticino enters the lake went very close to the area of the incile of the lake, covering this distance in between 900 and 1200 days, but then moved in the opposite direction to return northwards.

The example given in Fig. 6 refers to marker M65, which was positioned at 68 metres at a point to the east of Locarno. Its vertical migrations can be summarised as follows: after the first year of simulation it rose towards a depth of 40 m, and at the end of the second year rose to the surface. In its horizontal route the marker mainly followed southerly trajectories along the western part of the lake (though with some transversal oscillations) between Cannero and Luino and in the Gulf of Pallanza, covering a distance of around 50 km almost as far as the incile of the lake. Here it changed direction to return northwards, again with lateral shifts which were also dictated by the lake morphology, ending up at the level of Ispra after 4 years.

All the remaining 47 markers in the group of 90 placed at the northernmost end of the lake covered less than 20 km (always understood as being in the ideal direction towards the outlet, *i.e.* southwards).

The other 57 environmental markers had starting positions farther south than those referred to above, and starting depths greater than 100 metres. The results of the simulations for these markers can be summarized as follows.

f) Only 3 markers (Tab. 6) reached the zone of the incile, where the outflowing Ticino originates, within the 4 years. We can therefore say that they left the lake definitively.

The example given in Fig. 7 refers to marker M95. Inserted into the lake at a depth of 112 m, it remained static

Tab. 7. Starting coordinates and depths of the markers introduced between Ascona and Luino.

Marker	X (m)	Y (m)	Z (m)	Marker	X (m)	Y (m)	Z (m)
M_92	12125	50375	-106.0	M_111	12375	49625	-162.0
M_98	12125	50125	-120.0	M_112	12375	49875	-174.0
M_99	12375	50125	-120.0	M_113	12125	49875	-174.0
M_100	12375	50375	-128.0	M_133	10875	44125	-298.5
M_105	12375	50125	-138.0	M_144	14875	35375	-361.5
M_108	12375	49625	-150.0				

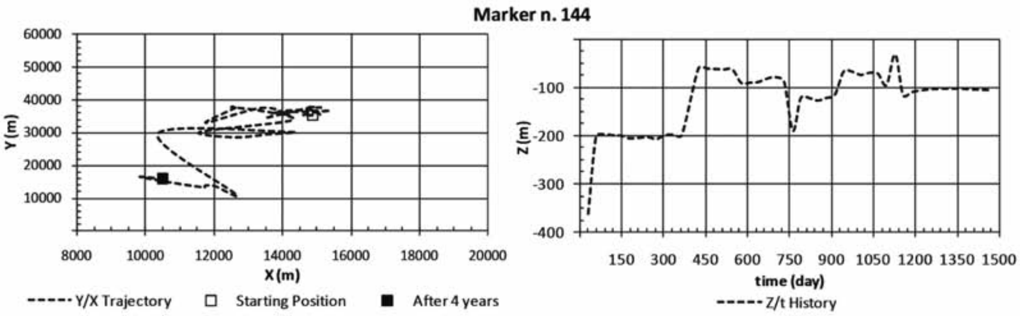

Fig. 8. Example of horizontal and vertical movements of marker M144.

Tab. 8. Starting coordinates of markers and depths introduced between Brissago and Ascona.

Marker	X (m)	Y (m)	Z (m)	Marker	X (m)	Y (m)	Z (m)
M_91	12375	50375	-106.0	M_117	12875	49375	-189.0
M 93	12375	50125	-106.0	M_119	12625	49125	-207.0
M_104	12125	50375	-138.0	M_121	12625	45375	-225.0
M_110	12125	49875	-162.0	M_122	12375	47375	-225.0
M_114	12375	49625	174.0	M_123	12625	47125	-225.0
M_116	16625	49125	-189.0				

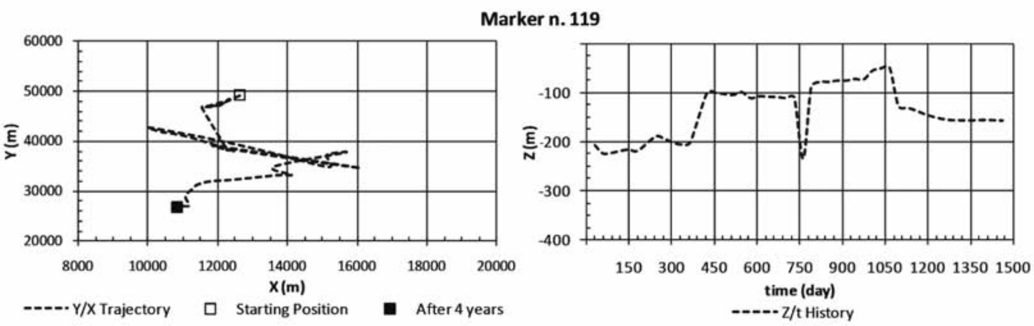

Fig. 9. Example of horizontal and vertical movements of marker M119.

for a year, and after rising to the surface began its southward progress along the eastern shore as far as the Cannero cross section, subsequently moving to the opposite shore, entering the Gulf of Pallanza and then moving towards the outflow, which was reached in around three years.

g) Eleven markers (Tab. 7) – albeit with total routes of different length and direction – moved as far as areas close (10-20 km) to the incile of the lake. Most of them rose to superficial depths except for M92, which sank to 220 m, M108, which rose to 70 m, and M144 (Fig. 8), which from 362 m was found at 105 m.

The example given in Fig. 8 describes the route of M144 which, from the Maccagno cross section where it had been placed at a depth of 352 m, rose in a few days to 200 m, and after about a year to 100 m. It then remained stationary in the area for a long period (two years), after which it sank briefly and began its progress southwards along the lake axis as far as the Bay of Ispra, then rose again and was found after 4 years in the area facing Stresa.

h) Another 11 markers (Tab. 8), though following different routes and directions, in their progress along

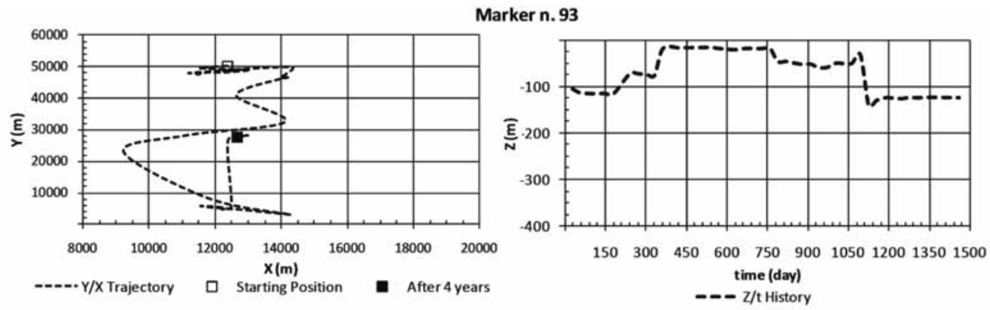

Fig. 10. Example of horizontal and vertical movements of marker M93.

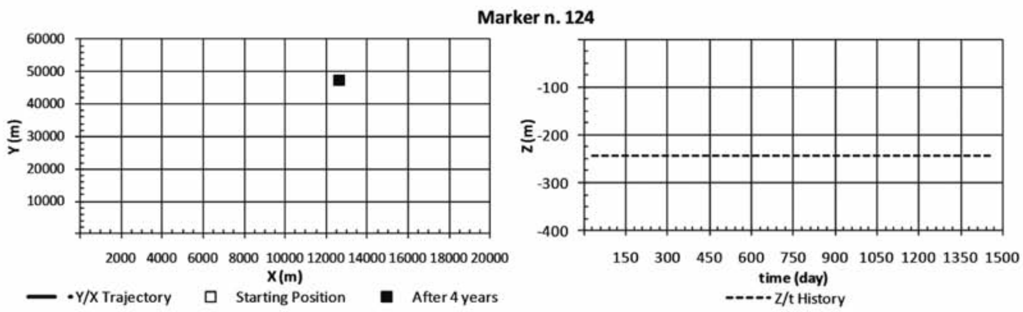

Fig. 11. Example of horizontal and vertical movements of marker M124.

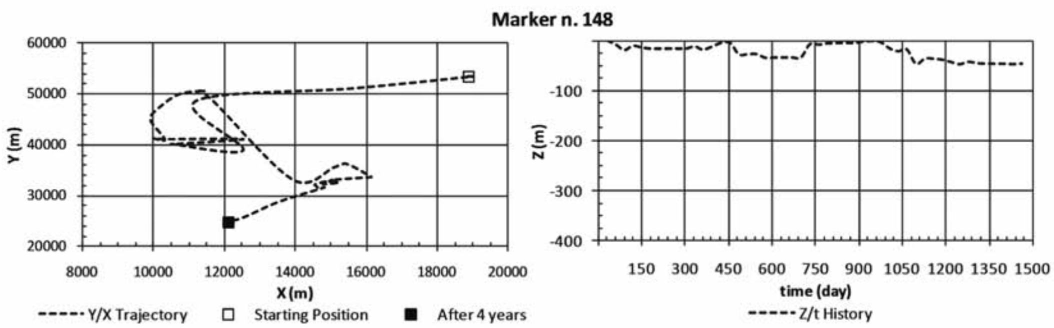

Fig. 12. Example of horizontal and vertical movements of marker M148.

the ideal line towards the outlet section of the lake, came close to this area, up to 20-30 km from the outlet. Some stayed below a depth of 100 m (M110, M119, M121 and M122), while others, despite having originally been placed in the deepest layers, rose to shallower levels.

The example illustrated in Fig. 9 refers to marker M119, initially placed south of Brissago at a depth of 207 m; it remained almost stationary for the first year, subsequently rising to 100 m and proceeding southwards with trajectories transversal to the lake axis in the Cannobio-Maccagno narrows, reaching a depth of 200 m. It rose to a depth of around 60 metres, and at the end of the fourth year moved to the area facing Ghiffa, after once again sinking, to a depth slightly greater than 150 m.

i) Fig. 10 shows the interesting route of marker M93; placed in the water south of Brissago at –106 m (x=12375, Y=50125), in the 4 years of the simulation it moved to 4 different depths. It went successively from a depth of –80-100 in the first year, to shallow levels (around 10 m) in the second, sinking to around 50 m in the third, and finally sinking to –120 m. Its southward progress was characterised by fluctuations transversal to the axis of the lake (it also entered the Gulf of Pallanza), and after around 900 days it arrived close to the outflow section of the lake, only to change its direction (and sink), returning northwards for over 20 km to the Oggebbio cross section.

j) The remaining 22 markers in this group, mostly placed in the water at depths of between 140 and 365 m in the area between the River Maggia delta and Luino, moved relatively short distances, never going farther than 30 km from the insertion point, or even staying almost stationary; see the example of marker M124 in Fig. 11.

SUMMARY OF THE ROUTES OF THE TRIBUTARY MARKERS

Tributary markers were placed at the incile of the inflowing Ticino, the rivers Verzasca, Maggia, Cannobino, S. Bernardino Toce, Erno, Vevera, Bardello, Boesio and Tresa; their courses are described below.

Inflowing River Ticino

- M148: positioned at a depth of 1.0 m, it gradually sank and moved towards the western shore. After a route moving transversally in the Cannobio-Maccagno narrows, it continued its progress to a point north of Ghiffa, at a distance of ca 25 km from its insertion point (Fig. 12).
- M149: from a starting point at 1.5 m, it proceeded initially on the western shore to the south of the River Maggia, where it remained for two years. It then sank to around 100 m, at the same time moving northwards, actually farther north than its starting point;
- M150: with a starting point of 2.5 m, in about 1000 days it proceeded down the western shore, covering the whole route almost to the outflow section of the lake, thereafter returning northwards as far as the level of the Gulf of Pallanza. It sank to a depth of 70 m during the first year, then returned to shallow depths:
- M151: starting point –5 m; its initial route was similar to that of M 150, with a long stay in the Gulf of Pallanza, after which it moved down to the bay of Ispra and again returned northwards towards Pallanza. Its depth was between 100 m and the surface;
- M152: starting point 9 m; its initial route was similar to the last two markers, with a temporary stay in the Maccagno narrows, then moving down to the bay of Ispra and finally back up to the Gulf of Pallanza. It moved at various depths within the top 100 m.

Inflowing River Maggia

- M178: starting point 0.5 m; its whole route was at the level of the river mouth, moving from the western to the eastern shore. For the first three years its depth varied from 70 to 100m, after which it returned to the surface.
- M179: starting point 1.5 m. It initially followed a route southwards as far as Maccagno, then returned northwards to the area south of the river delta. Depth: around 50 m the first year, 250-270 m the second, 30 m the third, and at the surface in the fourth year.
- M180: starting point 2.5 m. Its route was limited to movements transversal to the lake's axis in the area south of the delta. Depth: around 50 m the first year, about 10 m the second and third years, and 135 m in the fourth year.
- M181: starting point 5 m. It made a single transverse movement towards the eastern shore. Depth: from 25 m the first year to a few metres in the following years.
- M182: starting point 9 m. It initially moved in a southerly direction as far as Cannobio, then moved back northwards close to its insertion point. Its depth increased gradually to reach 86 m (Fig. 13).

Inflowing River Toce

- M163: reached the outflow section of the lake after a little less than 400 days;
- M164: starting point 0.5 m. It initially sank to 80 m, remaining in the Gulf of Pallanza; it later reached the outflow of the lake after a little less than 700 days at a depth of 25 m (Fig. 14);
- M165: starting point 2.5 m. Its route was similar to that of M163 but at variable depths above 100 m, reaching the lake outflow in around 1100 days;
- M166: starting point 5 m. It covered a similar route to M163 but at a depth restricted to 5-7 m, exiting the lake after about 750 days;
- M167: starting point 9 m. It went northwards initially, as far as Cannero, then sank to around 150 m, returning to the Gulf of Pallanza, and rose to 20 m, subsequently moving southwards at a depth of 100 m, as far as the Bay of Ispra.

CONCLUSIONS

Evaluation of residence times

The complexity of the results obtained from an analysis of the movements of the 202 markers used in the simulation model enables us to make some observations regarding the residence times of the water in Lago Maggiore.

1) Of the environmental markers placed in the northernmost area of the lake (Locarno Basin), around 12% exited the area in between 600 and 1100 days; the layers involved were mostly those in the top 100 m. A further 5% moved close to the incile of the lake in from 900 to 1100 days, but then moved away, returning in a northerly direction. Another 13% covered between 40 and 50 km towards the outflow of the lake, staying continuously within a depth of 100 m; 12% managed to cover between 30 and 40 km, and 9% covered only between 20 and 30 km. The remaining 49% covered less than 20 km (meaning always in the ideal direction of the outflow) or sank to deeper depths.

2) Of the 57 environmental markers whose starting point was the area south of the Locarno Basin at depths below 100 m, only 3 reached the outflow section of the lake in times between 900 and 1000 days. All the others got to 20-30 km of the incile, most of them having risen to depths of less than 100 m.

3) A good number of tributary markers leaving the

mouths of the major tributaries to the lake – apart from most of those placed farthest north (rivers Ticino, Verzasca and Maggia) – reached the outflow section of the lake, proceeding always at more superficial depths. The time taken for their progress ranged from 250 to 1100 days, depending especially on the distance between the insertion point and the lake's incile. The markers which sank to lower depths did not cover these trajectories.

The following initial conclusions can be drawn from an analysis of these results.

a) The water mass occupying the layers in the top 100 m has residence times between a minimum of 1 year and a maximum of 4-5 years.

b) The water from the tributaries has residence times between 250 and 1000 days, depending on their distance from the closing section of the lake. The waters of the Rivers Ticino (tributary), Verzasca and Maggia are excluded from this evaluation, as their residence times are in the order of 3-4 years, in common with the whole water mass of the Locarno Basin.

c) The lake waters occupying levels below 100 m have residence times which are still not quantifiable with any accuracy, but which can certainly be estimated at a number of years in double Fig.s, depending directly on the depth of the late winter mixing, which in the last 40 years has never exceeded 200 metres. If we think that the last full overturn of Lago Maggiore by convective mixing was as far back as 1970, we may presume that the exchange time by convective mixing of the deep waters goes back to that date. However, it is a fact that markers were often found to have risen towards the surface, a dynamic that seems to favour some specific areas, but also some particular moments in the annual cycle, and specifically the phase of late winter vertical mixing of the lake waters. All of these observations will be later integrated and analysed in detail through elaborations involving the use of hydrosoluble tracers to highlight species transport.

Observations on the hydrodynamics of the lake

The complex results of the movements of the markers according to the simulation model used in this study compel us to take account of, and apply to them, the current knowledge of limnological hydrodynamics, with particular reference to the situation of large, deep lakes like Lago Maggiore.

Water movement in lakes is well-known for its dependence primarily on the strength of the wind, the main driving force of currents, especially along the horizontal plane, but also as a determining factor of the lake winter vertical mixing. In the specific case of Lago Maggiore there are two main directions of origin in the wind field (from north and from south) along the main axis of the lake, which lies in a valley prevalently oriented to the south. The easterly wind also has a certain impact, especially in the Locarno Basin, as does the wind from the NW, primarily affecting the Gulf of Pallanza, and afterwards affecting the stretch as far as the Bay of Ispra as it turns towards the south-east, following the lake axis. Wind forcing on the lake surface has also been modelled by a wind field, highly variable in time, constructed on the basis of data recorded at the meteorological stations of Pallanza and Locarno Monti.

But the movements of the lake water mass responding to the triggering force of the wind are conditioned by other physical phenomena which in a limnological interpretation cannot be ignored.

Thermal structures arising within the water mass

The way in which thermal structures in the water mass can condition lake dynamics is well revealed by the vertical movements of the markers. The vast majority of these movements occurred in the late winter months, that is, in correspondence with the phases of maximum vertical mixing (and of the penetration of the deep layers by cold water) which in warm monomictic lakes occurs during and at the end of the limnological winter (Ambrosetti et al. 2010). These vertical upward or downward migrations were very frequent, and can also be seen in some of the Fig.s given here. A typical example of repeated variations of depth is shown in Fig. 8 with marker M144 which, around 40 days after the start of the simulation on 1st January 2000, rose for the first time from a depth of 362 m to 200 m, followed by a second rise which took it to 50 m after around 390 days (February of the following year). In the winter of the third year the marker sank again to 200 m, rising again to 100 m almost immediately; another double vertical migration (from 100 to 40 and *vice-versa*) occurred after around 1150 days, that is in the winter months of the fourth year of the simulation.

But the vertical position of the markers is also strongly conditioned by the summer thermal stratification, and the consequent deepening of the mixed layer in autumn. Clear proof of this is provided by the gradual sinking within the mixed layer of markers such as M148, shown in Fig. 12, and M182 (Fig. 13), following this thermal phenomenon.

Morphology and morphometry of the lake basin

The planimetric and bathymetric configuration of Lago Maggiore is obviously crucial for an understanding of its morphology-induced hydrodynamics. The uniform trend of the central part of the lake, with a flat bottom (over 360 m deep) and steep sides, is in contrast with the more complex morphology both of its northern and southern extremities and that resulting from the presence of a lateral arm (Gulf of Pallanza), which joins the main basin with a bathymetric step of around 150 m. Many markers, in their route towards the outflow section of the lake, entered the gulf, thus reducing their ideal time for covering the route; see, for example, marker M95 in Fig. 7, and also marker M164 (Fig. 14), which, placed at the mouth of the River Toce, made more than one circuit of the gulf before proceeding towards the outflow.

At the northern end of the lake, the large delta of the River Maggia contributes (also with its submerged part) to the almost complete isolation of the Locarno Basin, in which part of the water mass is confined and may stagnate for a long time. Marker M124 (Fig. 11) was one of a group of 22 which, initially placed at different depths in the Locarno Basin, remained practically immobile at the starting point or progressed only a very short distance. The area of the lake directly to the south of the Maggia delta also forms a wind shadow zone, sheltered from the northern winds, which also means the water can be stagnant for long periods (see M182, Fig. 13).

In contrast, the narrows between Cannobio and Maccagno farther south, confined between high, steep sides, reduces the width of the lake and is exposed to strong northerly winds that mean this stretch is affected by rapid, turbulent movement (M119 in Fig. 9 and M148 in Fig. 12). Like the Maggia delta, the less pronounced delta of the Rio Cannero, combined with the slight bend to the west of the lake at this point, determines an area of relative calm in the lake waters in front of its southern shores (M182, Fig. 13).

A morphological structure of importance for the hydrodynamics of the lake is the wide Bay of Ispra, which acts as an almost complete barrier to the lacustrine valley and is characterised in its submerged part by a gradual rise in the lake bottom. The water mass flowing into it from the north can therefore exit only *via* the lateral narrows of the western shore, which is further narrowed by the delta of the Erno Torrent. A fair number of markers did not succeed in overcoming this obstacle, and were trapped in the bay (M60, Fig. 3) or forced to return northwards (M93, Fig. 10).

South of this structure the lake basin becomes much narrower and shallower and proceeds towards the incile, gradually reducing its section and deviating eastwards in its final sector. The markers in this sector followed a regular, easier course, and were probably already affected by the drawing power of the outflowing Ticino.

Driving force of the tributaries flowing into the lake

We know that the lake's tributaries, especially those with the greatest volume of flow, can affect the circulation of water on a basin scale. This was confirmed in our study by the movements of the tributary markers placed close to the mouths of the tributaries.

As specified above, almost all the markers reached the outflow area, except for a good number of those inserted at the mouths of the three northernmost tributaries (rivers Ticino, Verzasca and Maggia); these were affected not only by the distance but also by the stability of the water in the Locarno Basin, where the tributaries have their confluence.

Also excluded from the possibility of exiting the lake were the tributary markers that sank straight away to depths below their insertion depth, which, as stated above, was limited to a maximum of 9 m. This vertical migration was probably due to the density ratios between the inflowing water and the water in the lake. According to a schema, highly simplified given the complexity of the phenomenon, the determining factor might be buoyancy forces, causing surface currents, or the presence of downward thrust, or again, the occurrence of neutral buoyancy flows at intermediate depths. The markers affected by the last two phenomena were not able to exit the lake.

The Coriolis force, due to the Earth's rotation

By the effect of the Earth's rotation, it is to be expected that in Lago Maggiore the Coriolis force will contribute to the tributary waters flowing towards the western shore, starting with the River Ticino and the River Maggia, and gradually involving the tributaries entering the lake farther south. While the relative narrowness of Lago Maggiore might make it difficult to identify the phenomenon, the routes followed by more than one marker on their progress southwards do seem to indicate a kind of "fast track" down the western shore of the lake. An example is provided by marker M95 (Fig. 7), along with all those entering the Gulf of Pallanza. This western current towards the south may be offset by another going in the opposite direction, up the eastern shore, which could be referred to as a compensatory flow. Contributing to this might be the barrier presented by the Bay of Ispra, and especially the promontory of Ranco; in this connection, see the last stretch of the route of M93 (Fig. 10), already mentioned above, which proceeded northwards along the eastern shore for more than 20 km from the Ispra Bay almost as far as the Germignaga cross section.

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