Numerical 3D modelling of the vertical mass exchange induced by turbidity currents in Lake Lugano (Switzerland)

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The extreme hydrological event of September 1994 on the southern part of the Swiss Alps produced an important flood on the Cassarate River. This was the origin of hypolimnic water upsets in the North Basin of Lake Lugano. The flood brought back into suspension the polluting elements accumulated on the ground and lifted up oxygen-poor and phosphorus-rich deep waters. A 3D numerical model using the CFX-4 code was developed in order to simulate turbidity currents in the stratified lake. The aim was to describe the physical phenomena and to test the efficiency of solutions to avoid this negatives effects.
The input data could be obtained thanks to a measuring station installed on the Cassarate River upstream of the mouth. Furthermore, currentmeters were placed at different depths in the lake. During two consecutive years, series of measurements were carried out in the Cassarate River and along the principal axis in the lake which allowed to document two others significant floods in 1999 and 2000. This dataset (turbidity, temperature, discharge) was used as boundary conditions to calibrate and validate the numerical model.
Throughout this work, extensive knowledge relating to the turbidity currents in a stratified lake could be acquired. The propagation of the currents and sediments at the bottom of the lake and just under the thermocline could be described. The progress of the currents was analysed down to their final stage in the lake. Their influence on vertical mass exchanges between deep and superficial water, which are at the origin of surface water pollution in the lake, could be estimated.
Finally, a solution was proposed to dissipate the kinetic energy of the turbidity current in order to attenuate its mixing effect. It consists of a vertical permeable diaphragm placed on the bottom of the lake close to the mouth of the Cassarate River.

Introduction

Turbidity currents in a stratified domain

Turbidity currents are flows driven by density differences caused by suspended fine solid material. They belong to the family of sediment gravity currents. These are flows of water laden with sediment that move downslope in otherwise still waters like oceans, lakes and reservoirs. Their driving force is gained from the suspended matter, which renders the flowing turbid mixture heavier than the surrounding water and its introduction into the lake depends on the density differences. Turbidity currents are often encountered in fluvial hydraulics when a sediment-laden tributary enters a lake (Fig. 1). During passage it may unload or, while flowing on the bottom, on the contrary resuspend granular material in the delta region.
Already in 1892 early observations of lacustrine turbidity currents were made by Forel (1892) in Lake Geneva. Recent significant observations of turbidity currents in Switzerland were made in Lake Geneva (Lambert and Giovanoli 1988) and in Lake Constance (Lambert 1982). Simpson (1987) and Garcìa (1992) give a good general overview of turbidity currents.
The vertical temperature stratification of a lake separates warmer, normally oxygen-rich surface water (overlying epilimnion) from cold, normally oxygen-poor deep water (underlying hypolimnion). In the thermocline, the temperature decreases rapidly with depth and sharply separates regions differing in temperature and therefore in density.

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The relationship between the density of the river flow ρ_c, epilimnetic, and hypolimnetic waters of density ρ_{a1} respectively ρ_{a2} determines the level at which the incoming river water will flow upon entering the lake. Thus density currents entering a stratified lake can behave as underflow, overflow, interflow (see Fig. 1) or, as been observed, as a combination of these types during a flood with variable sediment concentration and temperature in the river (De Cesare 1998, Bournet et al. 1999 and Monaghan et al. 1999).

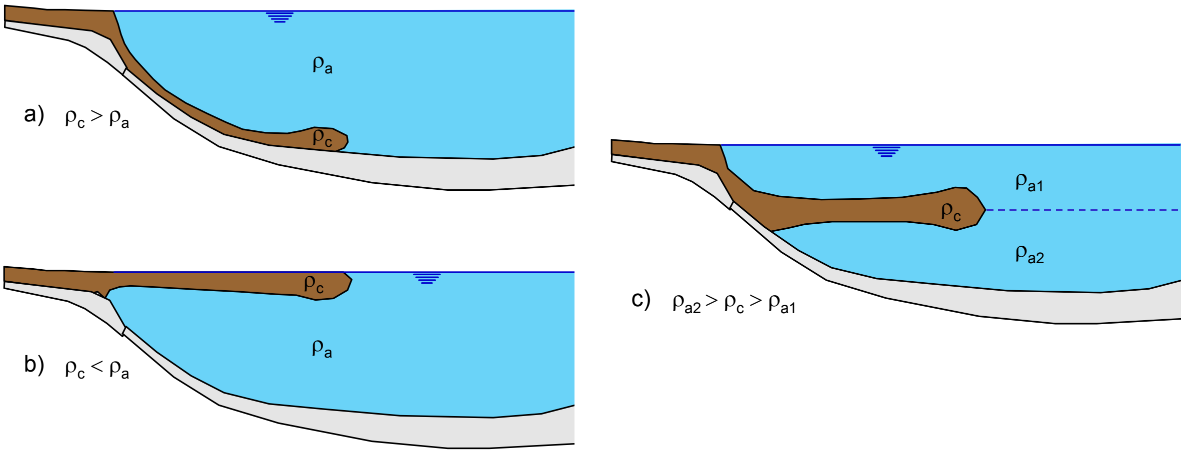

Fig. 1 Density currents of density ρ_c in a non-stratified lake of density ρ_a and in a stratified domain of density ρ_{a1} respectively ρ_{a2} in the form of a) underflow b) overflow and c) interflow (De Cesare 1998)

Short portrait of Lake Lugano

Lake Lugano is located at 271 m above sea level (a.s.l.) at the border between Italy and Switzerland and is divided into two major basins by the Melide narrows formed by a moraine front (Fig. 2). It has a surface of 48.9 km^2 and a total catchment area of 614.5 km^2.

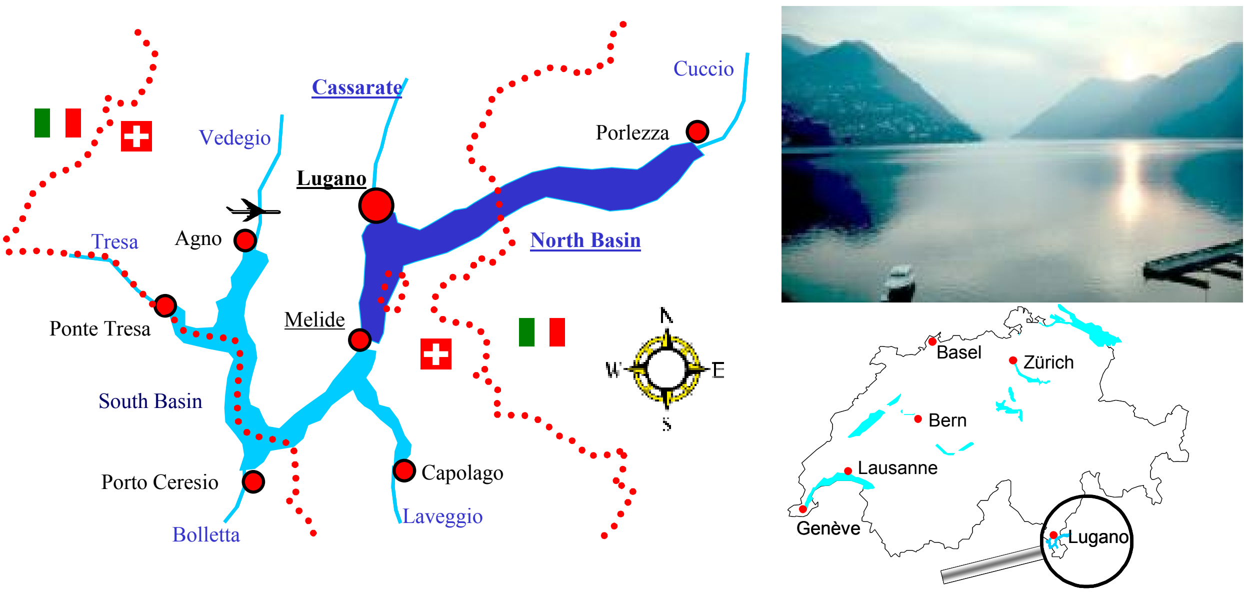

Fig. 2 View of Lake Lugano North Basin, location in Switzerland, and detailed area map with the North and South Basins, borderline between Italy and Switzerland, major tributaries and localities

The study focused on the fjord like North Basin (see photograph in Fig. 2) with the Cassarate River running through the city of Lugano as its major tributary. The North Basin has a surface of 27.5 km^2, a catchment area of 269.7 km^2, a maximum depth of 288 m and a volume of 4.69 km^3. Due to the vast volume compared to its tributaries inflow, the theoretical renewal

time of the North Basin is estimated at around 12 years (LSA 2000). Therefore every polluting event has a long-term effect on the limnological health of the lake.
In the summer period, and thus in the period with major floods, the lake is stratified. This increase in density with depth is due to the decrease in temperature with depth, resulting in a stable water column that does not mix vertically unless acted on by outside forces, for example currents or winds. The limnologic data collected these last few years in Lake Lugano by the Laboratorio Studi Ambientali (LSA 1996, 1998 and 2000) allows to describe the general evolutionary tendencies of the lake and to better understand the ecosystem acting under a recovery program aiming to reduce the phosphorus load from sewage treatment plants. The oxygen concentration in the hypolimnion waters is still very critical and Lake Lugano is still in eutrophic conditions. The strong thermal stratification during the summer period should be able to prevent any substantial vertical exchange between deep anoxic water and the oxygenated hypolimnion. A more detailed description of the state of Lake Lugano can be found in Barbieri and Mosello (1992) and Barbieri and Polli (1992).

Scope of the present Study

The objectives of the Lake Lugano project were:

- to determine the hydrodynamic impact of the river induced currents
- to investigate, over two summer periods, the varying ambient conditions using field measurements at the inflow river and inside the lake
- to determine the influence of the variability in characteristics and amount of the inflowing water and sediment (flood hydrograph and sediment concentration) on the circulation inside the lake
- to estimate the potential of exchanges in the vertical water column
- to propose and evaluate long term solutions to reduce the impact

The whole investigation used field measurements at the inflow river and inside the lake, the whole brought together in a full 3D CFD model of the entire lake (Lavelli et al. 2002).

Field Measurements

Hydrographical and sediment inflow characteristics

The Laboratorio Studi Ambientali (LSA), in close partnership with the Laboratorio di Fisica Terrestre (LFT) both of the Canton Ticino, the Limnological Research Center of the Swiss Federal Institute for Water Resources and Water Pollution Control (EAWAG) and the Laboratory of Hydraulic Constructions (LCH) placed a fully equipped measuring station on the inflowing Cassarate River about 1.2 km upstream of the lake. The following measurements were made during the summers of 1999 and 2000:

- Discharge Q, continuous
- Temperature T, continuous
- Photo-optical turbidity measurements, continuous
- Automatic suspended sediment sampling during floods Cs [g/l] beyond a water level threshold, for the calibration of the photo-optical turbidity sensor

The Cassarate River, as main tributary, drains a direct watershed of some 72 km^2. The mean annual inflow is 2.57 m^3/s. The 1994 flood peak was 115 m^3/s, 88 m^3/s were observed in 1999, and 59 m^3/s in 2000. Regarding the year 1994, no data is available in relation to the sediment concentration during the flood event; in 1999 the maximum sediment volume concentration reached 0.33 % and 0.35 % was observed in 2000. Fig. 3 shows the 1999 flood event with the observed values and the modelled ones with multi-polynomial approximations as time-dependent input to the numerical model.

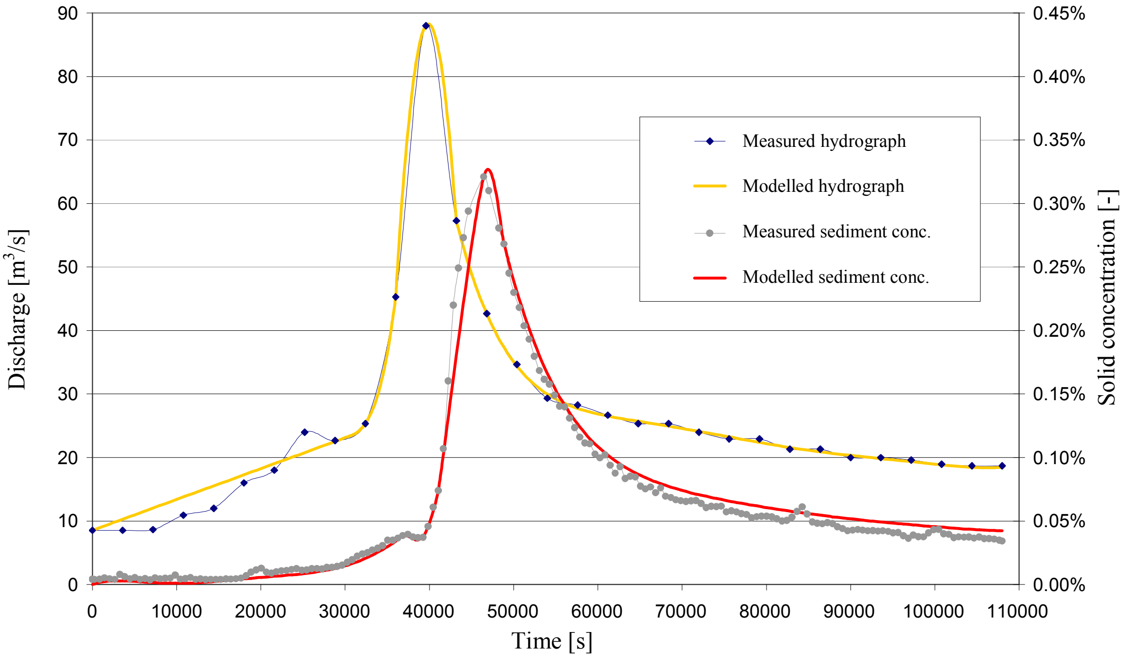

Fig. 3 1999 flood hydrograph and evolution of the sediment concentration in the Cassarate River, observed and modelled values

The temperature of the tributary was as high as 14.2 °C before the flood event; it continuously fell down to 10.8 °C at the end of the flood hydrograph.

Lake characteristics

Measurements inside the lake including flow direction, velocity, turbidity, water temperature and depth on vertical axes were planned and put into operations for two consecutive years. Fig. 4 shows the position of the measuring stations and the observed stratification by the end of summer. Unfortunately, due to severe technical problems over the whole campaign, only very few but precious flow direction and velocity data inside the lake is available.

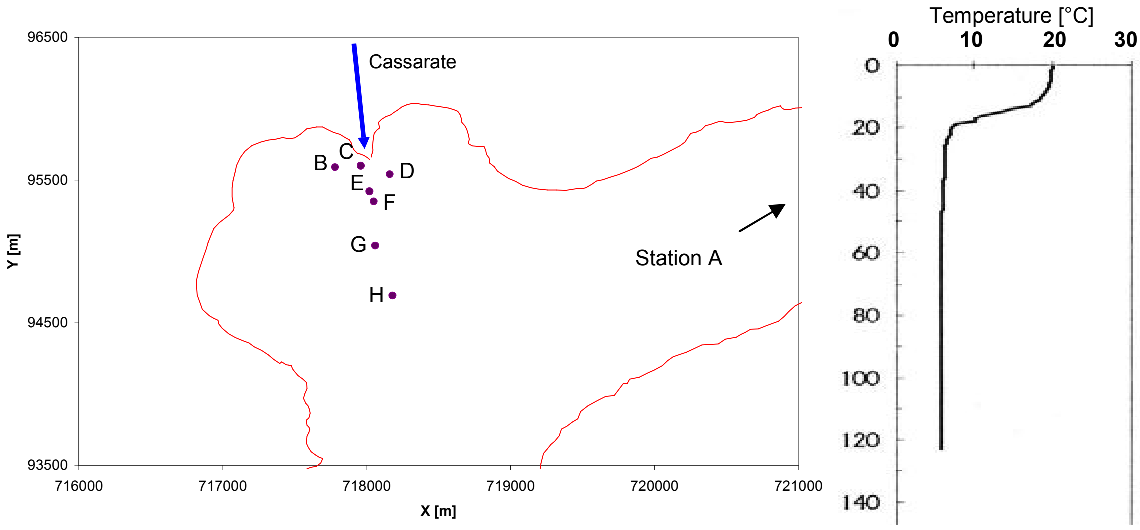

Fig. 4 Measuring stations close to the Cassarate mouth (operated by LSA); Station A is close to the deepest point in the lake (see Fig. 5). Measured temperature distribution at station F in September 1999.

In summer, the surface water temperature rises up to 24°C, the thermocline installs between 10 and 20 m water depth (Fig. 4), with a sharp drop in temperature down to 6°C, staying constant over the rest of the water depth.

Numerical modelling

Model features

The "traditional" models of the water column balance in lakes cannot explain the behaviour of the encountered type of event. Only a numerical hydrodynamic model in three dimensions will be able to simulate the water circulation resulting from a flood. In the present case the work was performed with the commercial flow solver CFX-4 (CFDS-CFX-4 1995). The standard equations of continuity, momentum and energy conservation are solved on a non-staggered grid by a finite volume approach. The k-ε model provides closure for turbulence.
The numerical simulation allows the three-dimensional simulation of turbulent flows with solid phase in the Lake of Lugano, giving the time evolution of every important hydrodynamic parameter as a function of the lake geometry, the temperature distribution and the inflow conditions. A detailed description of turbidity current simulation using CFX-4 is presented by De Cesare (1998 and 2001).

Grid generation and boundary conditions

The geometry of the lake was built up using a digitised Swiss national chart (scale 1:25'000). The spacing between the level lines is 20 m. The grid is of non-structured type, in other words the spacing between the values in x-coordinate and y-ordinate is not constant over the entire domain. The passage to a structured grid is necessary for the application with CFX-4. The resulting very fine grid has a constant spacing of 20 m on x and y. A linear type interpolation has been used. The built finite volume mesh is invariable with time. Since the newly formed local sediment deposit and scour do not influence the overall flow behaviour during a simulated event, their amplitudes are negligible compared to the lake size and depth of more than 280 m. The grid of the North Basin of Lake Lugano is presented in Fig. 5. The water surface is at 271 m a.s.l. and the deepest point is approximately at -17 m a.s.l.. The total number of cells in the computational domain is 195'750.

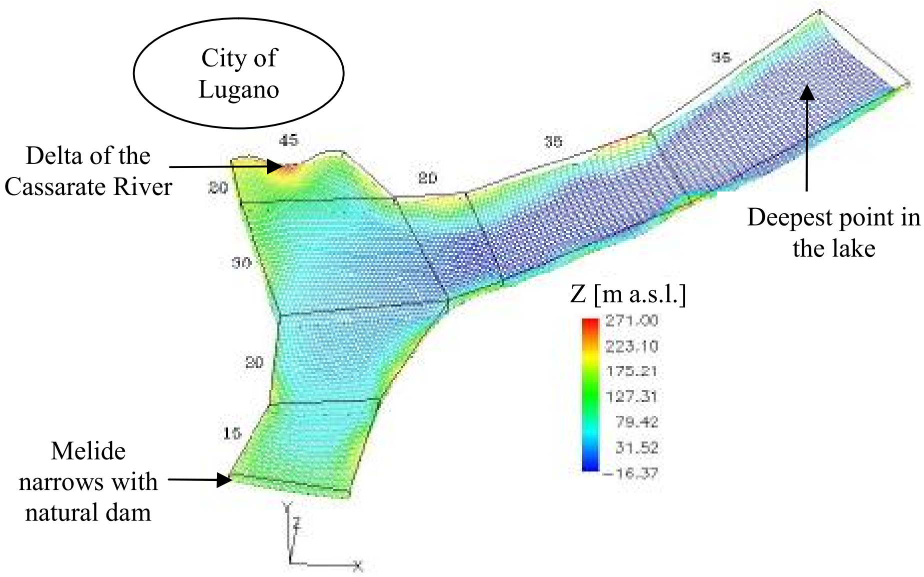

Fig. 5 Structured grid of the lake bottom of the North Basin with a total of 195'750 cells, distributed over seven blocks used for the numerical model

The size of the grid cells is defined as a geometric progression in the principal direction of the current, in other words the mesh is finer close to the mouth of Cassarate and it progressively increases with the distance from this point. In the vertical z-direction, the cell size follows a symmetric geometrical series centred towards the edges in order to have a fine mesh close to the bottom and in the region of the thermocline.

The boundary conditions have been set as follow: the tributary is a time-dependent inlet patch, the lake bottom is a fixed wall boundary patch, the lake surface is defined as free slip atmospheric pressure fixed boundary patch and the Melide narrows is the outlet patch.

Simulation of a flood event

The data mentioned in the previous chapters (discharge, sediment concentration and temperature of the tributary) were used as time dependent boundary conditions and the temperature distribution inside the lake as initial condition to simulate the 1999 event. This event has been chosen because of the well-defined flood hydrograph and the fact that the most reliable field dataset was available for the period.

Simulation results

The following points summarize the temporal evolution of the intrusive current and the bottom current:

- 2h50 before the flood peak: Intrusion of the current in the thermocline at a depth of 15 m.
- 1h07 after the flood peak: Quasi-radial progression of the intrusive current spreading out horizontally from the delta.
- 1h40 after the flood peak: The current of Cassarate exceeds the layer of temperature gradient and plunges on the bottom of the lake following the topography in North-South direction (Fig. 6 and Fig. 7a).
- 5h33 after the flood peak: The turbidity current changes direction and progresses towards the deepest point in the lake. The front is at 276 m depth. The intrusive current reached the side edges of the computational domain.
- 9h10 after the flood peak and around 21 hours after the rise of the hydrograph: The final point of simulation shows that the turbidity current reached the maximum depth of 280 m. The intrusive current remained stationary (Fig. 7b).

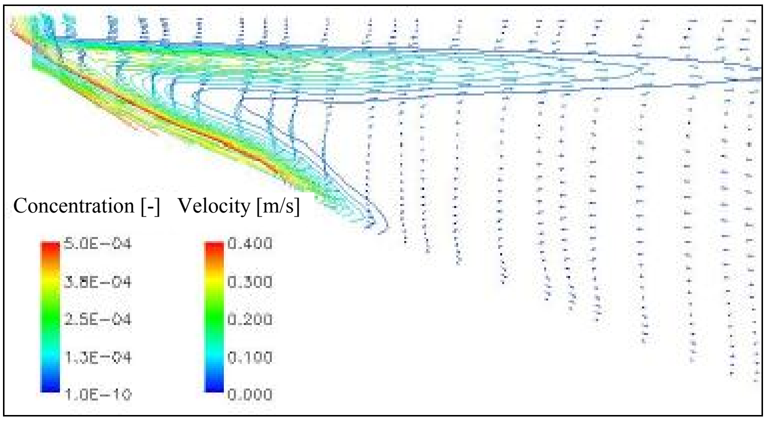

Fig. 6 Bottom density current (underflow) and intrusive current (interflow) as lines of equal concentration and velocity vectors in the axial longitudinal plane, one hour after the 1999 flood peak

The velocity of the front ranges between 0.10 and 0.15 m/s while that of the current body is 0.25 to 0.30 m/s. The intrusion has a calculated maximum horizontal velocity of 0.09 m/s (compared to measured velocities in the thermocline between 0.05 and 0.17 m/s). Both intrusion and bottom turbidity current with the same magnitude have been observed.

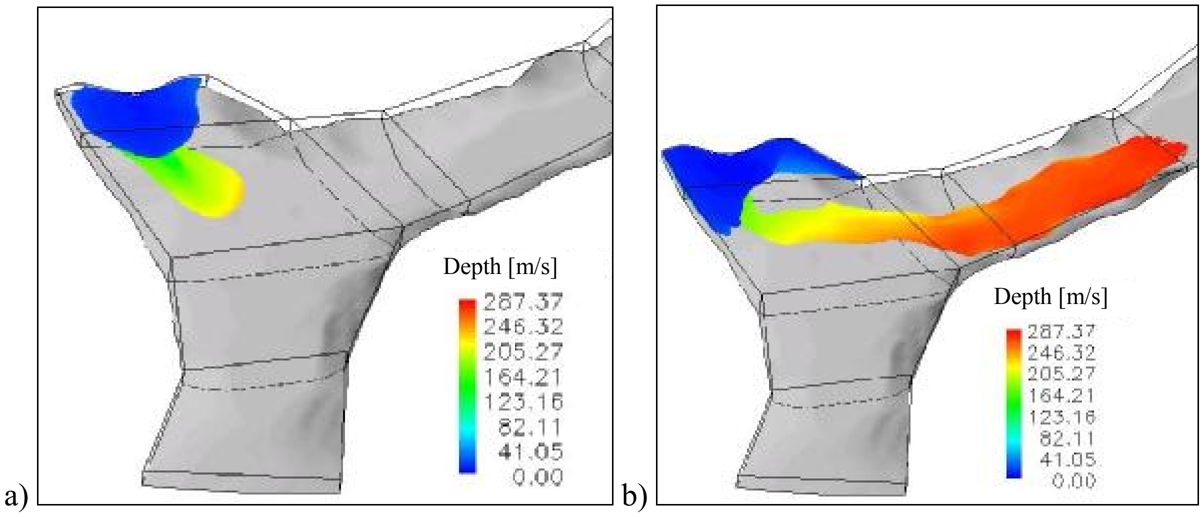

Fig. 7 Bottom density current (underflow) and intrusive current (interflow), global view with surface of equal concentration coloured according to depth, three hours (a) and in its final position nine hours (b) after the 1999 flood peak

The initial concentration in the tributary of 0.33 % is diluted in the intrusion to 0.02 % (compared to the measured 0.018 %), it still reaches 0.10 % in the bottom current. In the final position (see Fig. 7b) the concentration yet attains 0.0007 %.

The analysis of the vertical exchange of mass is made with the aim of evaluating the volumes of water moved under the effect of the turbidity current on the lake bottom. Initially, the vertical mean velocities are calculated and then water volumes are determined by space-time integration. An analysis on the position and on the intensity of the positive (upward) vertical flux was made with a time step of 1'000 s in nine vertical planes chosen on the basis of space-time analysis of the zones covered by the vertical velocity vectors.

The maximum vertical exchange takes place at a depth of around 210 m, with some 45 Mio. m^3 or 35 times the inflow volume in vertical ascending motion.

The modelled total phosphorus upward volume flux, integrated horizontally over the entire model domain and integrated temporarily over the 1999 flood event as a function of depth gave a total of 2.8 t P rising from the deep water below 100 m to the overlaying waters. This amount of phosphorus becomes mixed throughout the whole surface layer and is hence available for biological production during the seasonal convective mixing during the winter following the event. This result suggests that the exchange process possesses a big inertia and that it must be considered over a longer-term period. According to this hypothesis, the calculated fluxes, that may be even larger for more severe flood events than the simulated 1999 flood, are likely to contribute to the deterioration of the superior layers by bringing up substantial amount of phosphorus. Regardless of the quantitative aspect, all phosphorus input into the superficial layer contributes to feed in nutrient the latter and is contrary to the objectives fixed for the long-term sanitation of Lake Lugano (Dipartimento Ambiente Cantone Ticino 1982 and Barbieri et al. 1997).

Proposed solution

Description and modelling of a vertical diaphragm

One of the solutions to reduce the impact of such an event consists in avoiding the mixing induced by the bottom current. Thus, the propagation of this current must be prevented by the installation of obstacles acting like energy dissipators. After an examination of the range of possible remedies, the selected solution consists in positioning a permeable vertical

diaphragm on the bottom of the lake at a distance of approximately 70 m to the entry of Cassarate. The turbidity current should not be stopped but slowed down; its kinetic energy must be dissipated. Accordingly the authors opted for a 45 % porosity of the membrane.
The positioning and its distance from the entry of Cassarate were defined by considering the way the turbidity current spreads out on the bottom of the lake.
The principal geometrical characteristics of the membrane are the following: 80 m width, 15 m height, 70 m distance from the entry of Cassarate along the bottom of the lake. It consisted of 80 vertical cells faces in the computational domain (Fig. 8).

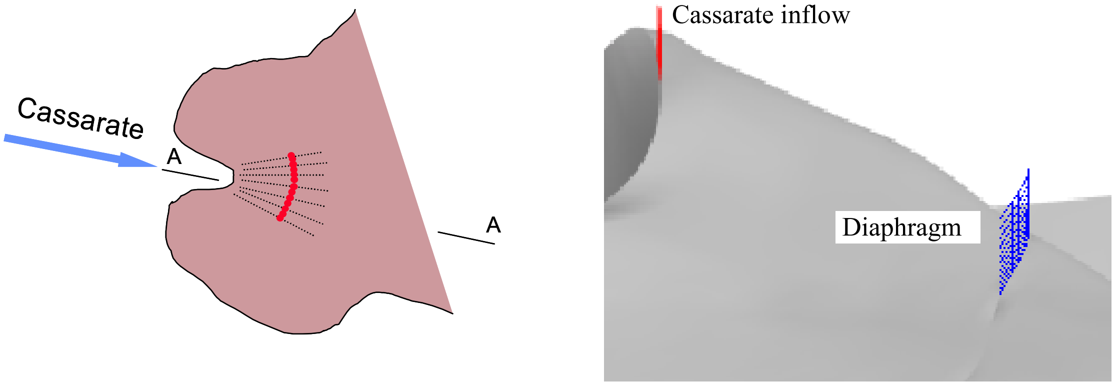

Fig. 8 Situation with axes A-A (left) and lateral view of the vertical diaphragm in the numerical model (right)

Effects on the plunging turbidity currents

At the time of the impact on the membrane, the turbidity current loses its energy and it is slowed down. The mixing downstream of the membrane is subsequently reduced.
Fig. 9 shows the iso-surface of vertical velocity of 10 cm/s at the moment t = 45'500 s, without and with the permeable membrane. Without membrane the zone affected by significant vertical fluxes extends on approximately 100 m. With the membrane, the region is limited to the front of the obstacle.

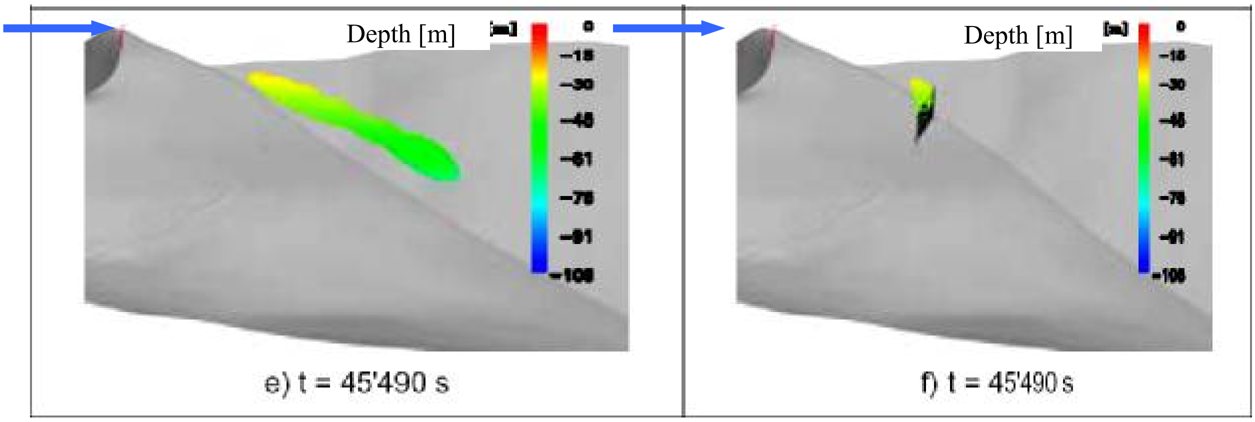

Fig. 9 Comparison of the vertical velocity field without (left) and with the diaphragm (right) in the delta region. The current is almost completely blocked by the obstacle during the flood event.

With the membrane in place, the current doesn't plunge any further and all above-mentioned vertical mass exchange from deep waters towards surface waters consequently disappears.

Conclusions

The limnologic data collected these last years in Lake Lugano by the Laboratorio Studi Ambientali allows to describe the general evolutionary tendencies of the lake. The strong thermal stratification during the summer period should be able to prevent a substantial vertical exchange between deep anoxic, polluted waters and the oxygenated hypolimnion. In spite of that, the exceptional flood of the Cassarate River in September 1994 partially overturned the balance of hypolimnic water of the North Basin of the lake. The present study showed that the tributary flow penetrated at various depths of the lake, partially under the form of bottom turbidity current, according to its apparent density. The applied numerical hydrodynamic model in three dimensions was able to simulate the water circulation resulting from a flood in the tributary. The total vertical phosphorus volume flux, estimated over the entire model domain due to a flood event, showed the capability of the turbidity current to move up a substantial amount of polluted deep water closer to the surface. The technical solution to reduce the impact of the tributary floods on the ecosystem of Lake Lugano consists in positioning a permeable vertical diaphragm close to the delta. This solution has been numerically tested and proved to satisfy the requirements.

Through this work, extensive knowledge relating to the turbidity currents in a stratified lake was acquired. It was possible to describe with a good precision the movement of the currents and sediments inside the lake, in the case of a flood of the Cassarate River with strong solid transport. These currents were followed until their final position in the lake and their influence on the vertical exchanges between deep and surface water could be estimated.

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