D24: Realistic Residence Times Studies

Work package No. 3:	**Realistic Residence Times**
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Table of Contents

1 EXECUTIVE SUMMARY

Many biological and chemical processes in lakes depend either directly or indirectly on the concentration of substances dissolved in the water. This water (and its ingredients), however, is constantly moved under variable hydrological and meteorological conditions, is mixed with surrounding water or stays very long in sheltered bays, and eventually leaves the lake via outflow or evaporation. A substance released to such a lake may stay in different parts (either lateral or vertical) for different time periods thereby having quite substantially different influences on water quality. By means of high-resolving numerical models it is now possible to compute a “residence time” as a function of space and not as historically done as a mean value determined only by the lake volume and the amount of inflowing water. Especially in deep lakes such a number has no or only a very limited validity. Measurements of passive tracers have already pointed to a more complicated answer to the simple question “how long does the water of tributaries stay in the lake or how fast is it transported through the lake and is leaving the system?”. The work described in this report accordingly was aimed at the calculation of more realistic residence times using three-dimensional models under varying meteorological and hydrological conditions with application to very different lakes in shape and bathymetry. The final objective was to present recommendations on how to use 3D model applications to enable (if possible) simplified 1D box models or 2D approaches to residence times which might be of sufficient quality for management purposes.

The lakes under consideration have very large volumes of water (between 2,600 and 88,900 Mio. m³) and water depths of more than 145 metres. The mean residence times accordingly amount to 2 to 12 years. By means of Lagrangian tracer methods to calculate pathways of water particles from three-dimensional model results and (where available) experiences from radioactive tracer measurements more detailed information on residence times in different parts of lakes can be drawn, e.g. near-bottom layers, different lake basins, epilimnion – metalimnion – hypolimnion. In addition clearly defined water masses can be marked (e.g. water originating from individual tributaries, the area above the Secchi depth or near-bottom water with a certain minimum oxygen content). In this way it will be possible to look at the waterbody lifetime defined by the condition that at least half of the marked water body is still under the same pre-defined condition. This leads to the possibility of biological interpretation for a large variety of processes which are dependent on certain physico-chemical conditions in lakes.

2 OBJECTIVE

The project EUROLAKES aims at the improvement of planning strategies and EU regulations (in particular the EU Water Framework Directive) concerning a sustainable water management of important deep European lakes and their catchment areas. Target lakes are especially the Bodensee (Lake Constance), Lac Léman (Lake Geneva), Loch Lomond (Scotland), and Lac du Bourget (France). They are all important for water extraction and which have already been subject to intensive, but individual scientific and management activities. These target lakes are investigated with their respective catchment area in close co-ordination with stakeholders and existing water management bodies and authorities. The project tasks are supported by specific activities concerned with important key processes for the limnology of deep lakes which have a marked influence on the current and future water quality. Part of the investigations of seasonal dynamics and quantification of limnological key processes and parameters in deep European lakes are concerned with the establishment of improved calculation of realistic residence times in large deep lakes considering meteorological, bathymetric and hydrological variability with suitable three-dimensional models. The improved knowledge about the calculability of residence times (or often called retention times) is the objective of this report. Results of these investigations were meant to lead to recommendations how to adapt these experiences in suitable 2D or coupled 1D-box-models for the different lake shapes.

By means of either long-term (seasonal to year) three-dimensional model calculations with naturally varying meteorology and hydrology or long-term measurement information it was planned to calculate residence times of water in different lateral areas and depth ranges of the lakes involved. This work had to be done for major EUROLAKES and in addition on Längelmävesi-Roine. As input data time series of wind fields (from project work package 2), stratification (from work package 4), and inflow/outflow (from data sources) were required. The effects of stratification, Coriolis force, internal seiches on river intrusions and on large scale current patterns were also tried to be extracted from field data. The potential influence on particle trajectories and thus water residence times would then have to be estimated and compared with predictions from numerical modelling. Empirical investigations on the inter-annual variations of the turnover in winter were to be carried out on the basis of long-term routine observations in Lac Léman and Lake Constance (Bodensee) with respect to meteorological causes in work package 6. The results of these investigations were planned to be used for validation of model calculations of realistic residence times of deep hypolimnetic waters in this report.

A more detailed information on the residence of different water masses in deep lakes than hitherto possible was the major objective of the work. This will certainly lead to improved information on the relative importance of different processes in separate lake areas whether they be defined as horizontally or vertically separate entities or by their different hydro-physical conditions. Here also a better definition of residence times in the WFD could be contemplated.

3 GENERALISED CONCEPTS FOR RESIDENCE TIMES IN LAKES

The main objective of WP3 “Realistic residence times” is calculation of realistic residence times in large lakes considering different lateral inflows/outflows with 3D model taking into account temporal and spatial variability of meteorological and hydrological parameters. For lakes under study in the EUROLAKES project theoretical residence time varies from 11.8 years (Lac Léman) to 0.04 years (Zegrzynski Reservoir). These are very rude estimates and they do not take into account the temporal and spatial variability of hydrological and meteorological parameters.

Traditionally theoretical residence time is defined as the average time water spends in a particular water body (lake, ocean, reservoir), or the average time required to fill the volume of a water body with average inflow rate, i.e.,

$$\tau = \lim_{t \to \infty} \left(\frac{\int_0^t V(t')\,dt'}{\int_0^t Q(t')\,dt'} \right) = \frac{\bar{V}}{\bar{Q}},$$

where $\bar{V}$ is the mean volume and $\bar{Q}$ is the mean value of inflow rate.
The general approach to describe water exchange and mixing processes in lakes is based on the concept of turbulence and turbulent transport. Turbulent diffusion coefficient introduced by Reynolds by analogy with molecular diffusion is used to characterize the intensity of mixing. In recent years geophysicists and limnologists start to realize the importance of the concept of Residence Time (RT) or more strictly Residence Time Distribution (RTD) for characterizing the flux pathways in water bodies.

3.1.1 Calculation by numerical modelling

The direct approach is to integrate the system of hydrodynamic equations with variable boundary conditions for a very long time span required for inflowing water particles to leave a water body and then to use Lagrangian method to calculate the travelling times of these particles. This method is not applicable in practical applications due to lack of computer resources and limitations of modern hydrodynamic models.

On the other hand the concept of residence time is widely used in technical areas of gas and fluid dynamics, chemical engineering, bio-hydrodynamics. The goal of these notes to discuss how this experience can be used in the field of physical limnology.

Definitions and methods

The local average age of the fluid represents at a given point **x** 0 Σ (Σδ$\mathbf{R}^3$ is a solution domain) the elapsed time since the particle of fluid located in this point entered the domain at its inlet. Suppose that natural or artificial tracers were injected at the inlet and their concentration C(**x**,t) was measured continuously at the fixed point. Then its distribution function is defined as (Sandberg and Sjöberg, 1983)

$$f_t = \frac{C(x,t)}{\int_0^\infty C(x,t')dt'} \,. \qquad (1)$$

The local residence time 0 is the first moment of f_t

$$\tau(x) = \frac{\int_0^\infty C(x,t')t'dt'}{\int_0^\infty C(x,t')dt} \,. \qquad (2)$$

The first approach to find the spatial distribution of 0 is to solve a transport equation derived by Sandberg (1981). In the case of laminar flow it may be written as

$$\frac{\partial}{\partial x_i}(u_i\tau) - \frac{\partial}{\partial x_i}\left[D_{AA}\frac{\partial \tau}{\partial x_i}\right] = 1 \,. \quad (3)$$

Here D_{AA} is the self-diffusivity of the fluid, for water at ambient temperature it equals $3.03*10^{-6}$ m^2s^{-1}. In the case of turbulent flow the modified version of the equation (3) was suggested by Baléo and Le Cloirec (2000)

$$\frac{\partial}{\partial x_i}(u_i\tau) - \frac{\partial}{\partial x_i}\left[(D_{AA} + \frac{\mu_t}{\sigma_t})\frac{\partial \tau}{\partial x_i}\right] = 1 \,. \quad (4)$$

Here ◣ is the turbulent viscosity of the fluid (water in our case) and ✱$_t$ is the turbulent Schmidt number. According to the authors equations (3) and (4) are valid under the following assumptions:

- the flow is steady and the fluid is incompressible;
- there is no diffusion against convective flow in the inlet section, hence residence time in a point upstream of the injection 0_{inlet}=0. The injection area is small compared to the characteristic dimensions of water body;
- the flow is "deterministic" in a sense that large-scale processes are not random. The authors note also "that rapid random processes due to turbulence, steady in

average, may be considered as "quasi-deterministic" and do not constitute a limitation to the application of the model".

At solid walls the zero "flux" (M0/M**n**=0, **n** is a normal to the boundary) boundary conditions are imposed. Baléo and Le Cloirec (2000) admit that there is no clear guide from physical point of view for setting this particular type of boundary conditions but argue that for both convective and diffusion dominated flows the influence of it on the general solution remains limited. Numerical experiments with simple 2d shear steady-state flow with different values of D_{AA} support their conclusions.

As it can be seen from the structure of the equation (4) the accuracy of determination of residence time 0 depends on the accuracy of the flow field and turbulent diffusivity. One can expect that results of residence time estimates using equation (4) will depend a lot on flow model structure and selected turbulent closure scheme.

The second approach is to use virtual particles within a Lagrangian reference frame. Once the flow field is calculated the pathways of particles injected at the inlet can be calculated using equations of motion d**x**/dt=**V**(**x**,t). These ordinary differential equations can be integrated with standard methods, as Euler, Runge-Kutta and others. Due to irregularity of the flow field travel time (retention period, detention time or residence time) of each individual particle differs from others (they arrive at the outlet at different moments of time). The result of the integration is the Residence Time Distribution (RTD) at the outlet point similar to empirical histogram. The RTD can be processed statistically, i.e. estimates of the mean, variance and other statistical characteristics can be easily obtained.

Results and discussion

It appears that a key point in calculation of realistic residence time is the estimation of mean or typical (climatological) flow fields and closely linked with them spatial distributions of turbulent diffusivity. To obtain the upper and lower limits of "realistic residence times" it seems feasible to consider two seasons with different types of circulation: winter (isothermal) regime and summer (stratified) regime. Since winter circulation is usually stronger due to higher winds and absence of baroclinic effects one could expect that estimates of residence times calculated using Sandberg or Lagrangian approaches should be smaller then for summer conditions. By this means the lower and upper limits of realistic residence time spatial distribution ("the statistical fork") can be obtained.

Two comments should be added on the selection of the method. There is limited experience with Sandberg approach in lake hydrodynamics. Applications found in literature are limited to small-scale technical case studies (air ventilation in rooms, wastewater treatment plants). The main advantage of this approach lies in the possibility to calculate the spatial distribution of "realistic residence time" using the same Eulerian computation grid of the hydrodynamic model. A drawback is the high uncertainty of these calculations due to absence of physically based boundary conditions and high dependence on the turbulent closure scheme. The influence of boundary conditions on the general solution can be minimal for convective dominated flows but this problem requires more detailed studies.

The usage of the Lagrangian reference framework is more straightforward but due to large spatial scales and complexity of flow fields in natural water bodies like presence of re-circulation or dead zones may lead to unbounded estimates of local residence time (infinite integration loop). The possible drawback of this method is that the estimates cannot be extrapolated over the whole solution domain (lake volume) because of the nature of the Lagrangian approach. As a consequence the total number of virtual particles is difficult to estimate a priori and the computations can very computationally intensive. An application of this technique for the modelling of inflowing water of the Alpine Rhine into Lake Constance is shown in fig. 3.1. This successful investigation is illustrated in more detail by Duwe, Fey and Hollan (1999).

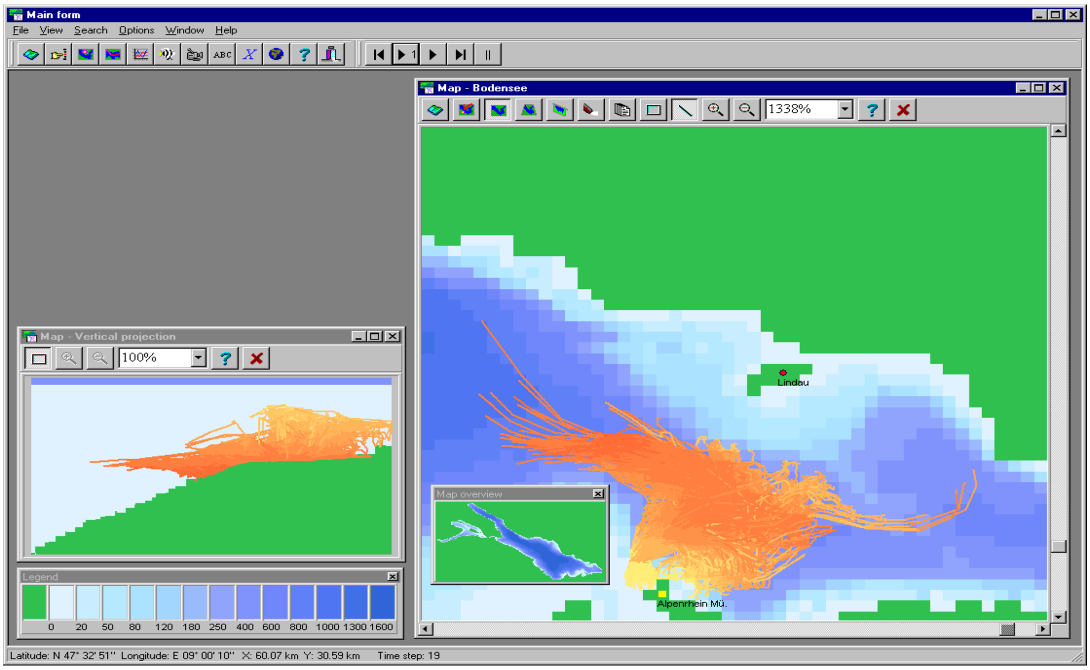

Fig. 3.1: Inflow of Alpine Rhine water into the eastern part of Lake Constance derived from Lagrangian tracer simulation – a possible tool for computing residence times.

To illustrate the above discussion the equation (3) for calculation of residence time initially derived by Sandberg (1981) and later modified by Boléo and Le Cloirec (2000) was solved numerically. The spatial distribution of residence time in lake Längelmävesi-Roine in the surface layer under the steady-state flow conditions is shown in Fig. 3.4. The stationary flow field under north-easterly winds with a speed 5 ms^{-1} was calculated using FEMFLOW3D. A constant value of horizontal turbulence diffusion coefficient 50 m^{2} s^{-1} was used. The results show a high variation of residence time. As expected it increases downstream and local maxima also can be found in bays where water stays longer due to closed circulation patterns. The theoretical residence time of the lake is 2.7 years. This number corresponds with maximum values obtained using the solution of the equation (3). Vertical distribution of residence time shows higher values for deep layers (Fig. 3.3).

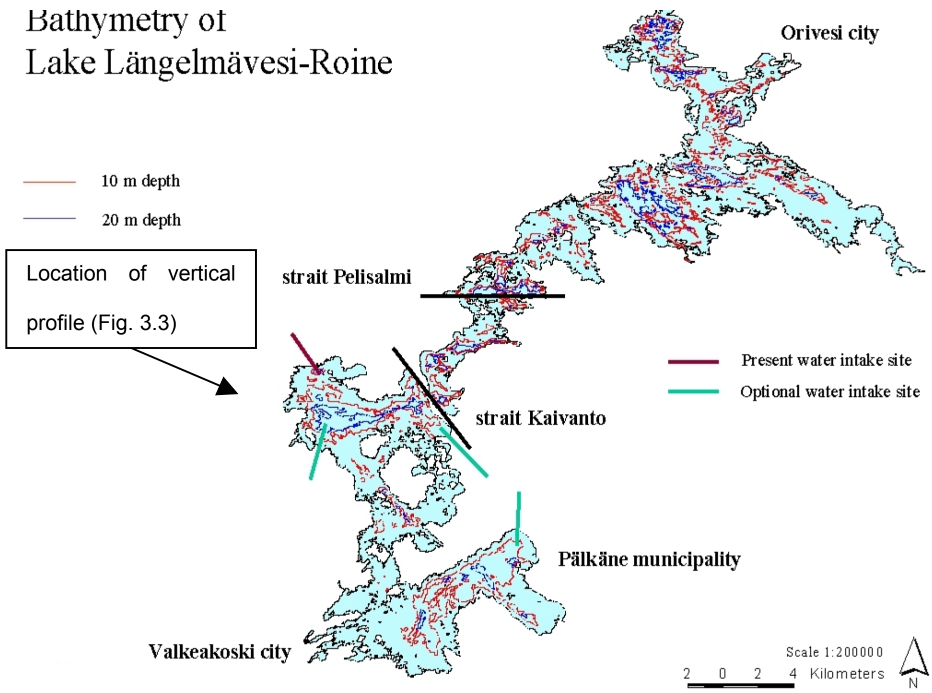

Fig.3.2: Bathymetric map of Lake Längelmävesi-Roine.

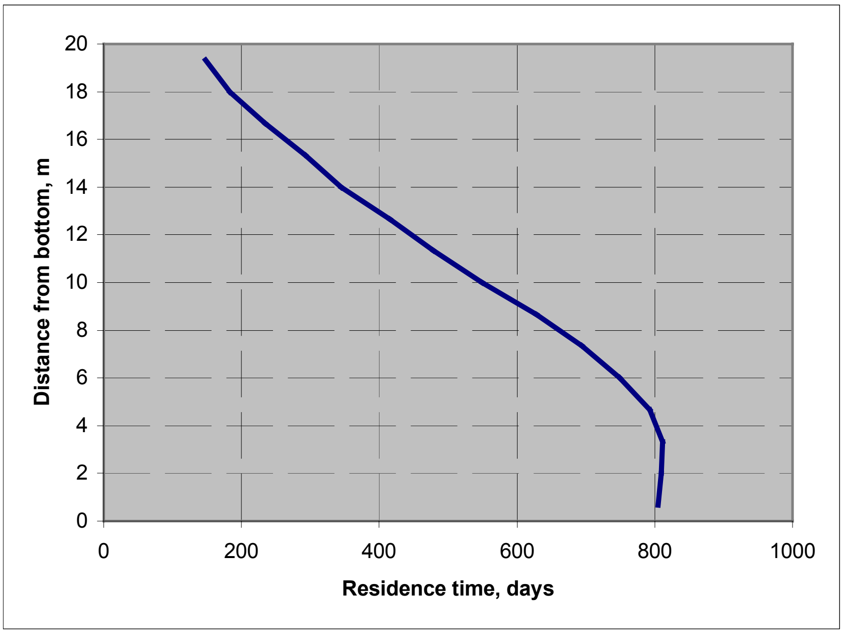

Fig. 3.3: Vertical profile of calculated residence time in the north-western part of Lake Längel-mävesi-Roine.

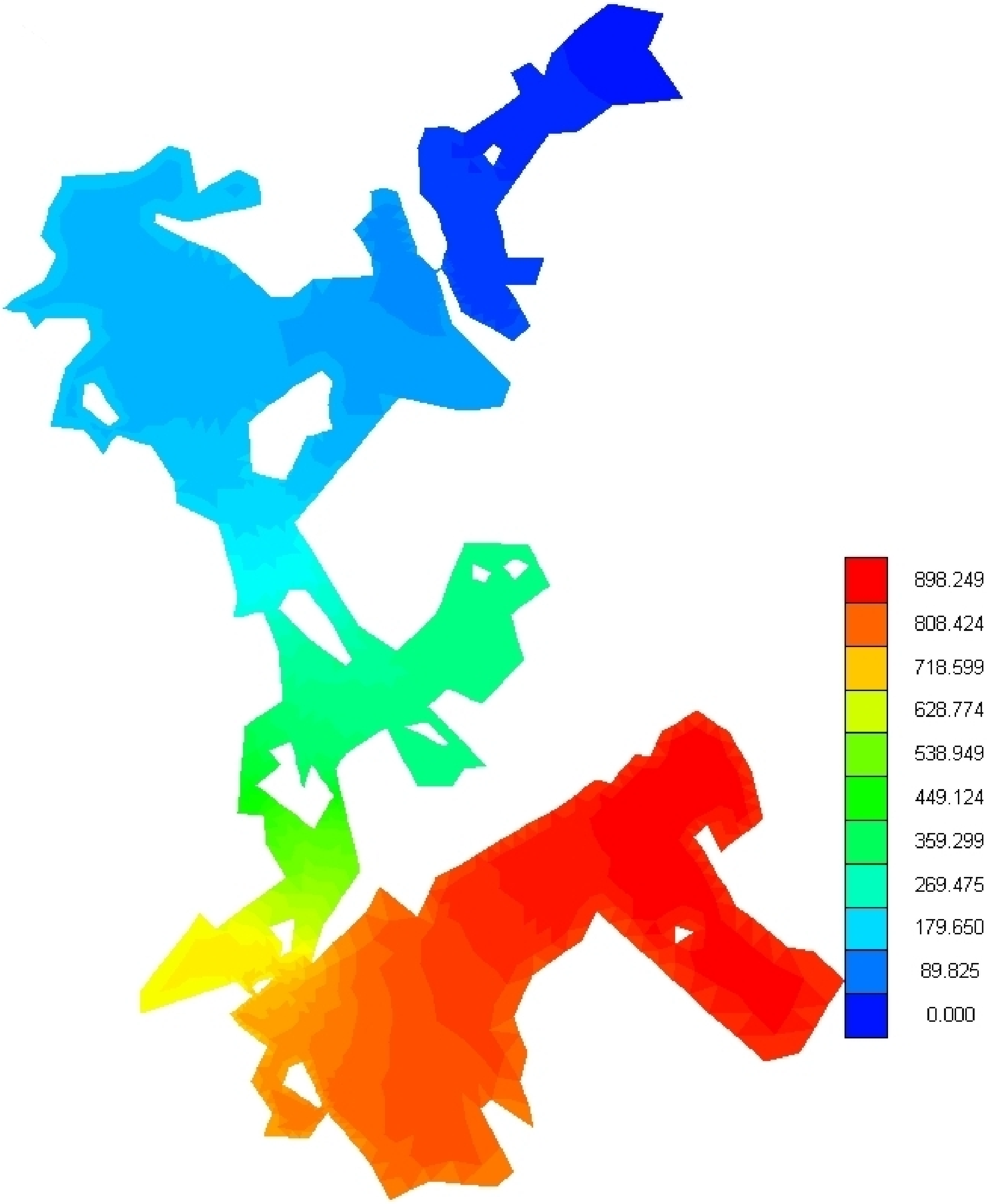

Fig. 3.4: Spatial distribution of residence time (days) in lake Längelmävesi-Roine at the surface. Case of North-Easterly winds with 5 ms^{-1} speed.

It appears that this approach is promising also in physical limnology but more experience is required to get the results with lower uncertainty. Rather high level of uncertainty of calculations can be attributed to our present poor knowledge of mechanisms of turbulence, especially horizontal diffusion.

3.1.2 Calculation by consulting field data including radioactive tracers

Residence time, also called water age or flushing time, is defined as the ratio of a volume by a mass transport rate. In the past, concepts of *residence time* and *water age* have been extensively discussed in the literature. They have experienced some recent revival. Residence time can also be seen as a water mass retention time within confined boundaries (Monsen et al. 2002). In almost all cases, authors acknowledged that the definitions of *residence time* and *water age*, and their quantitative evaluation in a particular case, require an idea of the physical processes involved. Moreover, it has frequently been remarked that a precise definition of the boundary of the investigated water body is helpful for both, definition and evaluation, even though this is evidently not a strict prerequisite for the applicability of these concepts (Wunsch, 2002). In lakes, the residence time is often compared to the typical time scales of biogeochemical processes in order to determine loading rates. It can be used to calculate flushing times particularly with respect to inputs or accidental spills of pollutants.

In order to make the ideas of *residence time* and *water age* useful at all in an ecological context, a water body should have some properties contrasting it from its environment. These properties can be physical quantities, such as temperature or salinity, but also significant biological and chemical variables, such as the concentration of chlorophyll-a, oxygen, and phosphorus.

Initially this concept has been applied to the whole lake. The total lake volume is divided by the river inflow rates or outflow rates for those lakes whose hydrological balance is dominated by fluvial processes. As a consequence, residence times obtained in this way can be considered global. A global residence time is often calculated to determine whether the river inflow is important in the dynamics of the lake. Typically global residence times for large deep lakes are of the order of several years to more than a decade indicating that river inflow may be of lesser importance compared to the other hydrodynamic processes occurring in the lake. Global residence times risk being of little practical use beyond this estimation because they do not take into consideration the hydrodynamic processes that occur in lakes. They can only be considered realistic for the case of a lake which is non-stratified and completely mixed at all times. Lakes with residence times of the order of weeks approach this condition. As is well known from experience for lakes with long residence times this situation does not correspond to reality, particularly in large deep lakes.

A more realistic choice of volumes and transport rates is required to apply this concept to large deep lakes. The range of time scales and length scales governing hydrodynamic processes in this class of lakes is sufficiently large to distinguish different subvolumes in a lake in which transport rates are dominated by certain of these processes. In the application of this concept the difficulty lies in correctly identifying suitable subvolumes and the dominant processes. This can only be done on the basis of a good understanding of “how a particular lake works.”

The residence time concept is a pragmatic simplification of the complex reality and it implies that a validation of its underlying assumptions is made before residence time can be established. It has to be realized in this context that most of the time water mass movement in a lake is not in a steady state condition because the forcing of the lake occurs in an event structure with individual events being of variable duration and intensity. However, experience has shown that forcing events are not totally random and as a consequence water mass movements in lakes often demonstrates a certain repeatability. An understanding of “how the lake works” therefore requires investigations over sufficiently long periods of time in order to capture a statistically significant number of repeated water mass movement events.

In order to archive this understanding one may resort to numerical modeling or field measurements. Numerical simulations need initial verification from field measurements and field measurements are often limited in spatial resolution. Once verified, numerical simulations can therefore provide spatially more detailed information on hydrodynamic processes in a lake than can be achieved by field measurements alone. The drawback of numerical simulations is the difficulty to provide reliable information on long timescales due to stability problems, numerical diffusion. Furthermore, it is often not easy to correctly reproduce the time history of the spatial forcing distribution. An understanding of lake hydrodynamics and a definition of residence times for sub-volumes may therefore be best obtained through a combination of field measurements and numerical simulations.

Field measurements can be carried out either in an Eulerian or a Lagrangian reference frame. The strategy for these measurements is developed on the basis of a predetermined concept for the water mass displacement.

Eulerian reference frame

In the Eulerian reference frame, the time development of a parameter is investigated by instruments at fixed positions. The instruments detect the motion of the water masses of a lake which are displaced within the lake basin in a pattern determined by the structure of the external forcing and the geometry of the basin. Typical parameters which are measured by these instruments are water mass movement, water temperature, conductivity and chemical species, mainly oxygen. If automatic autonomous instruments are moored in place, time series of these parameters can be recorded at fixed time intervals over periods ranging from days to years. The time step of recording of modern instrumentation may be less than a second. Due to the large memory capacity of modern instruments, processes with time scales in the range of seconds (mixing) to seasonal variation can be resolved. It has to be realized that a large number of such observations at different positions in a lake often has to be carried out before a coherent picture of the dominant water mass movements can be achieved. It is best to place instruments at a larger number of mooring positions simultaneously in the lake. However, this strategy may be limited by economic considerations.

Residence times cannot be determined directly from these data. However, characteristic time and length scales of the dominant processes at particular locations may be obtained from an analysis. This information may be extracted from histograms of speed and direction of water mass displacement, progressive vector diagrams, energy density spectra or higher order statistical analysis. Histograms of the speed of water mass displacement can provide a typical speed. When a cross section of a subvolume is divided by this speed and a unit depth, a residence time will result. The orientation of the corresponding cross section may be obtained from the histogram of the direction of the water mass displacement. Progressive vector diagrams serve to determine whether the transport is steady in a preferential direction allowing the application of a residence time concept. If the transport is not steady, spectral analysis can be used to specify whether periodic motions such as internal seiches are of importance. These are periodic motions and may often be reversible. They may render the application of a residence time concept difficult in particular when these seiche motions act across subvolume boundaries which have been specified on the basis of other processes.

Lagrangian reference frame

In the Lagrangian reference frame, a tracer is injected in the water masses at a given location and its displacement with the mean water mass movements as well as the way it is affected by turbulent mixing are investigated. A tracer can be solid or liquid. A solid tracer is typically a float which is made neutrally buoyant with respect to the layer of the stratified water column which it is supposed to follow. The trajectories of these tracers can be determined by acoustic underwater triangulation or by satellite if they track the water mass displacement at or near the surface. In the latter case tracers are often called drifters. In order to obtain a statistically significant information on the water mass movement either a large number of tracers have to be tracked simultaneously or the experiment has to be repeated a sufficient number of times assuming that the hydrodynamic conditions in the lake have not changed significantly.

Tracers can also be liquid but should be passive. As with solid tracers they are used to follow a water mass displacement. Water samples have to be taken to locate the tracer plume. Difficulties which may occur in the interpretation of the trajectories due to different time scales and length scales involved have been discussed in Wunsch (2002). In addition, various mixing parameters can be deduced following their spreading (Ledwell et al., 1993, Ledwell et al., 1998) if liquid tracers are injected locally. Sufficient samples have to be taken in this case to assure that the integrated mass is preserved.

If the source of a tracer is homogeneously distributed in the atmospheric boundary layer, it enters into the lake over its total surface. Most commonly used tracers of this kind are atmospheric pollutants introduced by man. They are referred to as transient tracers. In limnology, the application ^3H-^3He dating resulting from atomic bomb generated tritium is well established (Imboden et al., 1984). The ^3H-^3He age can be calculated using certain corrections (Schlosser et al., 1989).

The quasi-conservative tracers sulfur hexafluoride (SF6), chlorofluorocarbons CFC-11 and CF-12 are often used today. Their atmospheric concentration has continuously increased over the years. Dating based on these tracers compares the concentration in the water sample with the historic equilibrium concentration. The historic atmospheric equilibrium concentration is calculated from the atmospheric input function and the solubility of the gas at the temperature and the salinity of the water sample and the atmospheric pressure prevailing at the lake surface. The difference between the sampling date and the apparent equilibrium age gives the age of the tracer.

All these tracer ages are a measure of the time elapsed since the water was last in contact with the atmosphere, called isolation age. Non-linear variation with time and non-linear functional relationships of tracer ratios may lead to discrepancies between tracer age and isolation age. The above definition of tracer age implies that water masses with gas concentrations in equilibrium with the atmosphere have zero age. However, the level of saturation of the tracers near the surface is the result of the interplay between deep-water mixing and limited gas exchange. The saturation level of the near surface layers is found to vary seasonally, with temperature affecting the gas solubility and with the depth of the surface mixed layer affecting the flux of the tracer from the deeper layers.

Long residence times calculated from surface entering tracers require that the source strength is either constant or that its time variation is known. Technical aspects concerning the estimation of deepwater renewal by these tracers for a deep lake have been discussed in a note by Hofer et al. (2002). It has to be noted that one of the underlying assumptions in the tracer age calculations is that it is the result of lakewide homogeneous vertical mixing in most cases with a time constant mixing coefficient. In all lake applications water age curves have only been established in the vertical assuming horizontal homogeneity in each layer. While this approach provides for a reasonable first order information which is useful for small lakes, it does not allow for the determination of realistic residence times in large deep lakes where distinction in the horizontal may have to be made.

In large, deep lakes horizontal transport and spatial and seasonal differences in vertical mixing may require that the results be interpreted with caution. Water mass transport by plunging river plumes and cold density currents over the lateral slopes of the lake may also play an important role and may invalidate the simple one-dimensional concept. Therefore a correct interpretation of tracer information requires that a good understanding of the lake hydrodynamics has been acquired by other methods. In most cases, a combination of Eulerian and Lagrangian methods is desirable.

In both types of measurement techniques the sampling interval between two consecutive measurements has to be adjusted in order to capture the time and space scales of the processes to be studied. Evidently, the understanding of “how the lake works” can only be the result of an iterative process extended over a sufficiently long time and adapted and optimized while progressing.

3.1.3 Overview of former tracer experiments at Lake Constance

Many parameters that are regularly measured in Lake Constance can serve as tracers such as temperature, conductivity, turbidity, oxygen and other chemical substances. Due to their inhomogeneous distribution in the lake these parameters can trace water body motion as well as mixing processes. However these are generally non-conservative tracers often involved in complex biological or chemical cycles of matter transformation and their production or degradation rates are often unknown or difficult to determine. Their applicability for calculating residence times is therefore rather limited.

Kaminski et al. (1998) gives a concise description for the fate of artifical caesium radionuclides in Lake Constance, which originated from nuclear weapon testing and from the Chernobyl (USSR) accident in 1986. They summarize a decade of investigations of the caesium radionuclide content in the water, fish, settling particles and sediments of Lake Constance. Residence times of the caesium radionuclides in different water bodies are considered but the residence times of the water bodies themselves cannot be deduced directly from this as caesium is a non-conservative tracer, e.g. for its absorption properties to particulate matter. However, an estimation of the amount of caesium washed out from the epilimnion by the outflow could be made by mass balance calculation and give a rough idea of the water renewal in the stratified lake. Many other radionuclides have the same or similar limits for residence time investigations. Some of these studies are referenced in the above mentioned publication.

In the thesis of Zenger (1989) tracer experiments were carried out to investigate hydrodynamic phenomena of currents, transport and mixing in the western part of Upper Lake Constance. The water temperature as well as tritium and its decay product ^{3}He were used as tracers. Tritium and ^{3}He can be considered as conservative tracers in these experiments. Their inhomogeneous distribution in nature is mainly a result of nuclear weapon testing in the 1950’s and early 1960’s. The results of the study of Zenger as well as the method applied there could be useful for the calculation of residence times.

Also in the western part of Lake Constance tracer studies with SF_6 were carried out to investigate horizontal mixing processes (Maiss et al. (1994a, 1994b)). This non-toxic man-made substance is chemically and biologically inert and therefore ideal for tracing mixing processes. Residence times were not calculated in these studies, however, the results about mixing processes as well as the method itself might serve to such investigations.

4 DEDICATED INVESTIGATIONS FOR LAC LÉMAN

4.1 INTRODUCTION

The Lake of Geneva is a large deep lake: it is large because the Coriolis force is important in the force balance and it is deep because it does not destratify on a regular annual basis. It is about 70 km long and consists of two basins. The large and deep main basin is about 10 km wide and about 310 m deep in the central part (Fig. 1). A narrower (4 km wide; 20 km long) and shallower (maximum depth 70 m) basin forms the western end. Details about the lake and its catchment area can be found in EUROLAKES reports to D5 (WP30), D12 (WP14) and D2 (WP23).

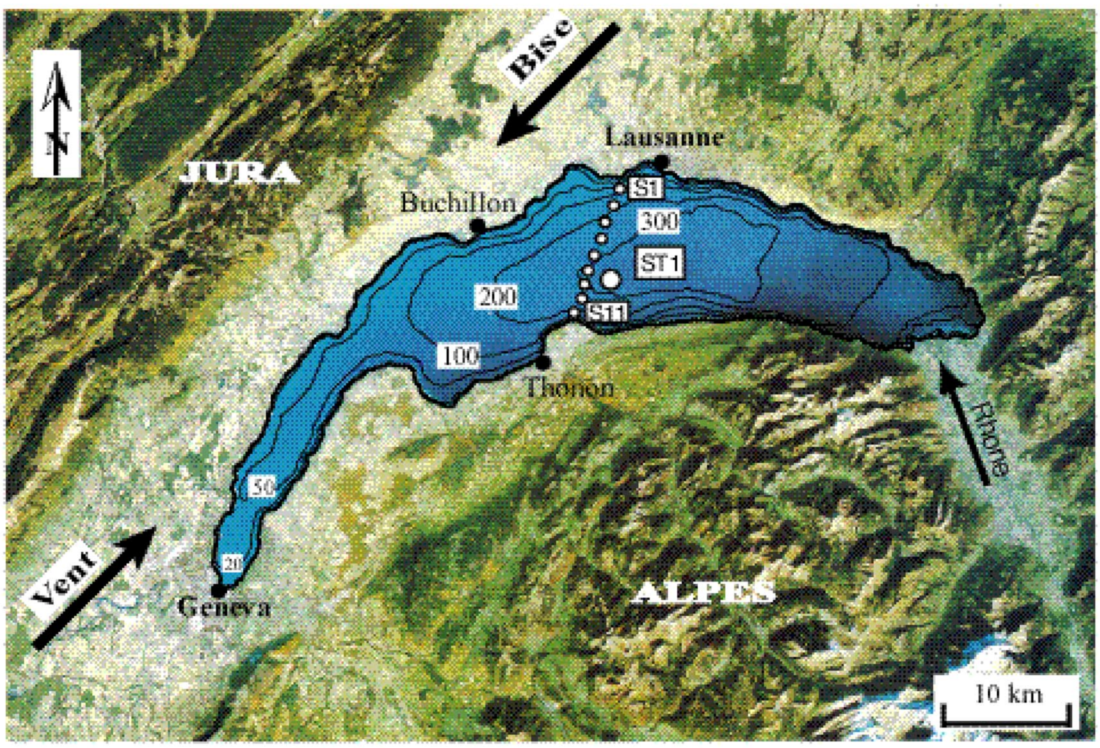

Fig. 4.1: The Lake of Geneva with depth contours relative to surface level. The directions of the most important winds (Bise and Vent) have been indicated. Mooring stations marked on the lake are referred to in the text.

Over the past twenty years the hydraulics laboratory (LRH) at the EPFL has carried out field measurements of water mass movements and water temperature in the Lake of Geneva by the Eulerian method. Water mass movements have been characterized by horizontal current speeds and current directions obtained from moored autonomous instruments. In most cases these instruments also recorded water temperatures. Instruments were placed in different parts of the lake, at several depths and during all seasons. Temperature profiles taken at about one month intervals over several years provide stratification information. An overview of the resultant current and stratification patterns can be found in Lemmin (1998). Large scale wind fields produce first and third mode internal seiches during the stratification period. Due to the curl of the diurnal wind field a direct circulation is initiated in the upper part of the water column.

Monthly temperature profiles and profiles of certain chemical and biological parameters have been taken in the center of the deep basin and in the center of the shallow Petit Lac basin by the Commission International pour la Protection des Eaux du Léman (CIPEL) over the past forty years.

4.2 DERIVING RESIDENCE TIMES FOR LAC LÉMAN

4.2.1 Analysis of field data

The Lake of Geneva has a mean water renewal time of about 12 years. This time period is often considered as theoretical residence time. The concept of "realistic" residence times has been applied to the Lake of Geneva by Meybeck et al. (1970) who called it dynamic residence time. According to tritium surveys carried out during the 1960s, Meybeck et al. (1970) and Huber (1972) estimated that the water residence time in the Lake of Geneva varies between 2 years for the surface waters (0-50m) and about 20 years for the deep waters (200-309m). The top layer is exposed to atmospheric forcing, particularly wind mixing. River plumes also discharge a surface branch into this layer. The deep layer is sheltered from surface forcing. Turbidity currents may discharge directly into the deep layer. Meybeck et al, (1970) observed an intermediate layer (50 to 200m) close to the river inflow areas. Particle laden river plumes which they followed for distances of several kilometers can be found in this layer.

However, Meybeck et al. (1991) gave evidence that intrusions of oxygen-rich waters may penetrate from the surface into the near bottom layers. Over a period of 10 years they observe frequent penetrations which may modify the near bottom oxygen profile for extended periods of time. These water inputs do not represent important volumes (≤ 1% of the lake volume). However, when occurring at the sediment water interface, they ensure a sufficiently high oxygen level to prevent diffusion of phosphate and ammonia from the pore waters. They may therefore strongly modify the characteristics of a water mass without significantly changing the residence time. Since they bring water of a different water age to these layers they may alter the concentration of tracers such as tritium. This will affect the residence time determined by these tracers. Loiseau (1999, personal communication) had pointed out that more recent ^3H-^3He measurements gave a mean age of 6 years for the deep layers which was four years younger than the last complete overturn at the time of measurement. This indicates that due to "leakage," water age measurements cannot correctly determine residence times if hydrodynamics processes are not incorporated in the analysis.

Studies of water mass displacement in different parts of the lake and in different depth layers have indicated that residual currents and internal seiches are important contributors to lake hydrodynamics in Lake Geneva. River plumes, particularly from the

Rhone river may affect certain parts of the lake. These processes have been detailed in the reports for WP4, 6, 7 and 8. In the present report we will summarize some aspects of lake hydrodynamics which may be relevant to residence time concepts.

4.2.1.1 Dynamics during summer stratification

In this section two examples will be presented. The first is representative for the currents on the lateral slope in the upper layers. The second gives some indication of deepwater dynamics.

4.2.1.1.1 Lateral slope currents

An RDI current profiler was moored at Ouchy (near station S1 in Fig. 4.1) on the northern slope of Lake Geneva. The instrument was placed in 100 m depth and recorded current profiles every 10 min in fifty 2m thick bins across the total water column. Recording started on 10 July 2001 and stopped on 5 October 2001. During this period of the year the lake is stratified with a thermocline at around 20 m depth moving somewhat downward from September onwards. Progressive vector diagrams were calculated and some of the curves are plotted in Fig. 4.2. Three different layers can be distinguished in this observation.

In the upper layer between 13 m and 23 m one observes a typical shear layer profile with trajectory length and thus current speed progressively decreasing with depth. Current trajectories in this layer are almost parallel to the local coastline. The predominant direction in this layer is towards the Northwest with a current reversal at all depths towards the end of the recording period. This pattern is typical for observations we have previously made along the northern slope.

Below this layer there is a second layer from 27 m to 43 m depth in which the current trajectories are again parallel to the local shoreline but in which the direction is opposite to the top layer during the whole recording period of three months. Note the 180° change in direction from 23 m to 27 m depth. This is the layer just below the thermocline. The three trajectories in this layer are almost equal in length indicating that the water masses in this nearly 20 m thick layer move homogeneously. However, the trajectories are significantly shorter than in the top layer. A reversal pattern similar to the one observed in the top layer is present again.

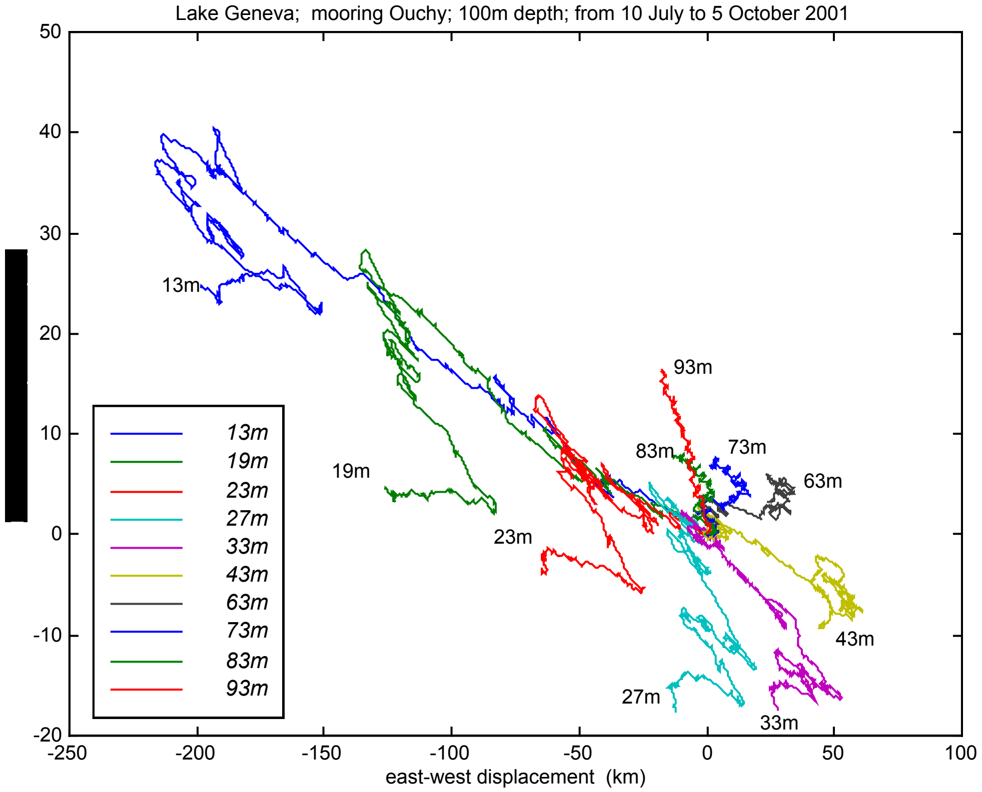

Fig. 4.2: Progressive vector diagram obtained for selected depths from current profiler measurements at Ouchy near station S1 (see Fig. 4.1)

In the bottom layer below 43 m depth the mean trajectory direction is almost onshore and trajectories are rather short indicating low current speeds. Superimposed on the mean direction is a fairly regular undulating pattern with a period of about 12 h.

4.2.1.1.1.1 Deep water dynamics

Several measurement campaigns have been carried out in the deep waters of the big lake basin. We will first analyze recent measurements in 2001 and 2002 at station ST1 and afterwards present some results from a cross section study from S1 to S11 (see Fig. 4.1 for station locations). The 2001/2002 data were recorded with a multiparameter Aanderaa RCM 9 current meter. Recording was started on 6 July 2001 and stopped on 12 October 2001. The recording interval was 10min.

Spectral analysis

Inspection of the original data indicated that current direction is dominated by oscillations on time scales of about 100h and 12h which were accompanied with significant changes in oxygen concentration. In order to better understand the dynamics of these oscillations, standard FFT spectral analysis was performed. For this purpose the current data were decomposed into a northward and an eastward component. These two orientations roughly align with the shore and the cross shore direction at this location (see Fig. 4.1). Spectra for the current components are shown in Fig. 4.3.

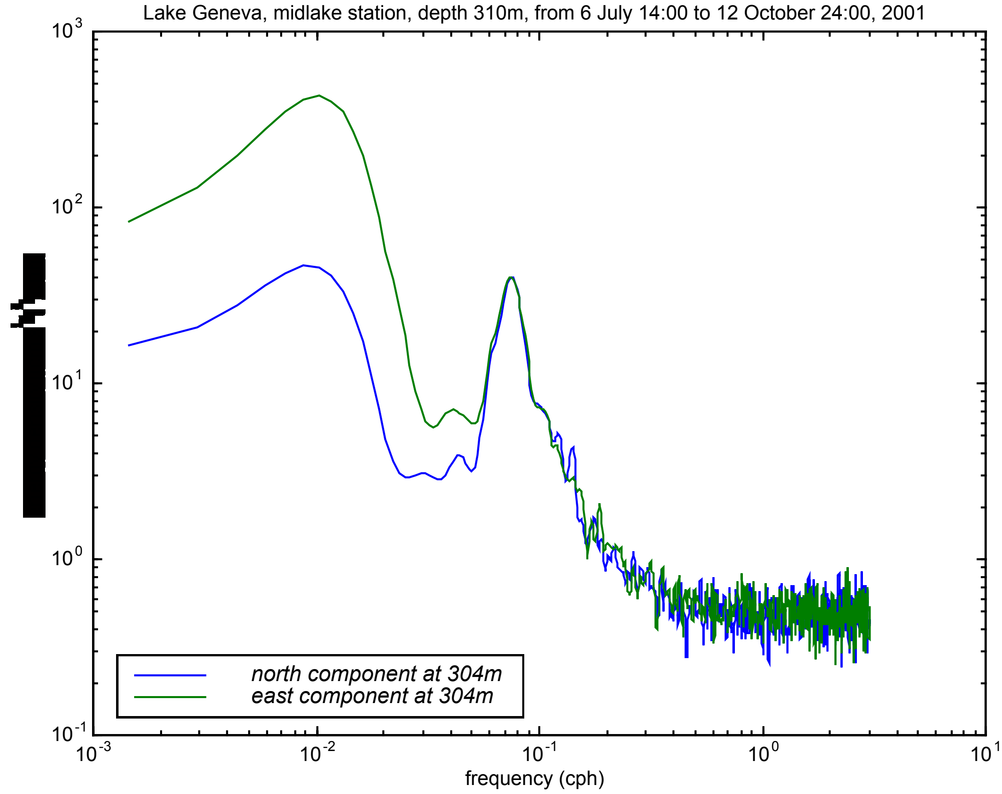

Fig. 4.3: Spectra of the north and east components during summer 2001

Peaks at two different frequencies mark the spectra: A broad low frequency peak corresponding to about 95 to 100 hours and a narrower peak at a frequency corresponding to about 12 hours. For the low frequency peak there is clearly more energy in the east component which is almost aligned with the long lake axis while the energy content of the two components is equal at the high frequency peak. This indicates two different types of motion. To further elucidate this pattern, cross-spectral analysis between the two velocity components was carried out. As expected, the cross spectrum peaks again at the same two frequencies. The phase angle at the low frequency peak is at + 60° while the one for the high frequency has an angle of – 90°. The high frequency peak relates to a clockwise moving pattern and at this frequency the most likely candidate for such a pattern is a Poincaré wave. The low frequency peak relates to a anticlockwise rotating wave for which we have no candidate yet. The period is too long for a Kelvin wave and a Kelvin wave should not be felt so strongly so far off the shore.

Progressive vector analysis

Progressive vector analysis was carried out for current components in order to better understand the pattern described above. Fig 4.4 shows the vector diagram for the full record. This is a predominantly eastward oriented transport and the maximum running length over the four months recording period is about twice that of the east-west length of the central bottom plateau. However, there are many intermediate sections when transport is in the westward direction. From the time markers it is obvious that there are periods of strong transport alternating with periods of relatively slow transport as would be expected during summer stratification with long quiet periods between events of wind. This pattern indicates that water masses in the deep part of the lake are displaced over significant distances during summer stratification when the deep waters are often considered stagnant.

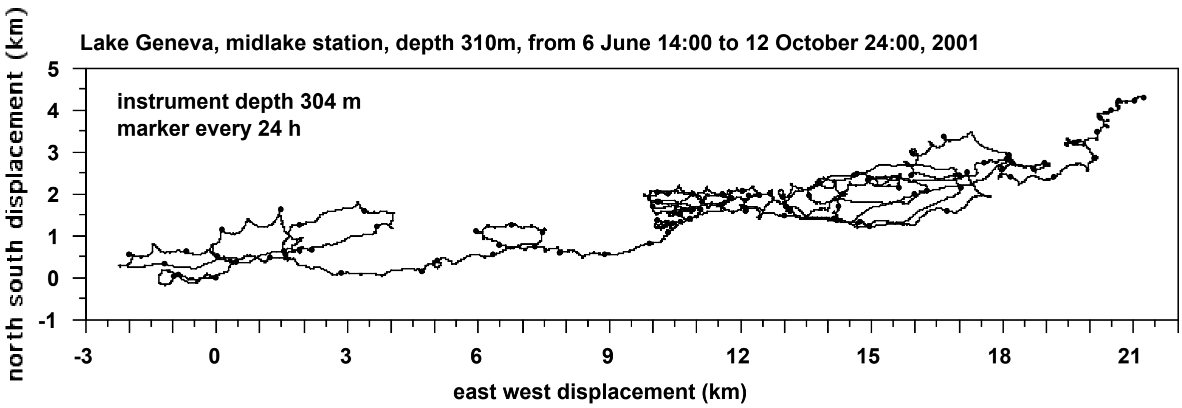

Fig. 4.4: Progressive vector diagram.

Frequently there are undulating sections in the progressive vector curve with two waves occurring between two 24 h markers. This obviously reflects the 12 hour period oscillation clearly seen in the analysis above. The cusped motion pattern is evidently a superposition of a circular motion with a linear motion having a mean speed which is greater than the rotating vector. Circular motions with periods close to 12 hours are always executed in a clockwise sense of rotation (details will be shown for the winter data below). This is typical for Poincaré waves which are the tenth mode of a standing wave pattern in Lake Geneva and the first transversal mode which turns clockwise.

4.2.1.1.1.2 Winter period (weak stratification)

During winter 2002 the RCM 9 instrument at 304m and a second RCM 9 at 299 m were placed at St1 at 310 m water depth (see Fig. 4.1 for station location) from 21 January to 17 April 2002. About a week after starting the recording a Seabird temperature node with a resolution of 1 mK was added in order to be able to determine whether deepwater renewal takes place, how it happens and how it can be characterized. All instruments were synchronized and recorded at a 20 min interval.

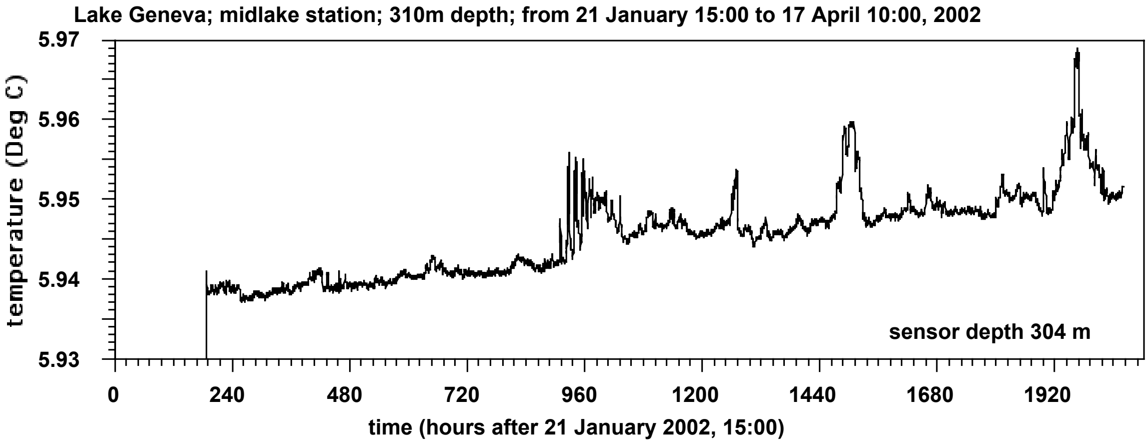

Fig. 4.5: Temperature timeseries at the bottom at midlake station

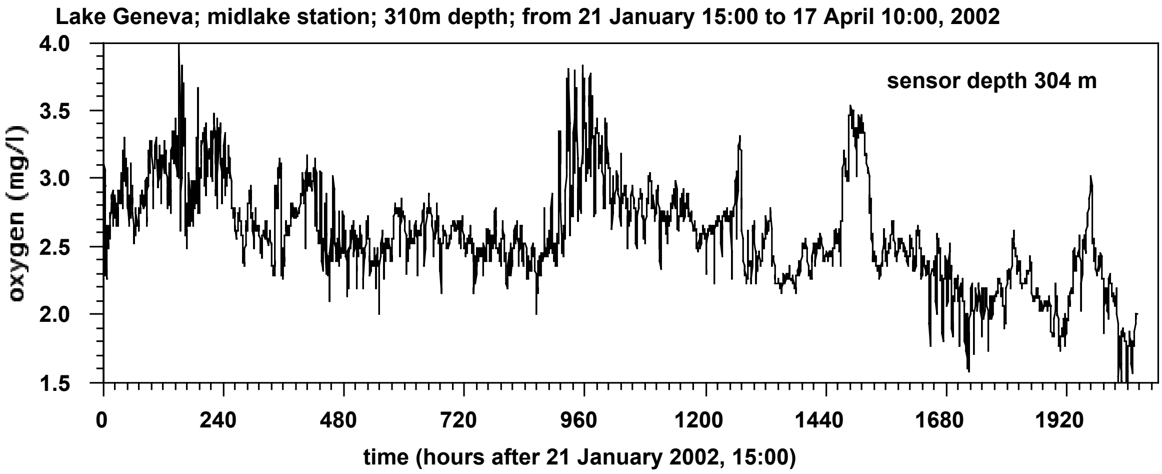

Fig. 4.6: Timeseries of oxygen content near the bottom at midlake station.

Temperature profiles taken during this period show that a stratification remained in the water column at all times, indicating that deepwater renewal through vertical processes was unlikely. From Fig. 4.5 which shows the timeseries of the temperature recording, it is evident that deep water renewal did not take place, at least not in the classical sense where a drop of temperature is recorded which indicates a cooling and thus the water renewal. Instead, during the recording period the temperature increased permanently and almost linearly, only interrupted by several short events of higher temperature. During these events, water from layers higher up must have been forced into the lake bottom boundary layer.

The oxygen content during this period is shown in Fig. 4.6. The sensor was checked after recovery and found to be within 10% of the reading before deployment. We compared our oxygen level with spot measurements by the CIPEL on the central plateau.

CIPEL oxygen content in this layer for two cases is about 0.6 mg/l higher than ours. We therefore consider that our data are representative and reliable.

Overall, oxygen shows a decreasing trend which is opposite to that of the temperature. Deepwater renewal should be marked by a strong and permanent increase in oxygen content and this cannot be seen in our data. The events of increased temperature in Fig. 4.5 can directly be related to events of increased oxygen content in Fig. 4.6. One may infer from this correlation that warm, oxygen rich water has been brought into the bottom layer. This could only have happened through transport because such strong gradients cannot be maintained by turbulent mixing. Furthermore the oxygen and the temperature levels fall back to those before the events and again, that cannot be the result of mixing. The current structure during these events does not show any particular pattern. Each time currents are from the NE and are about 3 to 4 cms^{-1}. This pattern closely resembles the one of intrusions of oxygen-rich waters which may penetrate from the surface into the near bottom layers described by Meybeck et al. (1991).

Spectral analysis

The same analysis as for the summer situation has been repeated. Spectra of the two current components are given in Fig. 4.7. In this case we treated the data from both current meters. Compared to the summer spectra (Fig. 4.3) the low frequency peak is not significant.

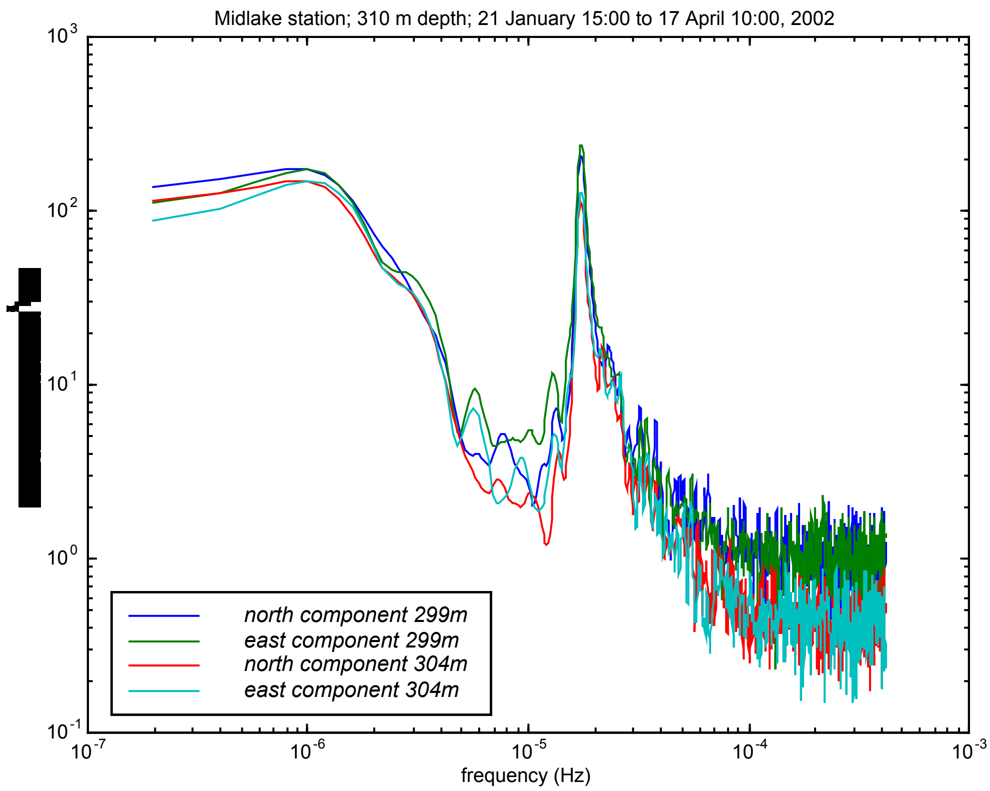

Fig. 4.7: Spectra of the north and east components during winter 2002.

The results are identical to those observed during the summer period. A low frequency hump which is less obvious in the data than during the summer is seen at the same frequency range as in the summer and the phase angle is identical to the summer situation. However, the high frequency peak is even more pronounced than during the summer period. Once again the energy content of the two components at both instruments are identical. The peak is situated at a slightly lower frequency than during the summer which corresponds to a period close to 17 h. This is close to the inertial period for the Lake of Geneva (17.43h). For the high frequency peak we find the coherence and a phase angle of –90° as during the summer situation. From this analysis it can be concluded that the Poincaré wave is again present during the winter situation and it is the dominant feature of the current field. The overall dynamics has not changed because the stratification was not sufficiently weakened to provoke a different deepwater pattern.

Progressive vector analysis

The same analysis as for the summer situation was carried out. In this case again both instruments have been included in the analysis. The pattern shown in Fig. 4.8 reveals that the current structure is similar to that of the summer situation. However, the mean transport direction is towards the SW during this period. The total transport distance is almost twice that observed during the summer even though the duration of the recording is only three months compared to four months during the summer. Thus mean transport is more active during this winter campaign.

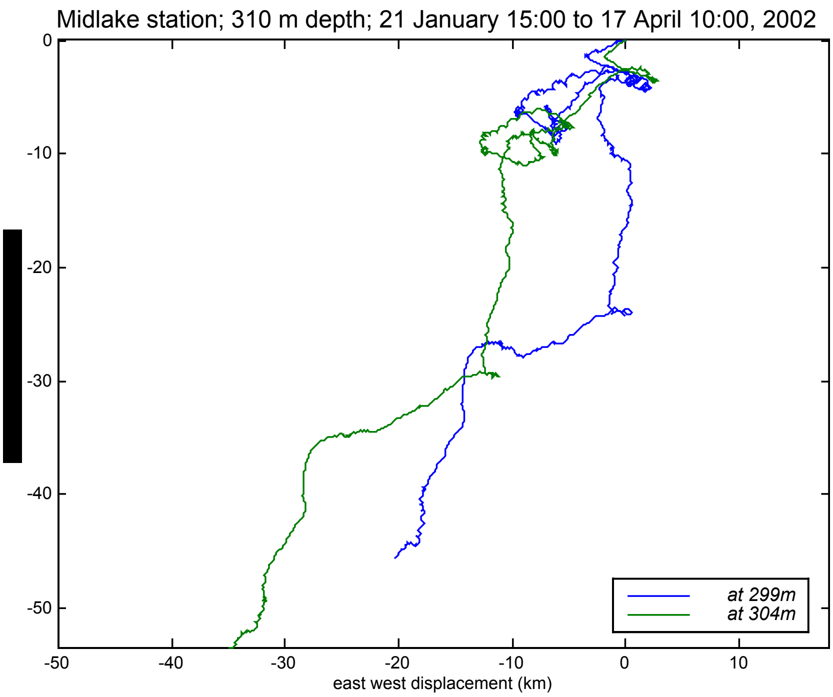

Fig. 4.8: Progressive vector diagram for the winter 2002 recording

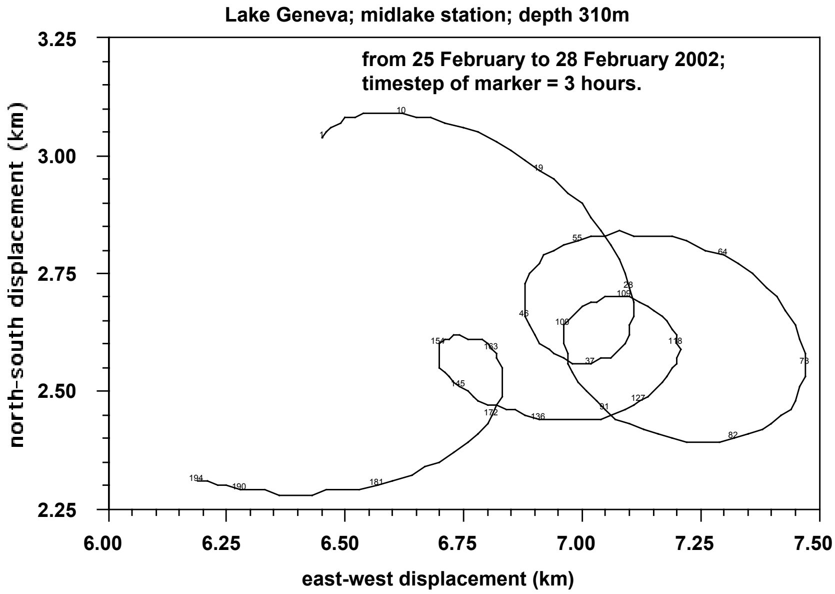

Fig. 4.9: Progressive vector diagram for 25 to 28 Feb. 2002; excerpt of Fig. 4.8.

In order to test for the internal seiche structure of the current pattern, a section of Fig. 4.8 was replotted in Fig. 4.9 providing greater detail. The clockwise rotation pattern is similar to that of the summer 2001. Thus further evidence for Poincaré waves is provided.

In order to investigate whether the change in trajectory direction during winter is of significance, we plotted a vector diagram from data recorded during the winter 1985/86 at 300m depth. These were recorded at stations S6 (for station location see Fig. 4.1) between middle of October and middle of February. However, the currents were measured with Aanderaa RCM 7 rotor current meters. They have a threshold speed of 2.5 cm/s. Nevertheless, results indicate that during that year the orientation of the currents is in the same quadrant.The mean direction of the total record from October to March falls again into the same quadrant. It has to be remembered that the vane of the RCM7 instrument is more sensitive than the rotor and therefore this information has great significance.

It may be asked whether this orientation of the deep currents can be explained by a general current pattern. Once again, 3-D modelling may have to be carried out to help answer this question. However, some answers may already be obtained from previous work. During the same winter 1985/86 we have also recorded with the same RCM7 instruments the currents at 11 stations nearly equally spaced across the lake from the north shore (station S1) to the south shore (station S11; see Fig. 4.1 for station location). Stations S1 and S11 are placed about 1 km from shore. At all stations the instrument was moored at a 12m depth. These records have been reanalyzed in the context of the present study and the results are presented in Fig. 4.10.

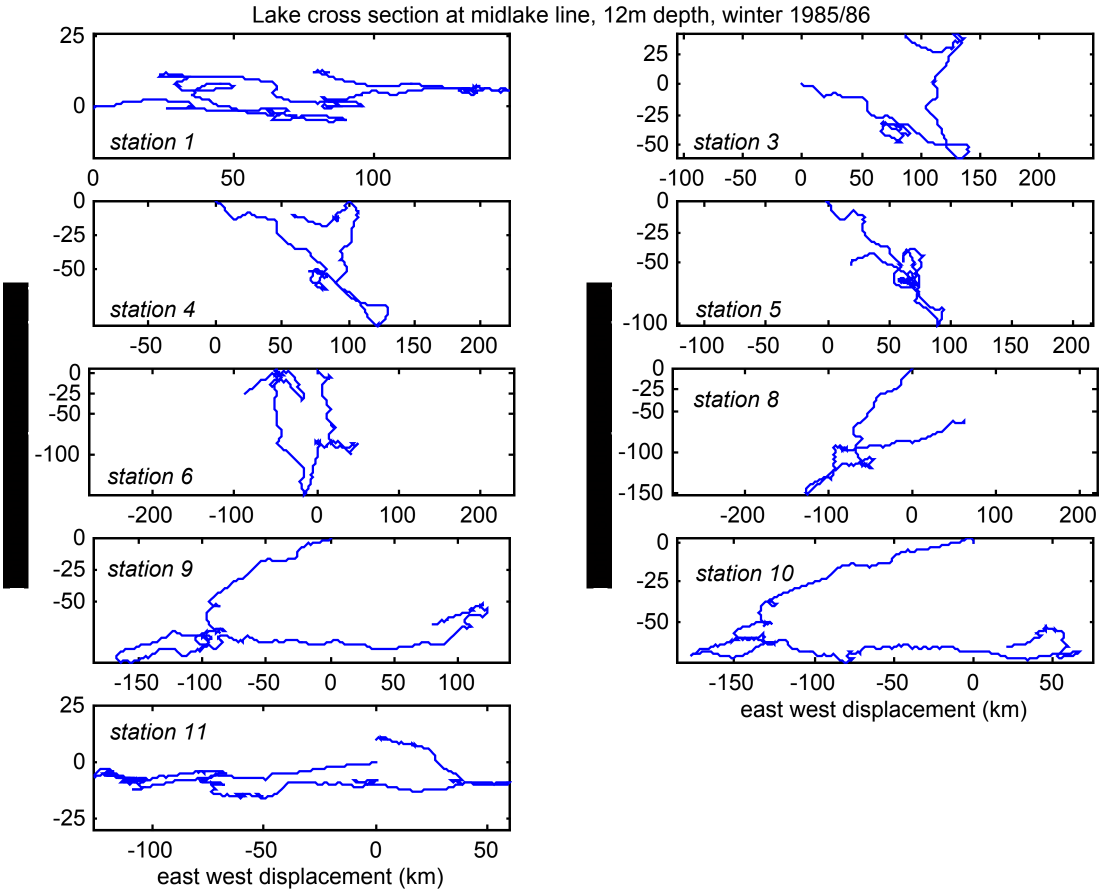

Fig. 4.10: Progressive vector diagrams for the winter period 1985/86 from middle of October to the beginning of March at stations S1 to S11 (see Fig. 4.1 for station location) at 12 m water depth.

One observes that in the near shore region the currents are parallel to the shore on both sides of the lake. With increasing distance from shore the orientation of the trajectories turns and becomes cross-shore in the center of the lake at station S6. It should be noted that during a period of 2.5 months the cross lake transport in the center of the basin is about ten times the lake width in that area. It can also be seen that the current directions are rather steady over extended periods of time. Furthermore, a reversal of the current orientation occurs and is found at all stations. Near-shore the trajectory orientation for the two directions nearly coincides. Further offshore a slight difference in the reversed angle is seen. Nevertheless the close resemblance of the pattern in the two directions is rather striking. It indicates that a large scale gyre current pattern is established in the center of the lake. This pattern is reversed, but at present the cause of the reversal cannot be identified. A simple, steady state, non stratified solution of the depth integrate transport equations from a numerical model predicts a two gyre pattern for the Grand Lac basin. From the above observations a gyre structure can be inferred. The mean current pattern resulting from current measurements in the upper 20 m of the water column carried out over the past 20 years further indicates that a gyre circulation in the eastern part of the Grand Lac basin is likely during late summer stratification (Lemmin and D'Adamo, 1996).

Longterm mean trajectories

River plumes provide for important water masses. Their displacement within the lake may strongly influence the residence times in certain subvolumes of the lake. When a river enters a lake there is usually a density difference between the inflowing water and the ambient water body. If the inflow is less dense than the surface water, it forms a surface buoyant overflow. Conversely, when the inflow is heavier than the surface waters, it plunges to form an underflow along the bottom boundary. In a stratified water body, an underflow may reach a level of neutral buoyancy where it separates from the bottom and intrudes horizontally.

As pointed out in the report for WP8, the thermocline is the layer in which interflows will most likely settle for a typical density structure in Lake Geneva. They are regularly observed during all seasons. Interflows resulting from the Rhone river plume and their effects have been investigated by several researchers over the past decades.

Little is known about the homogeneous and the plunge regions where the Rhone river enters the lake. The dynamics of these regions appear to be important for the formation of the interflow. However, since discharge and sediment load conditions have recently become unfavourable for underflow formation it can be expected that Rhone river interflows will become more frequent. The finer particle sizes carried with interflows will be redistributed over a larger portion of the lake than sediment loads from underflows. Finer particles also have larger surface to volume ratio and may percentagewise retain more pollutants.

Due to the Coriolis force the longterm mean of the Rhone river plume interflows are deflected towards the northern shore of the lake. Analysis of sediment samples confirms the long term integral effect of the passing interflows by a strong accumulation of pollutants originating from the Rhone river. These are the shallower regions of the lake where wind induced currents and currents related to Kelvin waves (see the Lake Geneva report in WP7) may cause occasional sediment resuspension. These are also the zones in which drinking water intakes are placed producing a certain risk that these pollutants may enter the drinking water either on the downward passage of particle settling or by resuspension.

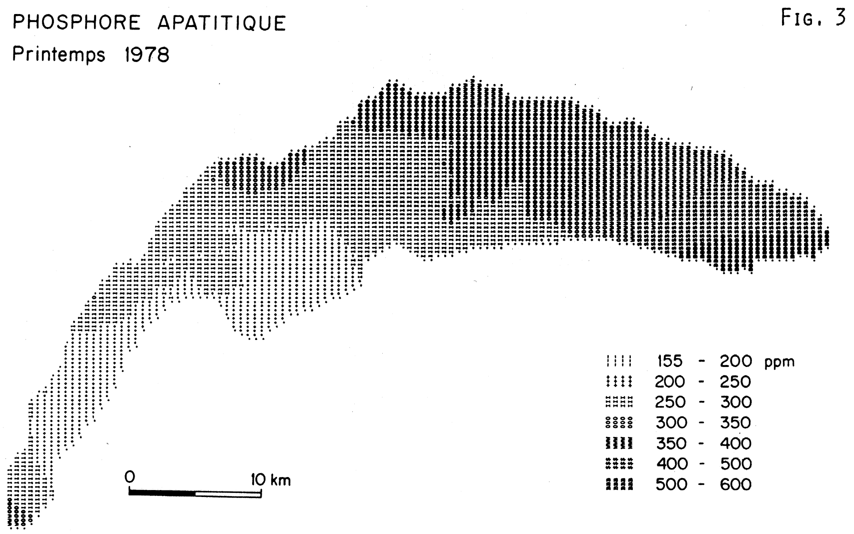

Fig. 4.11: Distribution of apatitique phosphorus in the lake sediments in the spring of 1978 (from Jaquet, 1979). The source for apatitique phosphorus is the Rhone river entering in the SE of the basin (see Fig. 4.1). Note the distribution which resembles the interflow spreading of the Rhone river plume.

4.2.1.2 Conclusions for the field data analysis

In the field data analysis we have presented some examples of water mass trajectories in different parts of the Grand Lac basin. A pattern of water mass displacement can be derived from these observations.

In the near shore zone (Fig. 4.2 and stations S1 and S11 in Fig. 4.10) transport is mainly parallel to the shore and a shear layer profile can be expected. Summer stratification causes the water masses directly below the thermocline to move in the opposite direction. This is the first time we have documented this pattern and further investigations are needed to explain this pattern. The understanding of the hydrodynamics of this pattern may be important with respect to pollutant laden particle settling through the water column.

In the upper epilimnion (Fig. 4.10) in the center of the Grand Lac basin we observe a trajectory pattern in which outside the near shore zone the current direction tends progressively cross lake with increasing distance from shore. At all stations trajectory lengths are nearly equal and reversals occur simultaneously. This pattern indicates that in the upper layer a strong water mass exchange takes place between the off shore and the near shore zones. Over a period of less than three months water mass displacement in the center is about ten times the width of the basin. While no residence times can be estimated from these observations it appears that significant exchange between the two zones occurs on time scales of weeks. Less detailed observations from other years confirm this pattern.

The water masses in the deepwater layer are not exposed to direct wind forcing. Compared to the progressive vector patterns in the upper layer (Figs. 2 and 10), trajectories are much shorter indicating that water mass displacement is considerably less in this layer. Trajectories are dominated by motion patterns resulting from internal seiches set in motion by the wind forcing at the surface.

In the deep layers currents are slow and turbulence is low. This will limit the contribution to homogenization within the water mass by turbulent mixing. However, due to the important contribution by Poincaré waves, looping motions are omnipresent in this water mass (Fig. 4.9). Even though they cannot cause mixing they can much contribute to homogenization within the deepwater body.

Our measurements confirm the observations by Meybeck et al. (1991) of intrusion penetrating into the deep layers. As was indicated by these authors these water inputs do not represent important volumes (≤ 1% of the lake volume). However, when occurring at the sediment water interface, they ensure a sufficiently high oxygen level to prevent diffusion of phosphate and ammonia from the pore waters. They may therefore strongly modify the characteristics of a water mass without significantly changing the residence time.

It is obvious that water mass exchange occurs between the near shore zone, the epilimnion and the deepwater layers. The trajectories shown here indicate that this exchange may be in the order of weeks to months in the near shore zone and the epilimnion, and of months in the deepwater layers. Assuming that the three different water bodies have different ecological characteristics, it can be expected that the exchange processes will provide for significant modifications of the residence time in the different zones. This may explain why Loiseau (1999, personal communication) had observed that ^{3}H-^{3}He measurements gave a mean age of 6 years for the deep layers which was four years younger than the last complete overturn at the time of measurement.

4.2.2 Analysis of numerical modelling: modelling of residence time and flushing of the Petit Lac

The concepts of *residence time* and *water age* have been discussed to a great extent in the literature. They have experienced some recent revival. In almost all cases, authors acknowledged that the definitions of *residence time* and *water age*, and their quantitative evaluation in a particular case, require an idea of the physical processes involved. Moreover, it has frequently been remarked that a precise definition of the boundary of the investigated water body is helpful for both, definition and evaluation, even though this is evidently not a strict prerequisite for the applicability of these concepts (see Wunsch, 2002).

In order to make the ideas of *residence time* and *water age* useful at all in an ecological context a water body should have some properties contrasting it from its environment. These properties can be physical quantities such as temperature or salinity, but also significant biological and chemical variables such as the concentration of chlorophyll-a, oxygen, and phosphorus.

An interesting example of such a water body is the Petit Lac, the smaller southwestern sub-basin of Lake Geneva (Fig. 4.1). This basin has well-defined boundaries and only a relatively narrow connection with the main basin of Lake Geneva. Its physical and chemical properties are somewhat different from the main basin during all seasons. In addition, several important drinking water intakes are situated near the shore of the Petit Lac, making the investigation of water renewal in this region of Lake Geneva particularly interesting.

It is evident from the outset that the residence time of water in (parts of) the Petit Lac should strongly depend on its stratification and the driving wind field. However, the contribution of key processes which determine the exchange of water between the main basin and the Petit Lac is not yet quantified. These processes, and their relationship to water renewal in the Petit Lac, will be addressed in the following.

From the numerous cases that could be investigated, we chose, as examples, two scenarios with typical summer stratification and idealized (i.e. constant and spatially homogeneous) wind fields corresponding to the typical winds ‘Vent’ and ‘Bise’, blowing from SW and NE, respectively. Due to the flat ambient topography and the channeling by the higher mountains these idealized wind fields are not very far form the true wind fields. The momentum flux caused by these winds was chosen to be 0.05 Nm^{-2}, roughly corresponding to a wind speed of 5 m/s. It was set to zero after 24 hours in each case. As shown below, the horizontal currents induced by long internal waves dominate the exchange between the two basins. The excitation of these waves does not strongly depend on details of the wind field, and we believe that even with the idealized winds, the essential physics of the exchange process can be described.

The initial temperature profile at all locations in the lake corresponds to that shown in Fig. 4.12, which has been measured in July 1982 and is typical for this season (CIPEL, 2001).

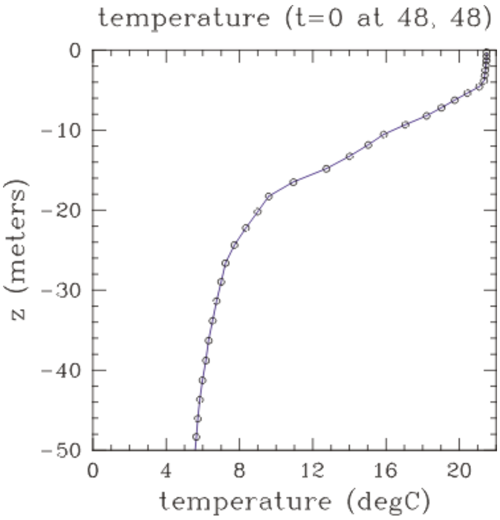

Fig. 4.12: Initial temperature profile for all runs.

In this study, we only consider the residence time and the fate of water masses in the epilimnion of the Petit Lac. The residence of water in this layer of the lake is most likely of greater relevance for ecological indicators than an average residence time computed for the whole Petit Lac because the largest part of planktonic and microbial species are living above the thermocline. As a working hypothesis, we define epilimnetic water as the water mass with a temperature greater than 10 degrees Celsius. Clearly, this choice is somewhat arbitrary, but due to the strong temperature gradient in the thermocline (see Fig. 4.12), it would not have made a great difference if some neighboring value had been used. The so-defined epilimnetic water in the Petit Lac was marked with a passive tracer of concentration 1. The horizontal boundaries of the marked region are visible from Fig. 4.13. Starting from these initial conditions we subsequently investigated the cases of 'Vent' and 'Bise' wind fields.

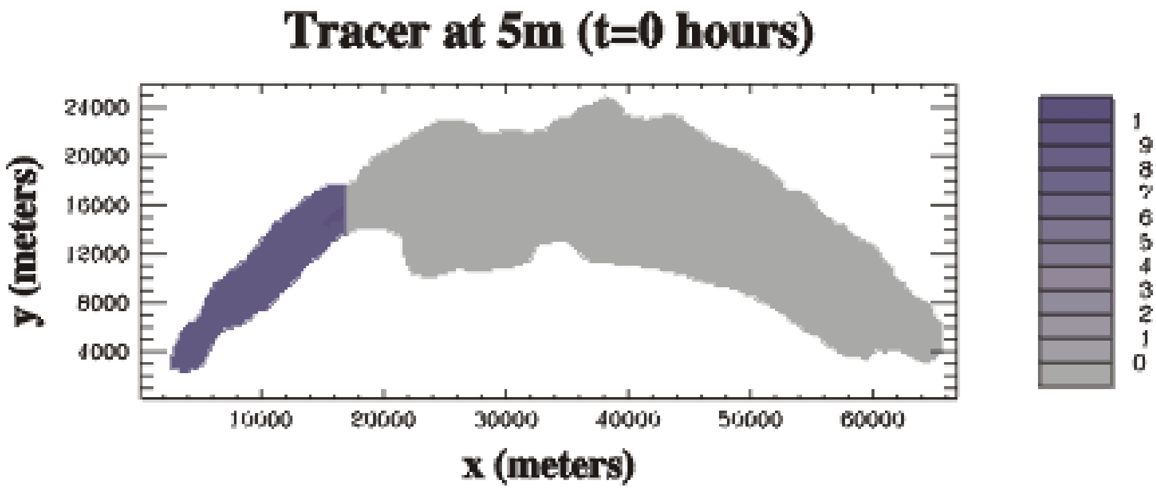

Fig. 4.13: Horizontally homogeneous initial distribution of tracer in the Petit Lac. Only epilimnetic water (with T > 10 ºC) has been marked. Note, that in this and all following plots, the topography of Lake Geneva has been turned by 17 degrees clockwise.

4.2.2.1 The 'Vent' case

The mechanisms of the renewal of water in the epilimnion of the Petit Lac in the case of a 'Vent' from SW are best visualized by a horizontal cut through the data at different times. Fig. 4.14 to Fig. 4.16 show the concentration of the tracer at 5 m depth (representative for the epilimnion) 24, 48 and 72 hours after the onset of the 'Vent'. We use these figures to illustrate the key processes determining the residence time of water in the Petit Lac for this particular wind field.

After 24 hours, just at the time when the wind stopped, epilimnetic water has been pushed out of the Petit Lac to form a plume of high concentration in the main basin (Fig. 4.14). Driven by inertia, the outflow continues several hours after the wind has ceased (not shown). At 48 hours (Fig. 4.15), the return flow into the Petit Lac, resulting from the internal horizontal pressure gradient, has started. This return flow is part of the first phase of a basin-wide internal oscillation. However, this oscillation does not simply lead to a reversible in- and outflow of *the same* water which would result into very long residence times in the Petit Lac. In Fig. 4.15 and Fig. 4.16, it is clearly visible that *different* water masses with low tracer concentration originating in the Grand Lac basin replace the epilimnetic water in the Petit Lac, when the return flow becomes strong. The original water from the Petit Lac is rapidly dispersed by large horizontal structures in the main basin. It is obvious that the processes that determine the residence time of water

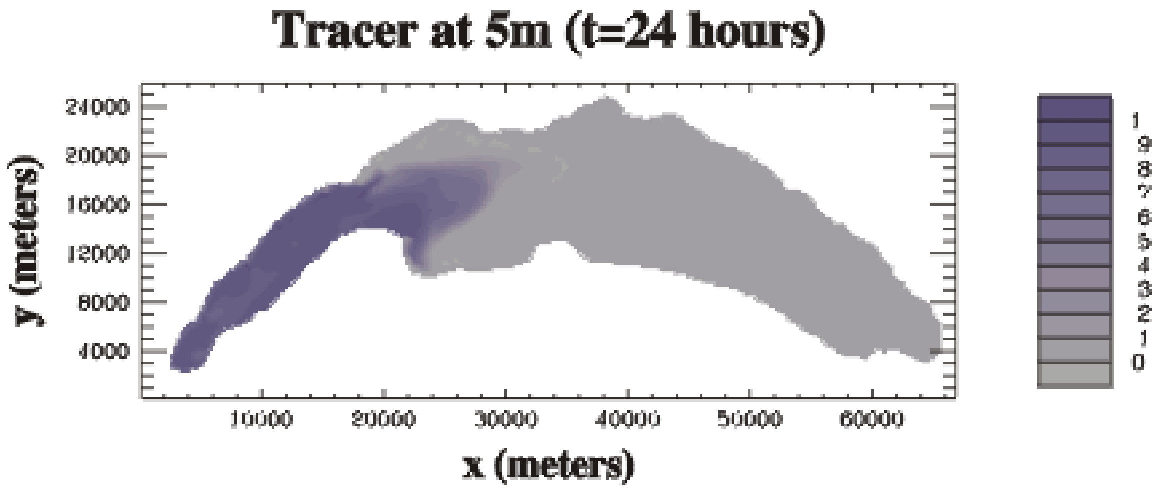

Fig. 4.14: Tracer distribution in 5 m depth after 24 hours for the 'Vent' from SW.

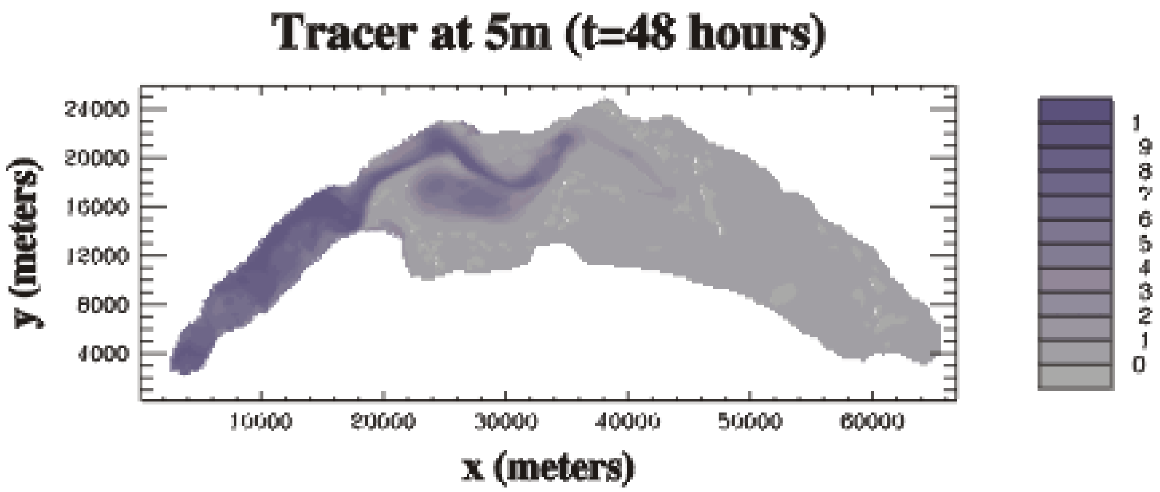

Fig. 4.15: As in Fig. 4.14, but now at 48 hours.

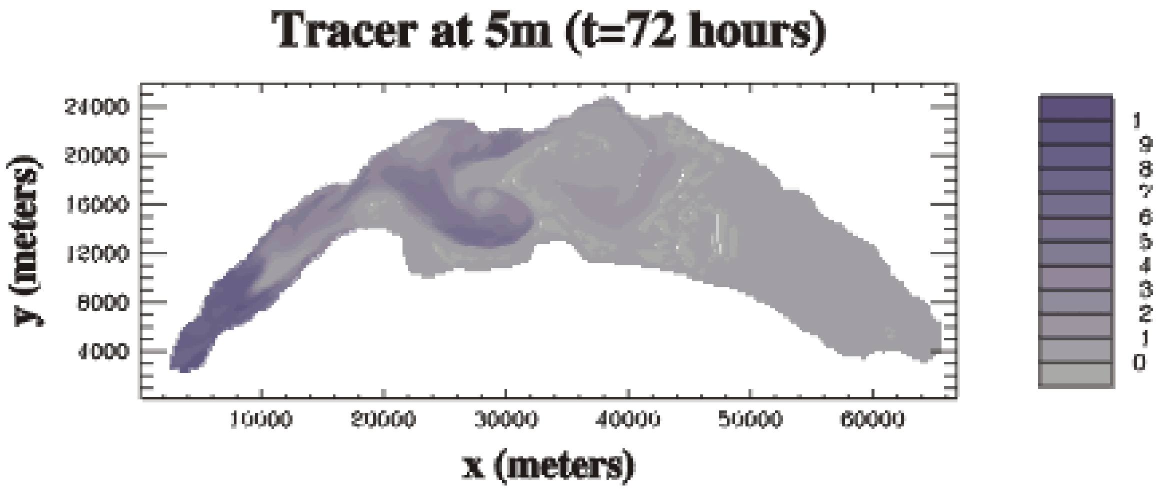

Fig. 4.16: As in Fig. 4.14, but now at 72 hours.

in the Petit Lac are highly non-linear, even when the basin-scale internal waves can be approximately described by linear theory. However, as in outlined our contribution to WP 8, internal waves tend to become non-linear rapidly.

4.2.2.2 The 'Bise' case

The mechanism of tracer dilution in the case of a 'Bise' from the NE is quite different, at least in its initial stages. Fig. 4.17 illustrates that, as expected, this wind field drives fresh water into the Petit Lac. This results in a depression of the thermocline at the western end of the Petit Lac and a downwelling of epilimnetic water with high tracer concentration. Recalling that the epilimnion corresponds to the volume of water warmer than 10 ºC it is noted that at the western end of the Petit Lac it is no longer separated by an approximately horizontal surface from the hypolimnion due to the downwelling. Thus, *horizontal* mixing can play an important role in the exchange of epi- and hypolimnetic water, and this was in fact observed in our simulations: horizontal structures in the hypolimnion entrain water with low tracer concentration into the epilimnion. In addition, vertical straining of "old" epilimnetic water by bottom shear and subsequent vertical mixing in the turbulent bottom boundary layer near the western end of the Petit Lac cause a dilution of the downwelled water from the epilimnion. These effects add up to a lower concentration of the rising water, after the wind has ceased to blow.

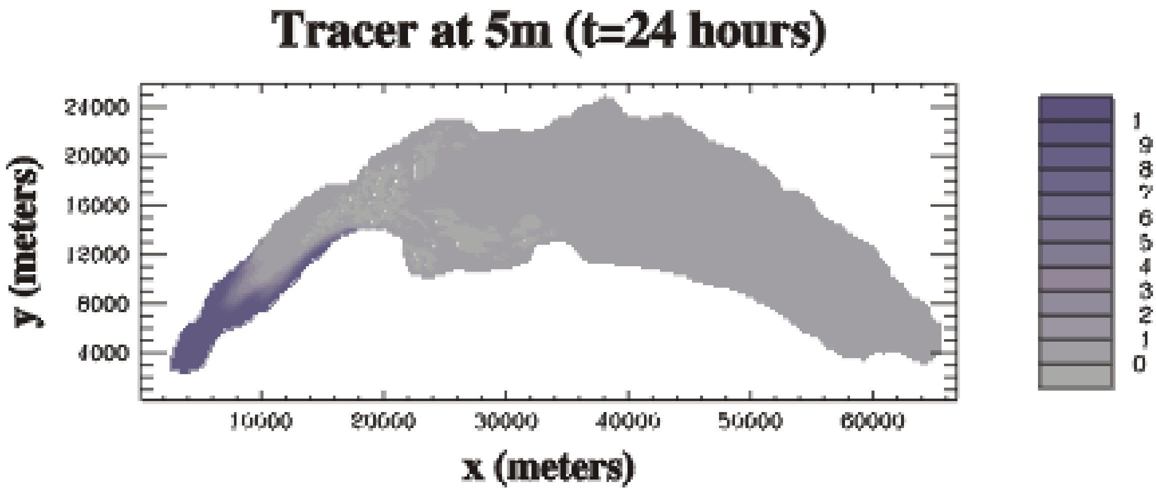

Fig. 4.17: Tracer distribution in 5 m depth after 24 hours for the ‘Bise’ from NE.

Besides this local mixing of epi- and hypolimnetic water occurring at the western end of the Petit Lac, however, there is also a strong contribution of horizontal mixing processes in the epilimnion, as is obvious from Fig. 4.18. After the flow reversal in the Petit Lac, ‘new’ water from the main basin and residual water with high tracer concentration (mainly stemming from boundary layers near the shores) are horizontally mixed by large flow structures. This makes the inflow of fresh water from the first quarter of the internal seiche motion (Fig. 4.17) partly irreversible.

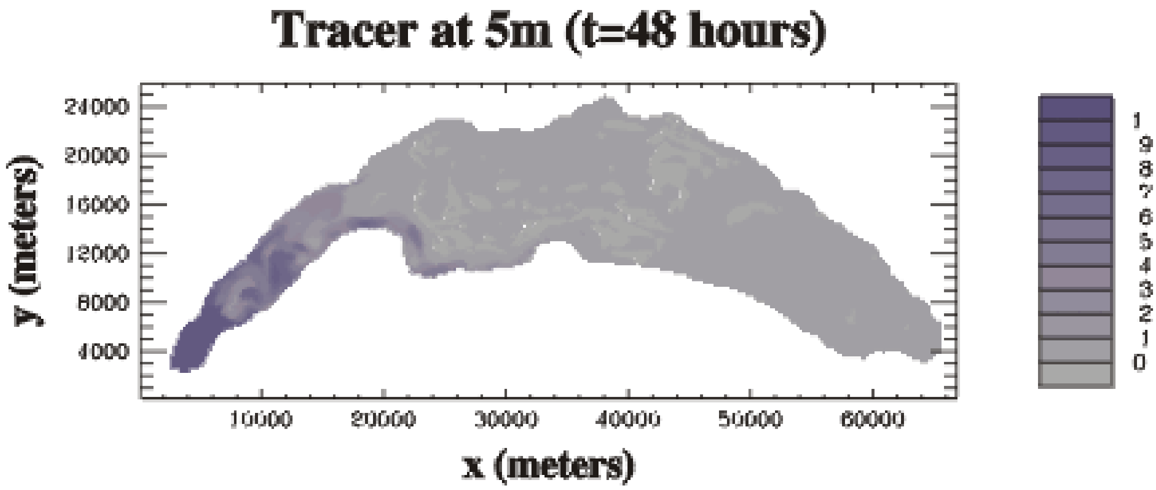

Fig. 4.18. As in Fig. 4.17, but now at 48 hours.

Indeed, water leaving the Petit Lac in the last quarter of the seiching motion results in an effective loss of tracer substance (see below). Fig. 4.19 illustrates that this water enters the main basin and is further dispersed by horizontal structures. Hence, when the second period of the internal wave motion starts, water with very low tracer concentration enters the Petit Lac and leads to a strong reduction of the mean concentration in way very similar to that described already for the ‘Vent’ case.

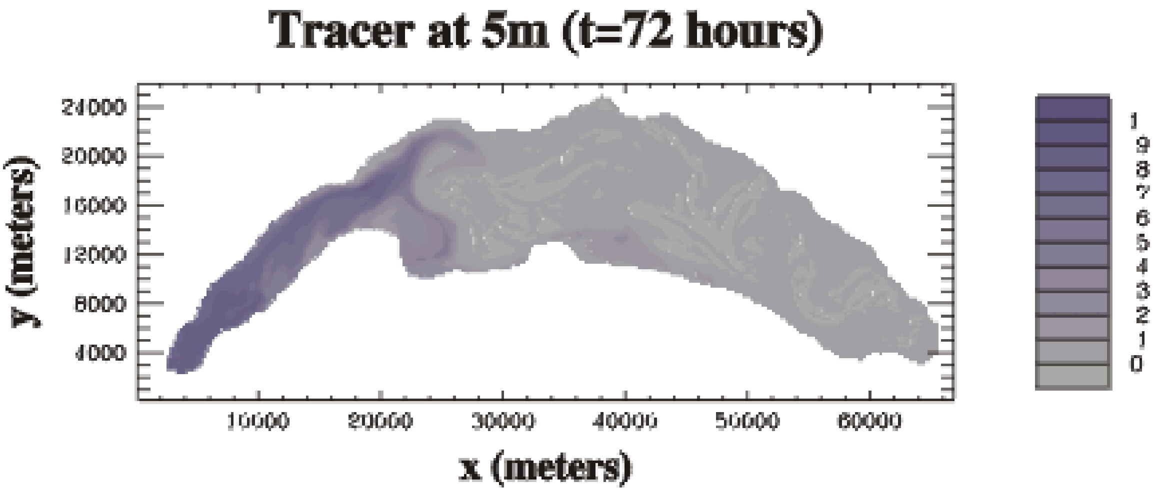

Fig. 4.19: As in Fig. 4.17, but now at 72 hours.

4.2.2.3 Integral budgets from numerical results

In this section, we investigate the time evolution of the total budgets of water and tracer masses in the epilimnion of the Petit Lac. These will be obtained from numerically computed integrals of the water volume and tracer mass contained in the epilimnion of the Petit Lac with its open boundary as suggested in Fig. 4.13. The integral flux of water and tracer masses from the epilimnion of the Petit Lac through its open boundary into the main basin has also been monitored. From the integral budgets typical average residence times for water in the epilimnion of the Petit Lac can be defined.

Keeping in mind the mechanisms described above, the overall budgets of water and tracer mass in the epilimnion of the Petit Lac for the ‘Vent’ and the ‘Bise’ cases, both illustrated in Fig. 4.20 and Fig. 4.21, can easily be interpreted. For the ‘Vent’ case, the outflow of water through the open boundary into the main basin is, to a good approximation, balanced by a reduction of the volume of the epilimnion of the Petit Lac. The reduction in volume is evidently connected to the ascending and tilting motion of the thermocline. The periodic variation of the volume of the epilimnion, as seen in Fig. 4.20, is a strong indicator for the importance of internal oscillations in this process. Note, that the sum of volume deficit and in/outflow yields a value somewhat different from zero. This positive value can only be attributed to an increase of volume of the epilimnion caused by entrainment of hypolimnetic water (with a temperature less than 10°C) by turbulent mixing. The fact that the volume of the epilimnion after one wave cycle is not very different from its initial value does, of course, not imply that *the same* water mass now fills the epilimnion. To what extent ‘old’ water has been replaced by ‘new’ water from the main basin can only be examined by studying the tracer budgets.

The tracer budget for the ‘Vent’ case is displayed in Fig. 4.21. When epilimnetic water is leaving the Petit Lac during the initial period, the budgets for water (Fig. 4.20) and for tracer mass are similar, because water of high tracer concentration is simply advected out of the Petit Lac (see Fig. 4.14).

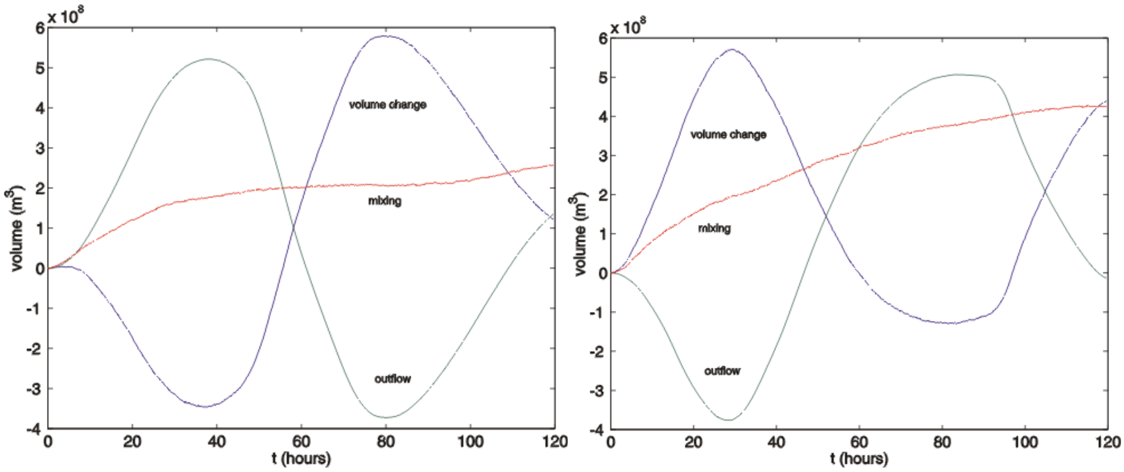

Fig. 4.20: Budgets of water contained in the epilimnion of the Petit Lac for a 'Vent' (left panel) and a 'Bise'. 'Volume change' denotes the difference between the initial and the actual volume of the epilimnion, 'outflow' the time integral of the total flux of water crossing the open boundary of the Petit Lac (outward flux positive), and 'mixing' the difference between the two.

However, as soon as the return flow starts, the total tracer mass in the Petit Lac decreases only slightly because the epilimnetic water is replaced by fresh water from the main basin (also see Figs. 4.15 and 4.16). This simple but efficient mechanism of replacement is similar to *tidal flushing*, playing a major role in the determination of water residence times in estuaries. In the present case, the driving periodic motion is due to internal seiches with periods much longer than the frequently dominant M_2 tide in tidal situations.

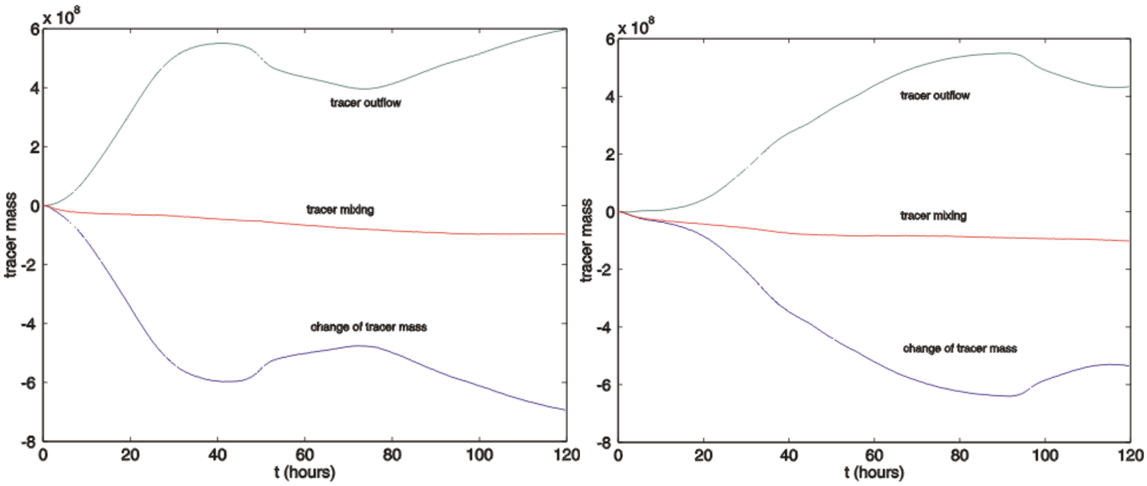

Fig. 4.21: Same as Fig. 4.20, but now for the tracer mass.

Similar to the volume budget, the difference between the outflow of tracer mass from the epilimnion and its total deficit in the epilimnion of the Petit Lac is not exactly zero. In this case, the negative difference indicates that a small amount of tracer is lost from the epilimnion by mixing inside the Petit Lac. This 'detrainment' of tracer, however, is negligible for the overall budget (see Fig. 4.21).

Budgets are somewhat different for the 'Bise' scenario. Fig. 4.20 documents again a strong correlation between the volume deficit of epilimnetic water in the Petit Lac and its outflow. Due to the opposite direction of the wind, the phases of in- and outflow are now reversed. Most remarkable, the contribution of mixing in the Petit Lac is much more important than in the 'Vent' case. This is clearly related to the downwelling and mixing with hypolimnetic water (see above) occurring at the western end of this sub-basin. The amount of cold water entrained from the hypolimnion is comparable with the contribution of in- and outflow (Fig. 4.20). Even though this mechanism cannot change the tracer mass in the epilimnion, evidently it changes its concentration.

This observation is mirrored by the tracer budget for the 'Bise' case shown in Fig. 4.21. Although the wind is blowing during the first 24 hours no tracer enters the Petit Lac, because the tracer concentration in the main basin is zero. However, tracer mass leaves the Petit Lac through the open boundary for most the remaining computation period with water that has been horizontally mixed *inside* the Petit Lac (see also Figs. 4.18 and 4.19).

A small gain of tracer mass can be observed after about 95 hours. This is due to an inflow of water with low tracer concentration from the main basin into the Petit Lac, and is related to the beginning of the second period of the internal seiches oscillation. Mixing of tracer mass from the epilimnion into the hypolimnion inside the Petit Lac does not play a significant role when compared to entrainment of hypolimnetic water (with very low tracer concentration) into the epilimnion.

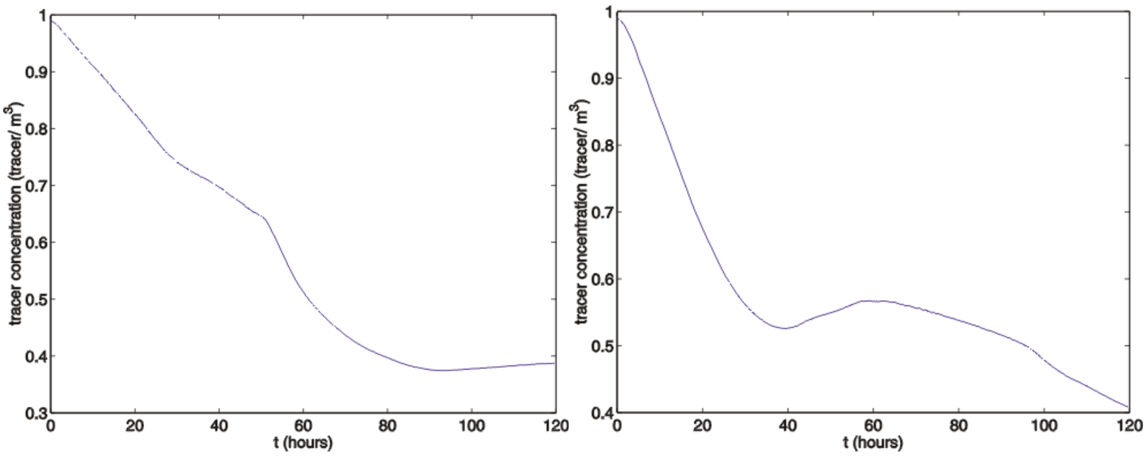

Fig. 4.22: Averaged tracer concentration in the epilimnion of the Petit Lac for the 'Vent' (left) and the 'Bise' (right).

Residence time can be estimated from the mean tracer concentration in the epilimnion of the Petit Lac, depicted for the 'Vent' and the 'Bise' in Fig. 4.22. Even though the processes that lead to a dilution of water are quite different in the two cases, their net effect is very similar. The tracer concentration decays to about 50% of its initial value of 1 within a few days. Despite strong local horizontal tracer concentration gradients, this time period seems to be a reasonable estimate for the mean residence time in the epilimnion of the Petit Lac.

It should be mentioned that the total mass of the tracer in the whole lake was also monitored to assess the conservation properties of our numerical schemes. During the computation period (120 hours) only a negligible amount of tracer mass (less then 10^{-5} %) 'disappeared'.

4.2.2.4 Conclusions for the numerical simulations

The most frequently occurring winds at Lake Geneva, 'Vent' and 'Bise', transport large amounts of the water into and out of the epilimnion of the Petit Lac within periods of a few days. For this motion to be effective in replacing water masses in the Petit Lac, a transported water volume must be either replaced by a different one, or it must be mixed with fresh water before it leaves through the open boundary. The former effect typically occurs for the 'Vent' case, where water which is advected out of the epilimnion of the Petit Lac and transported along the Northern shore of the main basin is replaced by fresh water from the Southern shore of the main basin.

The second effect takes place in the case of a 'Bise'. Fresh water from the main basin is advected into the epilimnion of the Petit Lac, horizontally mixed inside the Petit Lac, and then transported out. This leads to an irreversible net loss of tracer mass. Interestingly, the time scale for substantial horizontal mixing inside the Petit Lac is comparable to the period of the internal seiche of Lake Geneva, making the process of tracer advection into the Petit Lac an irreversible process. In contrast to the 'Vent' case, direct entrainment of hypolimnetic water, and hence dilution of the tracer in the epilimnion, plays an important role for the water renewal.

The importance of internal seiches motions as a key process also in ecological questions (to which the question of residence time is, of course, related) has become evident during this discussion. It should also be noted that, at least for the examples chosen here, the computation of inter-basin exchange based on residual currents, i.e. on currents remaining after averaging over the internal seiche period, cannot yield realistic results due to the inherent non-linearity of the horizontal mixing processes.

We want to conclude this section with some remarks on the most important requirements regarding the performance of numerical models used in studies of this type. First, it is evident that the numerical model should be able to reproduce the dominant internal oscillations, because they are the main agent of water in- and outflow in sub-basins. Second, the model should also be able to deal with strong horizontal gradients caused by horizontal straining of scalar fields due to coherent structures (see Fig. 4.16) without producing too much numerical diffusion. Third, the turbulence model should at least be able to yield a reliable prediction of entrainment. As was demonstrated here, this process can significantly contribute to epilimnetic water renewal.

4.3 CONCLUSIONS WITH RESPECT TO MANAGEMENT CONCEPTS

The above results indicate that a unique residence time distribution for sub volumes of the lake cannot be established with certainty in the Lake of Geneva. Water age calculations resulting from transient tracer measurements and based on a one-D concept are not reliable because water mass motions lead to spreading and dilution. A more reliable and more precise quantification could be obtained by inverse numerical modeling of these tracers. Such a model would require a substantial amount of information on mixing and transport processes involved, on the conditions limiting gas exchange at the lake surface and on tracer inputs from the catchment (Hofer et al. 2002). This information is not yet available.

The event structure of the wind forcing, the effect of the Coriolis force and the importance of internal seiche motion all indicate the strong interaction between different sub volumes of the lake. This interaction changes over a wide range of time scales and length scales. Nevertheless, a potential residence time concept resulting from theory and experience in Lake Geneva may be schematically present in a lake cross section as shown in Fig. 4.1. In the most simplified concept which still has significance for lake management questions, the lake can be divided into three zones which have different characteristics:

- near shore zones; this is the part of the lake comprising the coastal zone and the adjacent layers down to about 40m depth. The air-water exchange processes and bottom friction control its dynamics. Water-sediment interaction is important in this part of the lake (Lemmin et al. 1995).

- an upper offshore layer (labeled epilimnion); as in the near shore zone, its dynamics is controlled by the air-water exchange processes.

- a deep layer (labeled hypolimnion); hypolimnion dynamics results from processes initiated in the epilimnion and the near shore zone.

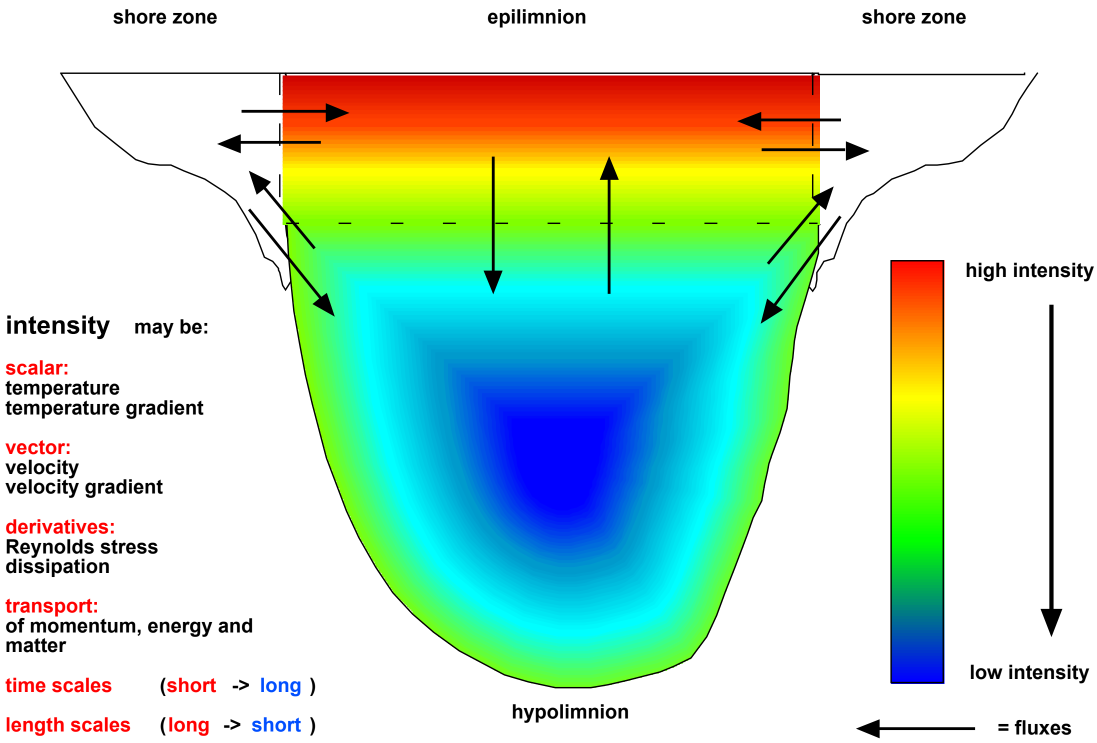

Fig. 4.23: Schematic representation of key processes dynamics in Lake Geneva

The three zones are not isolated but are interconnected by exchange processes indicated as fluxes in Fig. 4.23. A colour scheme indicates the intensity of the different parameters and processes. A few examples of the physical parameters/processes are given in the figure. It is realized that the combined effect of different key processes leads to the highest dynamics in the near shore zone followed by the epilimnion. The hypolimnion is the least active zone.

This distribution has direct consequences for the development of managerial strategies (Fig. 4.24). Direct interaction between man and lake occurs most intensely in the near shore zone through such activities as drinking water intake, sewage discharge, boat traffic, tourism, and fishing. At the same time, river discharge and thus the connection to river basin inputs occurs in this zone. Therefore most biological and chemical tracers that enter or leave the lake system will pass through this zone.

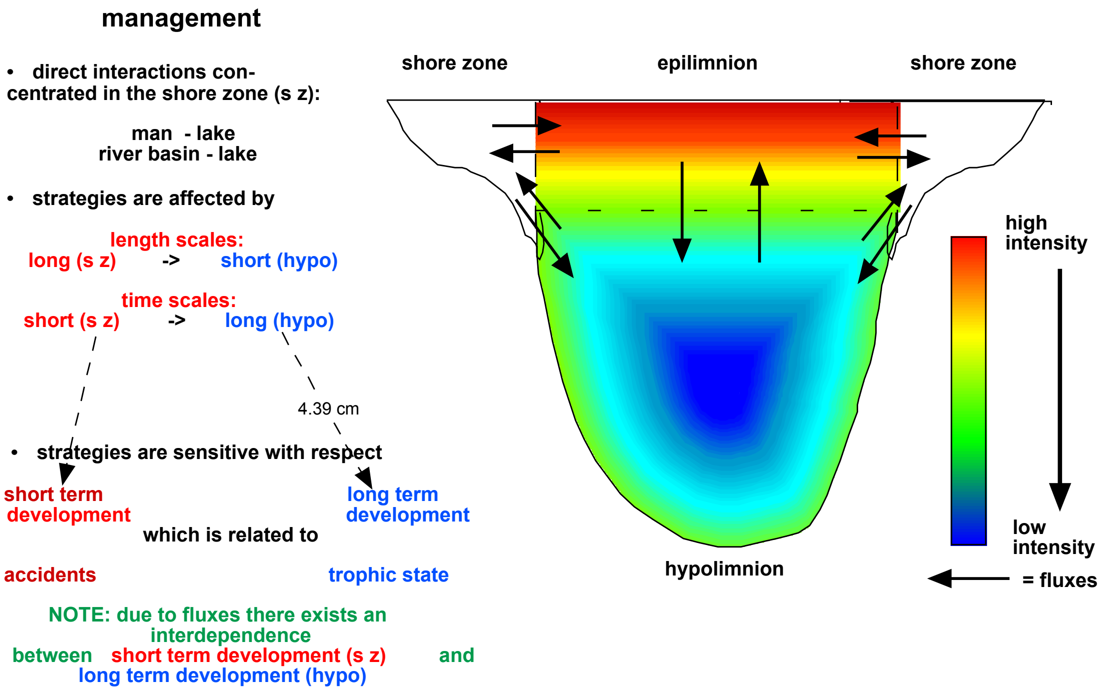

Fig. 4.24: Management concepts related to key process dynamics in Lake Geneva

Management concepts related to the potentially conflicting interests in this zone have to take into consideration the high level dynamics of physical processes in this zone but also the exchange with the other zones through the fluxes. Any tracers introduced in this zone will disperse quickly making recovery of harmful tracers a matter of precise short term planning. Repeated introduction of harmful tracers (i.e. through sewage discharge or diffuse sources) risks to affect the other zones of the lake through the flux exchange between the different zones and may therefore have longterm consequences which are particularly harmful in the hypolimnion due to its long residence times.

Due to the sheltering from direct near shore activities and air-water exchange processes, long time scales important in longterm development dominate deep-water dynamics. The consequence is that this zone is sensitive to the accumulation of harmful tracers which can only be eliminated from the system lake on very long time scales, most often through sedimentation. In this respect the fact that the Lake of Geneva remains stratified throughout the year on a long-term mean (see report of WP 4) further aggravates the situation.

Thus, water quality in the deep layers may be influenced by particle settling. This indicates that for water quality management concepts not only the residence time in a particular water mass layer is of importance but also the understanding of the way in which any pollutant may be brought into this water mass. This means that good management concepts have to combine concepts of realistic water mass residence time with realistic hydrodynamic concepts of water mass displacement.

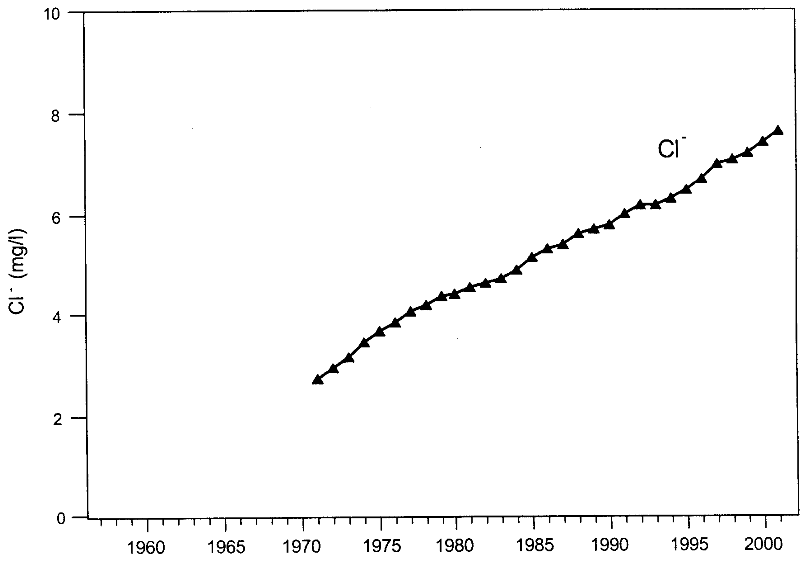

Fig. 4.25: Chlorine (Cl) concentration in the center of the Grand Lac basin of Lake Geneva (Depth averaged and volume weighted; from CIPEL 2002)

A different situation occurs for dissolved chemical species. These cannot be eliminated by particle sedimentation. As a consequence, elimination is only possible by river outflow. The fate of chlorine is given as an example in Fig. 4.25. The two main sources for chlorine are chemical industry (50%) and road salting (30%). Both sources enter the lake in the near shore zone. Chlorine concentration in the center of the lake continuously increases and is spread throughout the water column. This indicated the importance of water mass displacement between the nearshore zone and the open waters. At present, chlorine concentrations are well below danger levels. However, from the results presented above it is obvious that any measures to reduce chlorine concentration in the lake will require very long time scales. Similar patterns can be expected for micropollutants which may have much more severe effects on the life in the lake and on human beings through fish consumption.

Finally, these concepts need to be continuously reconsidered. Meybeck et al. (1972) had suggested that a realistic residence time of the deep hypolimnion of Lake Geneva is about 20 years. Due to continuous warming of the lake over the last 30 years (see report of WP 4) this residence may from now on shorten to several years (Lemmin, 1998). This shows that any residence time concept has to be adjusted to longterm dynamics of the forcing conditions of the physical processes.

5 DEDICATED INVESTIGATIONS FOR LAC DU BOURGET

5.1 INTRODUCTION

Lac du Bourget is located in the French Alps in Savoie and is the biggest natural lake situated on the French territory. This deep lake is situated in the vicinity of two important cities: Chambery and Aix les Bains (400 000 inhabitants – equivalents). General morphometric characteristics are presented in the table below:

Bathymetric and hydrologic characteristic of Lac du Bourget	Value /units
Length of the lake	18 km
Minimum width	1.6 km
Maximum width	3,2 km
Water surface area	44.6 km^2
Mean depth	81 m
Maximum depth	145 m
Volume	$3,6 \cdot 10^9$ m^3
Shoreline length	43,3 km
Mean lake surface altitude	231 m
Theoretical retention time	7 years

Table 5.1: General characteristics of Lac du Bourget

The catchment of Lac du Bourget consists of six sub-catchments. Five of these sub-catchments are catchments of main inflows to the lake i.e. Leysse, Belle Eau, Sierroz, Tillet and Chautagne rivers. One sub-catchment does not contribute with significant inflow.

The rivers Leysse and Sierroz are the two biggest tributaries discharging into the lake. The Savières channel, connected to the Rhône river, is the main outflow. A sketch of the lake and the main rivers is shown in figure 5.1.

The annual mean flow of the Leysse river is about 8.5 m^3/s with a peak value of average 100 m^3/s during flood events. The annual mean flow of the Sierroz river is about 3.5 m^3/s and the flow reaches 30 m^3/s during flood events. The western part of the lake catchment is very steep and consist of bedrock. The eastern shore is much more flat and transformed by people living in small villages and towns. Lac du Bourget serves as drinking water reservoir for Aix-les-Bains.

Two physical characteristics are of special importance. The first is the maximum depth of the lake, which does not allow for complete overturn every year. Therefore, Lac du Bourget is a meromictic lake. The second important physical characteristic is the relatively long mean residence time, which allows only for small year-to-year changes in the ecosystem characteristics, apart from the effect of meteorological forcing.

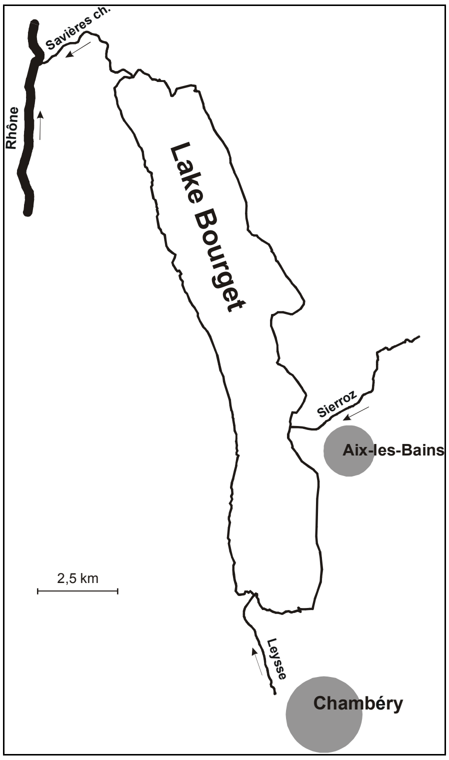

Fig. 5.2: Schematic view of the lake

5.2 DERIVING RESIDENCE TIMES FOR LAC DU BOURGET

5.2.1 Methodology

Transport processes in lakes, which are of the most importance for biochemical cycle and as a result for water quality changes, are inherently three-dimensional [Hodges at al., 2000]. Scientific investigations (research) in water quality field (management), like calculation of residence times should be therefore carried out by means of full three-dimensional numerical models running over 10 or 20 years period. Unfortunately, computational and memory constrains of recent computers restrict our modelling horizon to weekly to monthly simulations. For the purpose of estimating of residence time, following assumptions and simplifications has been made:

- Three-dimensional triangle finite element numerical mesh representing Lac du Bourget has been build basing on the real topography (bathymetry) of the lake.
- Two types of boundary condition were applied:
    - Imposed fixed inflow rate in the river Leysse and Sierroz mouth;
    - Constant free water level on the Savieres channel outflow.
- The model was run for several (approx. 2000) time steps to obtain “quasi-steady” state of the flow.
- Streamlines starting in river mouth were constructed basing on the velocity field mentioned above. These were calculated using the second order Runge-Kutta method with adaptive time steps using two integration steps within one grid “cell”.

- A sample of zero mass particles was released into the velocity field. The particles have their initial positions at the river mouth. The particles move through the velocity field according to the magnitude and direction of the vectors at the nodes in the volume (following previously calculated streamlines). A forward differencing method was used to estimate the next position of each particle as a function of its current position and velocity.
- For the river Leysse sample of 50 particles, spaced 4 meters horizontally and grouped in 4 vertical layers (0.5 m distance) were located in river mouth. River Sierroz outlet was sampled by 18 particles, located in similar manner.

5.2.2 The numerical model

A three dimensional numerical model of the lake was built using the TELEMAC-3D software. The finite element software TELEMAC-3D solves the Navier-Stokes equation with a free surface boundary condition and the advection-diffusion equations for temperature and other active or passive scalar variables [Janin et al., 1992]. Density effects, wind stress on the free surface and the Coriolis force are included in the model. Variations of the density can be taken into account in the momentum equations via Boussinesq approximation.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\nu_H\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_H\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_H\frac{\partial u}{\partial z}\right)+F_x$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\nu_H\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_H\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_H\frac{\partial v}{\partial z}\right)+F_y$$

$$p=\rho_0 g(S-z)+\rho_0 g\int_z^S\frac{\Delta\rho}{\rho_0}dz$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial x}\left(\nu_{HT}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{HT}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_{HT}\frac{\partial T}{\partial z}\right)+Q$$

where

h (m)	water depth	Z_f (m)	bottom elevation
S (m)	free surface elevation	ρ_0 (X)	reference density
u, v, w (m/s)	velocity components	$\Delta\rho$ (X)	variation in density
T (°C)	active or passive tracer	t (s)	time
P (X)	pressure	x, y (m)	horizontal space components
G (m/s²)	acceleration due to gravity	F_x, F_y (m/s²)	source terms
ν_H,ν_Z (m²/s)	velocity diffusion coefficients	Q (tracer unit)	tracer source or sink
ν_{HT},ν_{ZT} (m²/s)	tracer diffusion coefficients		

The computational mesh consists of approximately 212,000 nodes, formed in 388,000 prisms and grouped in 18 horizontal layers. Horizontal element size varied between 3 to

120 meters. A plane and 3D isometric views of the mesh are shown in figures 5.2 and 5.3.

5.2.3 Results

Hydrodynamics calculations were done for the following scenarios:

- No lake stratification, no wind.
- No lake stratification, constant wind from North – according to the wind statistics report preferred wind direction in the lake region.
- No lake stratification, constant wind from SSE.
- “Weak” winter stratification, no wind[1].

In all scenarios, constant mean annual flow of the river Leysse and river Sierroz – 8.5 m/s and 3.5 m/s, respectively was imposed [Bournet, 1996].

Exemplary pictures of the streamlines starting at the river mouth and travelling through the lake domain were given in Figures 5.3 and 5.4.

Travelling time statistics, computed according to the chosen methodology are shown in Figures 5.4 and 5.5.

5.3 CONCLUSIONS

According to the model investigations described above the following conclusions can be drawn.

1. Travelling times obtained for particles starting in the two rivers recharging Lac du Bourget lie in the correct intervals of values (lower for river Seirroz and higher for river Leysse).

2. The results obtained with the two rivers’ inflows are consistent with the mean residence time calculated for lumped model of the lake and equal to MRT = 13 year.

[1] Remark: Due to problems with obtaining necessary accuracy in the numerical model it was impossible to calculate residence times statistics for scenarios 4. Numerical schemes and so-called *σ-transformation* approach used by TELEMAC-3D are quite unstable dealing with thermal gradients on non-vertical lake shores.

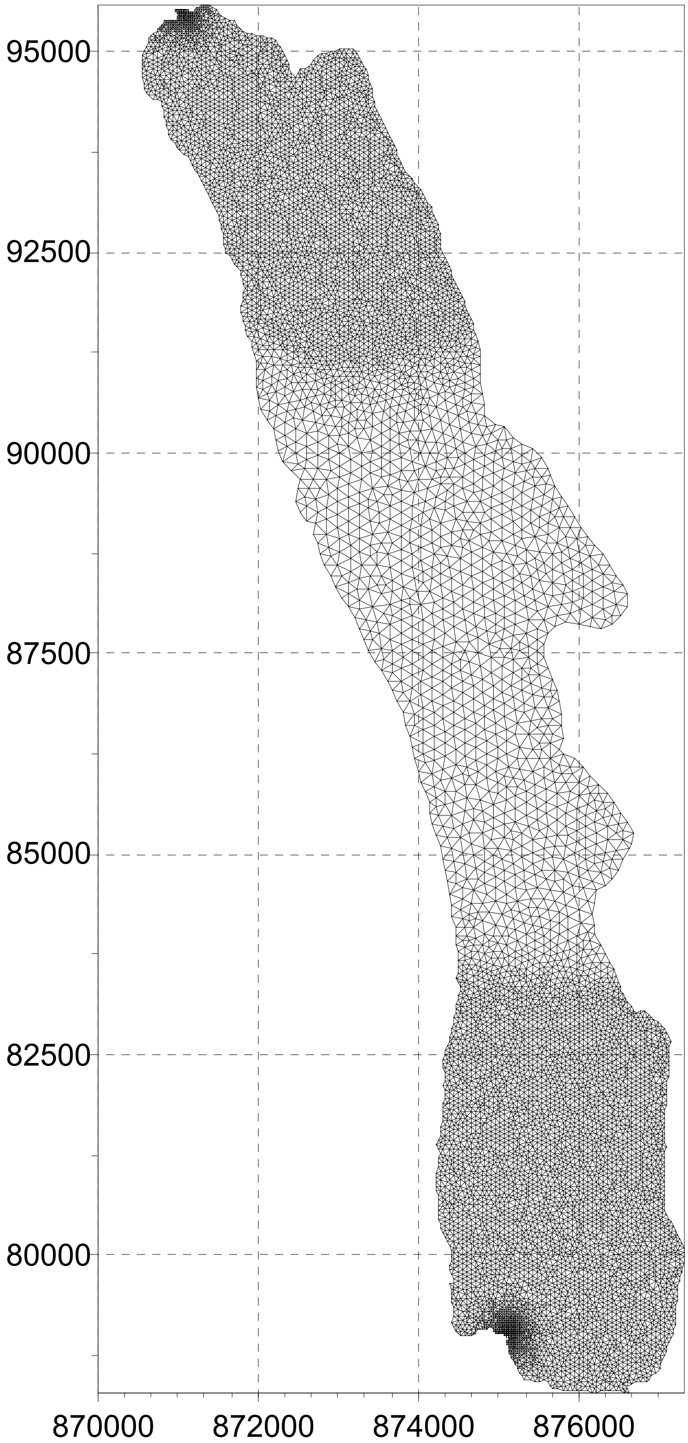

Fig. 5.1: Plain view of the finite element computational mesh (co-ordinates in meters)

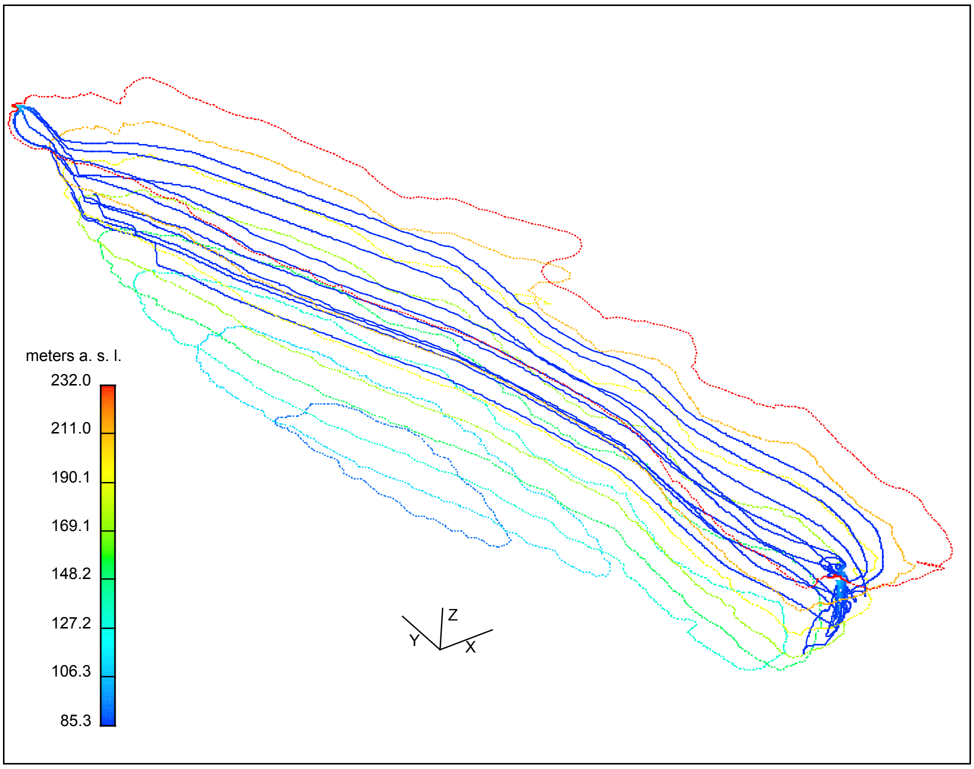

Fig. 5.2: 3D view of the Leysse streamlines (from right to the left of the picture)

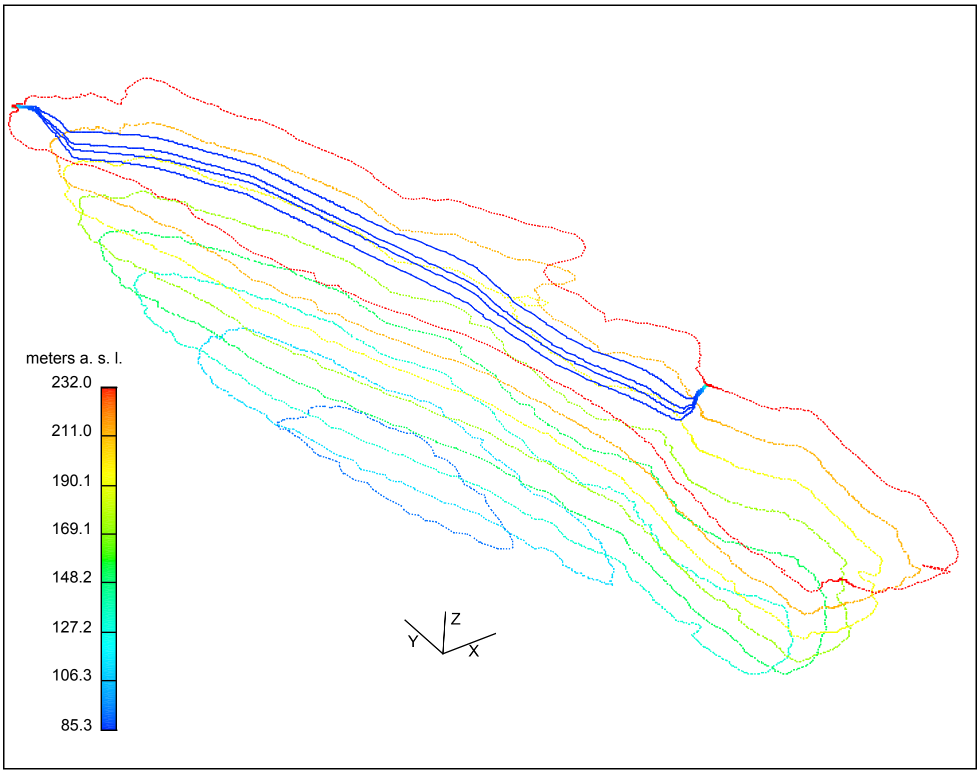

Fig. 5.3: 3D view of the Sierroz streamlines (from right to the left of the picture)

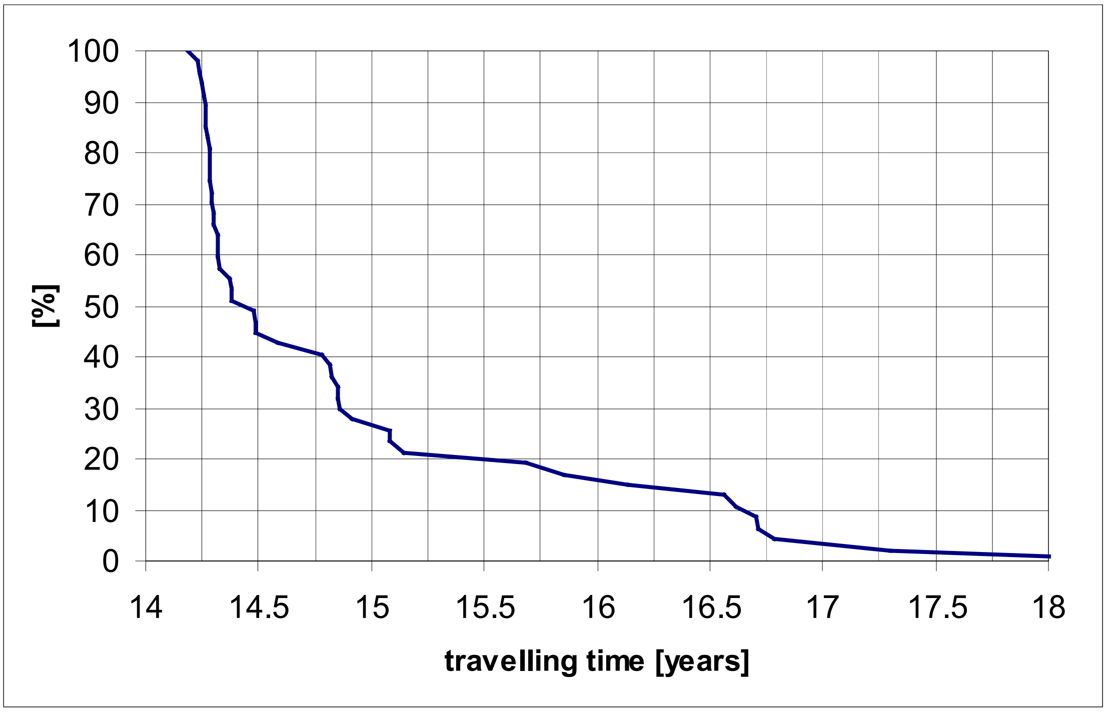

Fig. 5.4: Percentage of particles recharged by river Leysse remaining in the lake at the given time

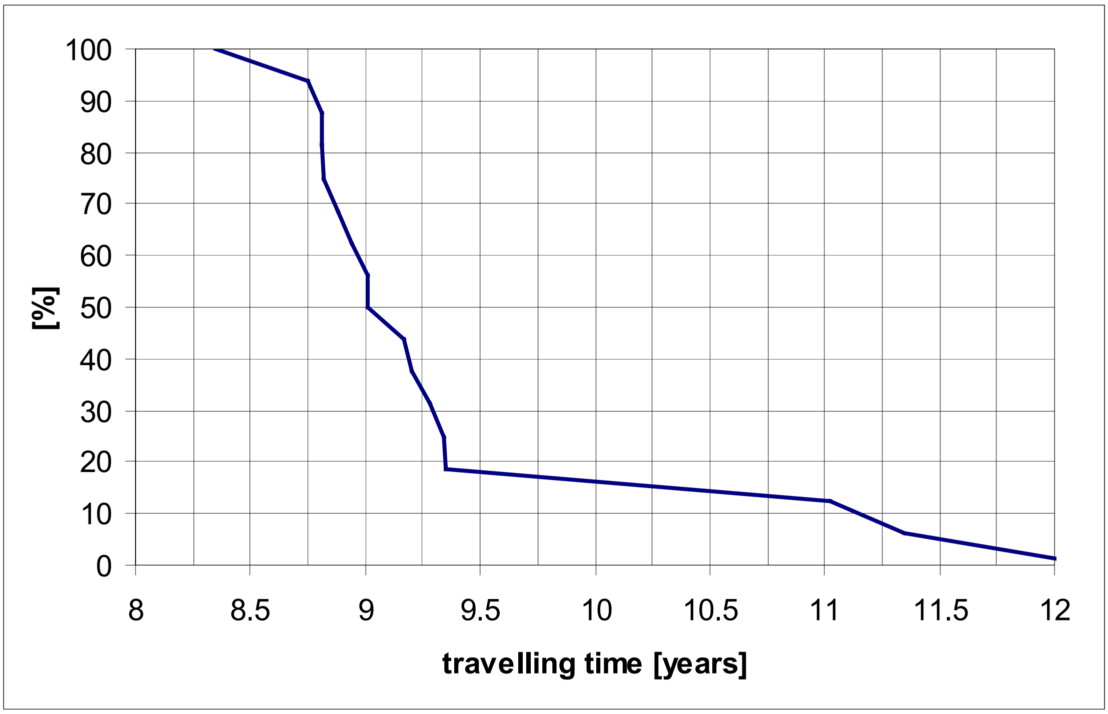

Fig. 5.5: Percentage of particles recharged by river Sierroz remaining in the lake at the given time

6 DEDICATED INVESTIGATIONS FOR LOCH LOMOND

6.1 INTRODUCTION

Parts of the EUROLAKES investigations are concerned with the seasonal dynamics and quantification of limnological key processes and parameters in deep European lakes. An improved calculation of realistic residence times has to consider meteorological, bathymetric and hydrological variability; this can reasonably be done only with suitable three-dimensional models. In this chapter results of dedicated calculations concerning Loch Lomond are described where a wealth of field observations were available for model purposes.

Activities concentrated on investigations by means of finite difference circulation models (stratification and vertical mixing taken from 1D model calculations in work package WP 4) and Lagrangian tracer methods. Residence times were then calculated by water particles as well as by waterbudget calculations for smaller lake compartments and vertical levels. Basic information on the used model formulations and numerical techniques are described by Duwe, Hewer and Backhaus (1983) and Pfeiffer and Duwe (1990).

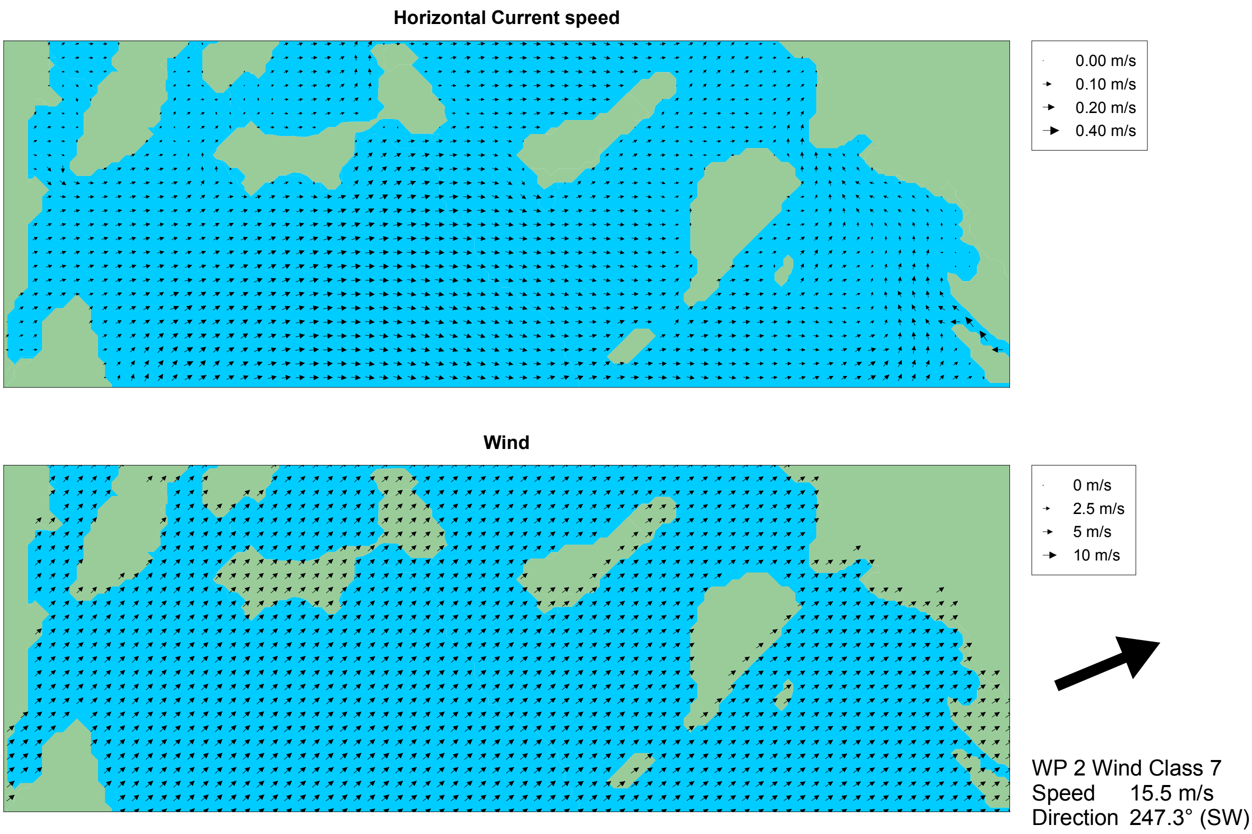

Fig. 6.1: Distribution of surface currents around the central islands of Loch Lomond for wind class 7 of WP 2 (south-westerly wind)

6.2 DERIVING REALISTIC CURRENT FIELDS FOR LOCH LOMOND

An important prerequisite for nature-like calculations with current models is the availability of suitable field observations. In the case of deep large lakes this includes comprehensive information on meteorological and hydrological conditions. The most important parameters to be known are river inflow, solar radiation, and of course the energy influx by wind into the watercolumn. The latter could fortunately be derived for Loch Lomond from dedicated meteorological model investigations which were provided in the EUROLAKES work package WP 2: horizontal distributions of wind speeds for 48 different wind classes of equal probability. In fig. 6.1 an example of such wind distributions (and the resultant surface current distribution computed by the model) is given for a situation with south-westerly winds at higher altitudes. The orography in fact modifies the wind distribution over the lake surface considerably.

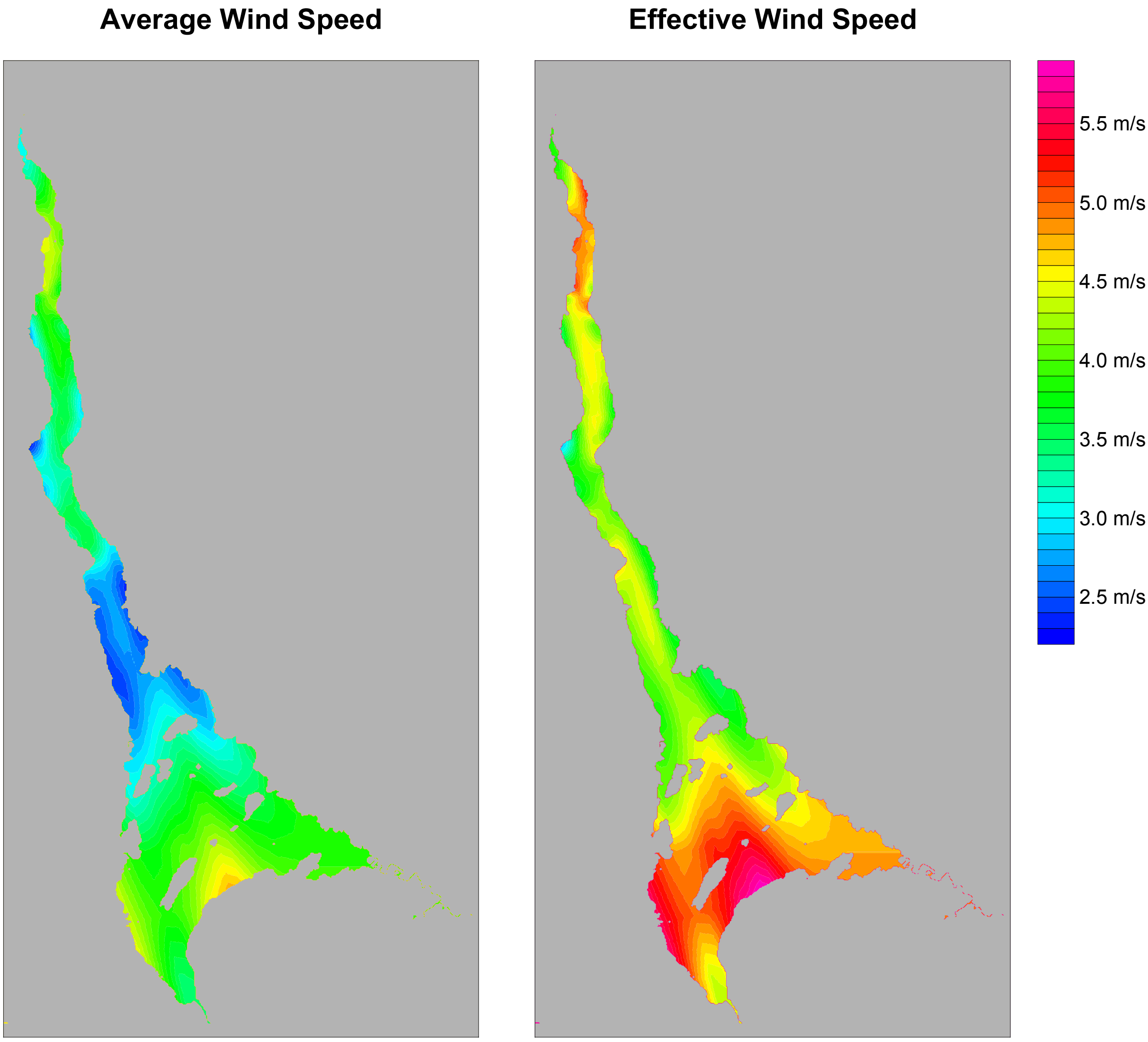

Fig. 6.2: Mean wind speed taken over 20 years of prediction derived by simple averaging wind speed w (left) and averaging w^3 (right) which is a measure of energy flux into the water column

When looking at the impact of wind on the vertical circulation in a lake the complex current features become especially apparent in a highly structured deep lake like Loch Lomond. In figures 6.3, 6.4 and 6.5 very pronounced upwelling (blue colour) and downwelling (red colour) regions can be detected in the deeper northern basin as well as in the island region in the central basin of the lake. In northerly wind situations downwelling is mainly confined to the western shores of the fjord-like northern basin, during southerly winds it is concentrated on the eastern shores. This fact points to the importance of the Coriolis effect for the circulation characteristics of Loch Lomond. In shallow lake regions pronounced vertical velocities can be observed in the landward and leeward regions of the islands.

In addition of course winds cause morphologically induced horizontal gyres and counter currents in deeper lake regions – in the case of stratification this picture is even more complicated due to long internal wave motions and the occurence of higher vertical modes in the horizontal current distributions. Fig. 6.4 and 6.5 show currents near the surface and at 30 m depth for two wind directions clearly depicting features of this complex hydrodynamic regime.

Besides a good resolution of the horizontal wind speed distribution for a given mesoscale meteorological situation it has to be kept in mind that the momentum flux from the atmosphere through the lake surface is dependent on the third power of the wind speed (as the wind drag coefficient normally used in hydrodynamic models is also a function of the wind speed). When calculating the wind stress for a given period from measurements this fact has to be taken into account. It is absolutely necessary when averaging in time and space to use values to the third power. An example of the very different results obtained can be depicted from fig. 6.2 where the left hand distribution was calculated by linear averaging neglecting the effect of strong wind speed fluctuations in the time underlying observational time series. It can easily be seen that the results is startingly different. Very important became this phenomenon when reliable energy flux from these wind fields had to be calculated for one-dimensional (vertical) box models of the three lake basins where the horizontal distribution of wind stress had to integrated over each area. At first glance it is clear that such an integration would have totally different effects when using either the left or right hand values from fig. 9.2. Especially important was this item because the one-dimensional (horizontaly averaged) model (described in the report on EUROLAKES work package WP 4) was used to compute temperature stratification conditions which were in turn necessary to be introduced in the three-dimensional long-term model calculations described below.

A good approximation of both horizontal and vertical current patterns is necessary to derive reliable predictions of the transport of water (or dissolved water ingredients) for specific meteorological situations whereby enabling a realistic computation of retention times in different lake regions. This is the objective of the next subchapter of this report.

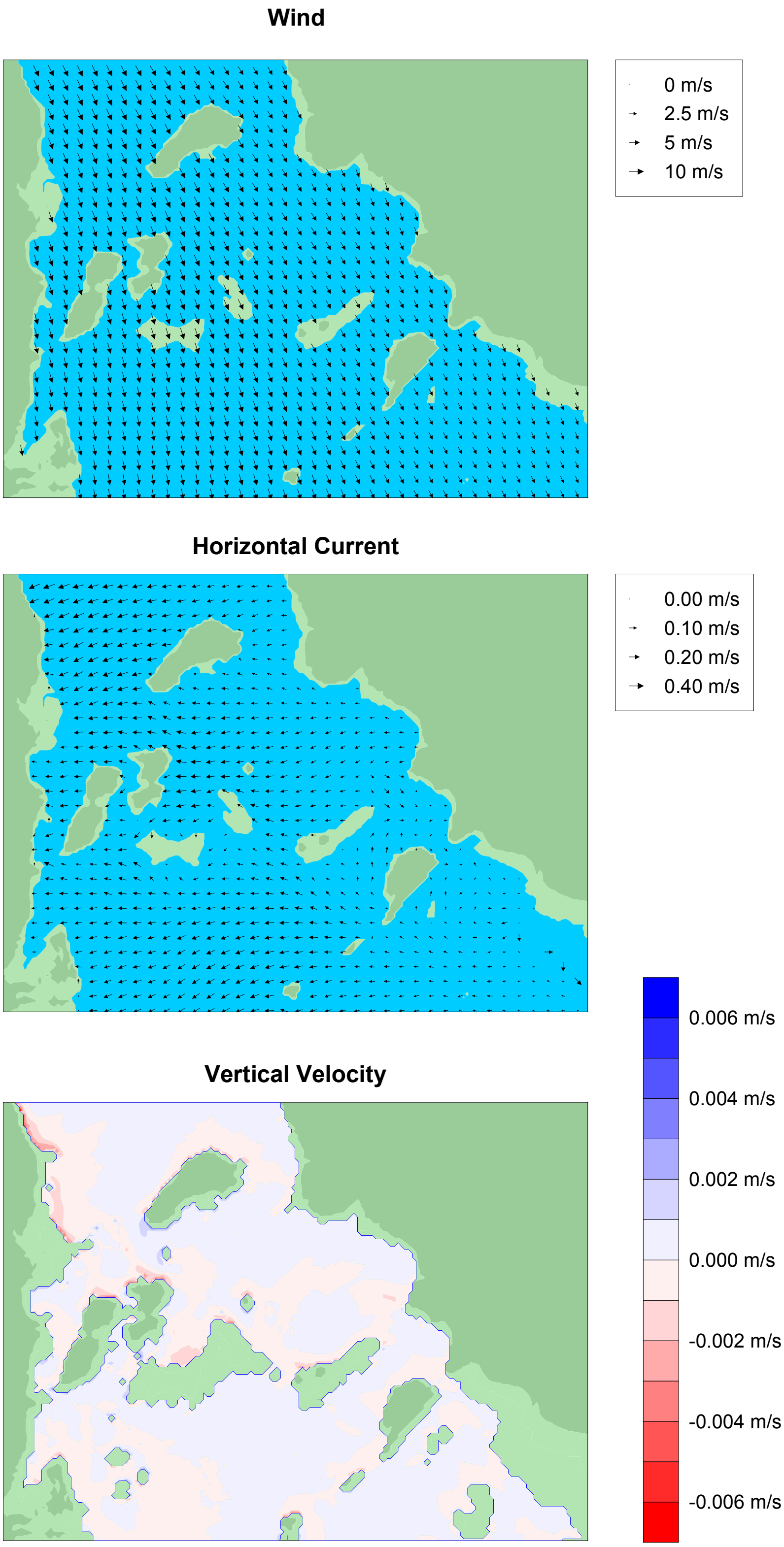

Fig. 6.3: Distribution of surface winds, surface currents and vertical velocity in the archipelago area in Loch Lomond for predominantly northerly windfield

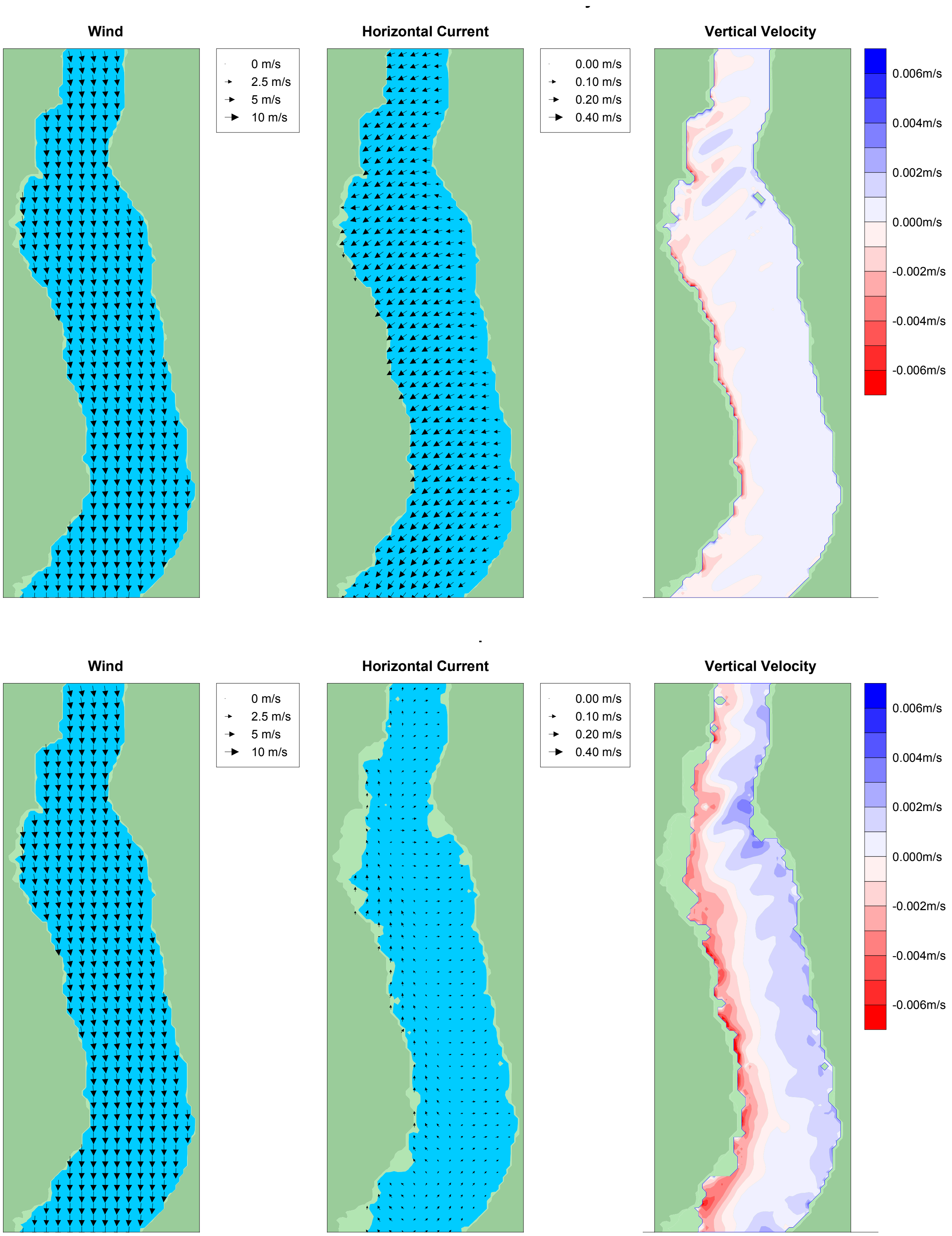

Fig. 6.4: Distribution of winds, surface currents and vertical velocity in northern Loch Lomond for predominantly northerly windfield at the surface (above) and at 30 m water depth (below)

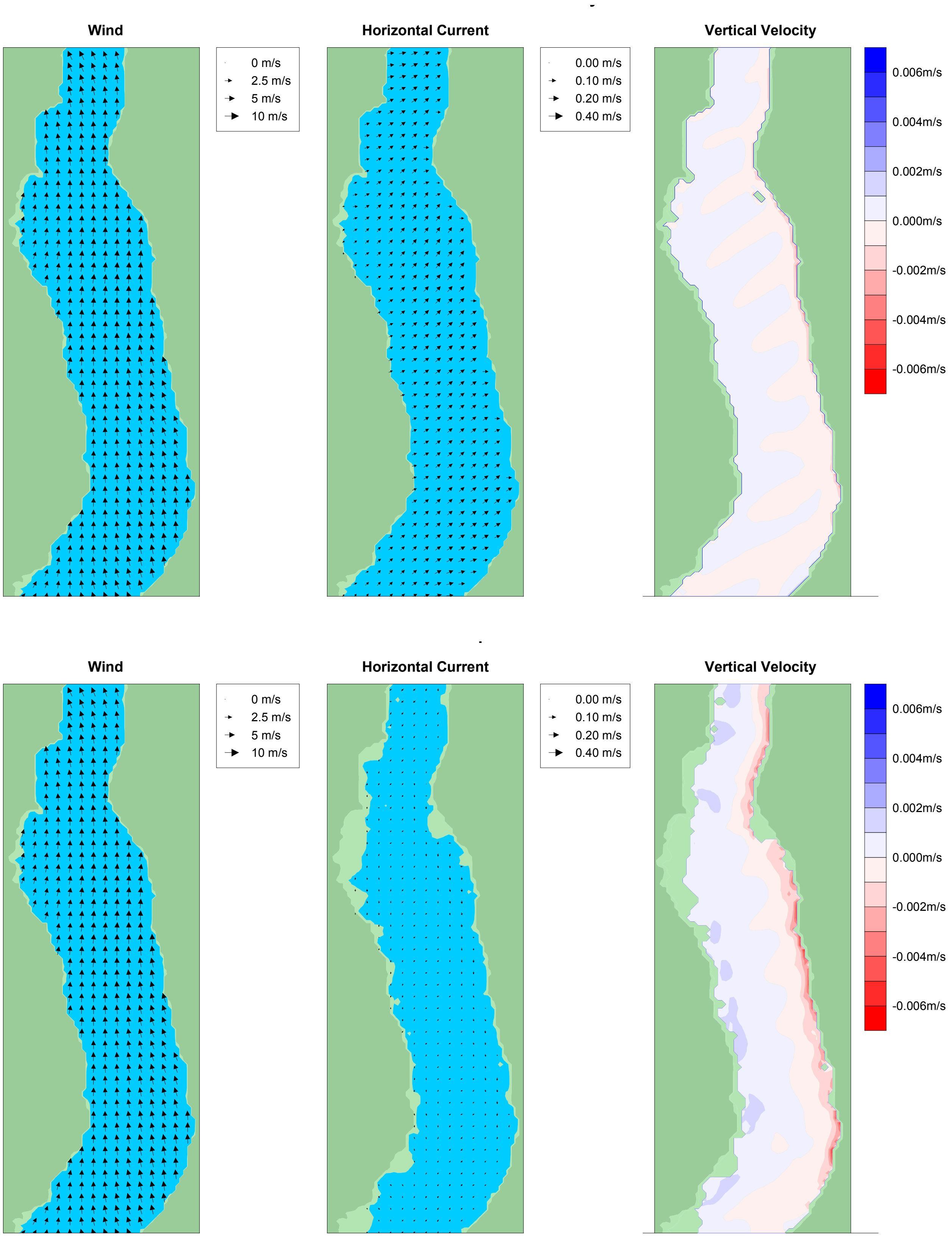

Fig. 6.5: Distribution of winds, surface currents and vertical velocity in northern Loch Lomond for predominantly southerly windfield at the surface (above) and at 30 m water depth (below)

6.3 DERIVING RESIDENCE TIMES FOR LOCH LOMOND

The studied Loch Lomond in Scotland can be divided into three basins (see location in fig. 6.6). Its main tributaries are the River Endrick in the South and the River Falloch in the North. Whereas the southern basin is rather shallow (less than 25 m), the two other basins are fjord-like and reach a maximum depth of over 190 m. The “mean” residence time in the lake is about two years when calculated by the ratio of mean lake volume and mean river inflow. However, this work is dedicated to derive more detailed information on water retention times in separate lake regions and for different inflowing waters.

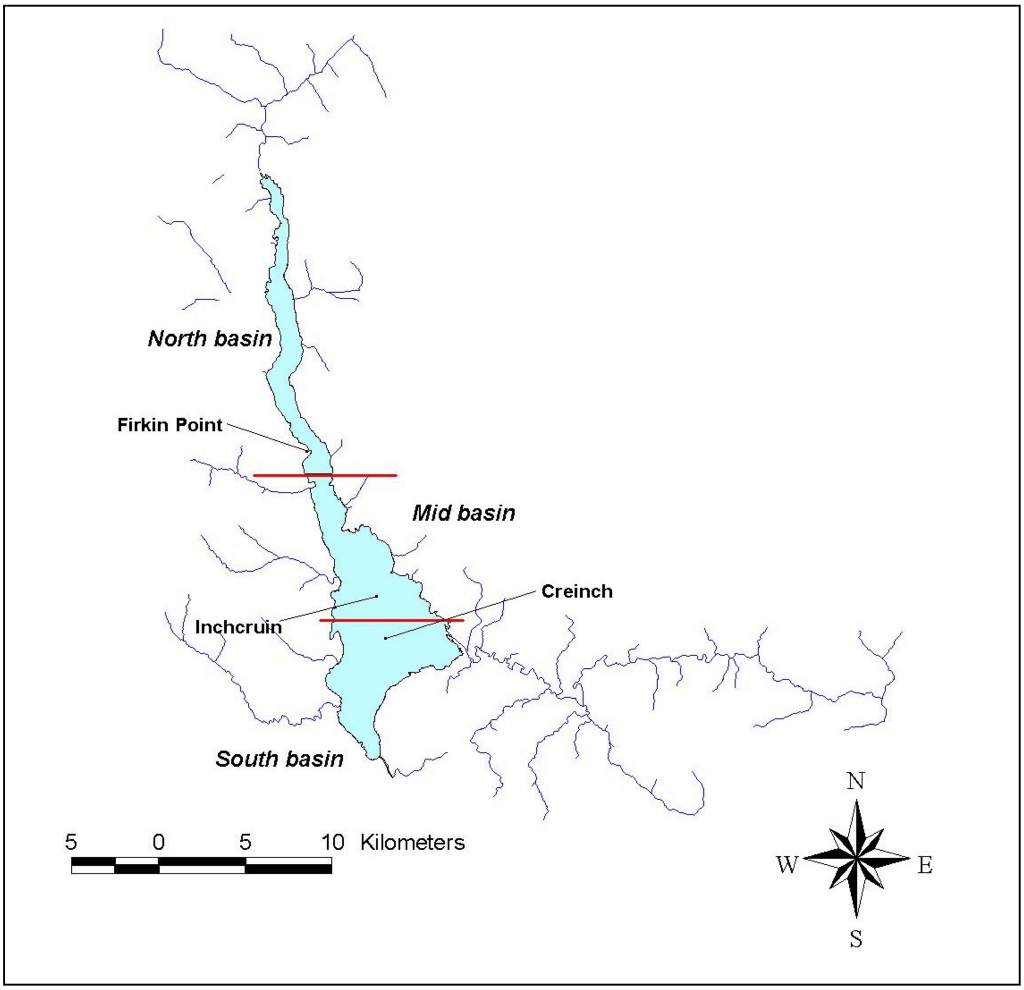

Fig. 6.6: Definition of the three main basins of Loch Lomond

Water Transport Fluctuations between Lake Basins of Loch Lomond for Weak Stratification Derived from Calculations with HYDROMOD-3D driven by METCON Wind Field Statistics						
Mesocscale Sector of Synthetic Wind Statistics					Mean Water Transport Fluctuations	
Direction Sector	Speed Class	Mean Wind Direction		Mean Wind Speed	North Basin - Mid Basin	Mid Basin - South Basin
		degrees		m/s	m³/s	m³/s
1	3	29,9	NNE	8,5	640,5	1.130,2
2	3	110,1	ESE	9,2	141,6	236,7
3	3	165,5	SSE	10,4	275,5	95,8
4	3	196,9	SSW	12,5	627,6	379,2
5	3	217,5	SSW	13,5	301,9	199,5
6	3	234,1	SW	14,9	323,5	218,7
7	3	247,3	SW	15,5	325,8	162,7
8	3	260,4	W	16,6	432,6	233,8
9	3	274,5	W	15,9	200,8	296,1
10	3	290,1	NW	13,9	107,7	187,7
11	3	312,0	NW	11,7	85,4	369,1
12	3	340,8	NNW	9,9	763,3	1.444,2
Mean Value		223,3	~SW	12,7	352,2	412,8

Table 6.1: Fluctuations of water transport due to different wind fields in Loch Lomond

By means of a high resolution 3D model with 50 m horizontal grid size and 1.0 m vertical grid spacing the circulation patterns for all relevant wind directions and temperature profile information was used to obtain a long time series of current fields for the lake. This information was meant to be used to calculate the path of numerical tracers which were released at different positions within the lake. This enables the calculation of residence times of defined water masses within a water body such as a lake. Loch Lomond was a good example for these investigations because of the irregular shape and depth distribution.

A first idea of the variability of the water transport in different lake sections was provided by integrating model transports between the three lake basins for a selection of 12 wind direction classes (see table 6.1) for steady state conditions. Maximum water exchanges between basins were calculated for northeasterly and northwesterly wind directions.

When looking at residence times, however, time-varying long-term meteorological conditions have to be taken into account. Such data were derived from a number of sources and field sites but mainly observations of wind, relative humidity and air temperature from Glasgow Airport and global radiation records from Dunstaffnage. These data were then generalised for the period 1966-2000 by taking into account local weather observations on or near Loch Lomond to obtain a “Loch Lomond integrated meteorology”. In fig. 6.7 a part of this time series is described in detail.

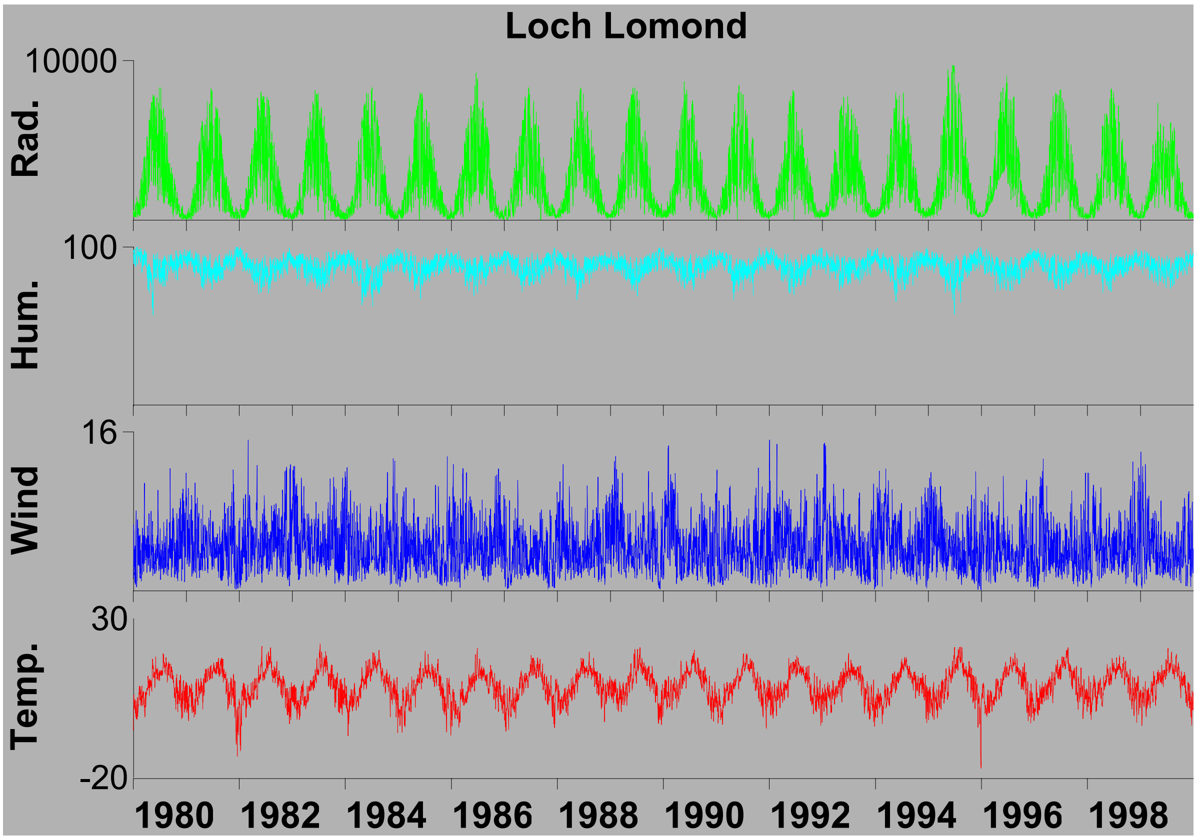

Fig. 6.7: Air temperature, wind speed, relative humidity and global solar radiation during 1980 to 1999 for Loch Lomond - Source: BADC - Hydromod

The knowledge of the meso-scale meteorological conditions and hydrological circumstances over a large time period enabled the computation of lake current fields over 10 years starting from June 1966. This current and temperature information was then the basis of dedicated Lagrangian tracer calculations to look at the fate of water in Loch Lomond over a large period of time. Numerical calculations started with the marking of a defined water mass with a certain number of particles (in the order of one million) and then tracing these small water parcels through time until they eventually left the lake through the outflowing River Leven in the south. For the described investigations two different avenues were chosen:

1. Marking the whole waterbody of the lake at a certain date with particles.

2. Marking incoming water from a tributary at a certain date with particles.

The resulting pathways of the tracers were then computed and the spatial distribution was then used to compute residence times of defined water bodies in Loch Lomond. Fig. 6.8 shows as an example the short-term fate of water marked in a channel between small islands in the southern basin. Whereas water near the surface is mixed and dispersed very rapidly, near-bottom water shows a quite different behaviour until it is vertically transported to the surface and disperses (but in another region of the lake).

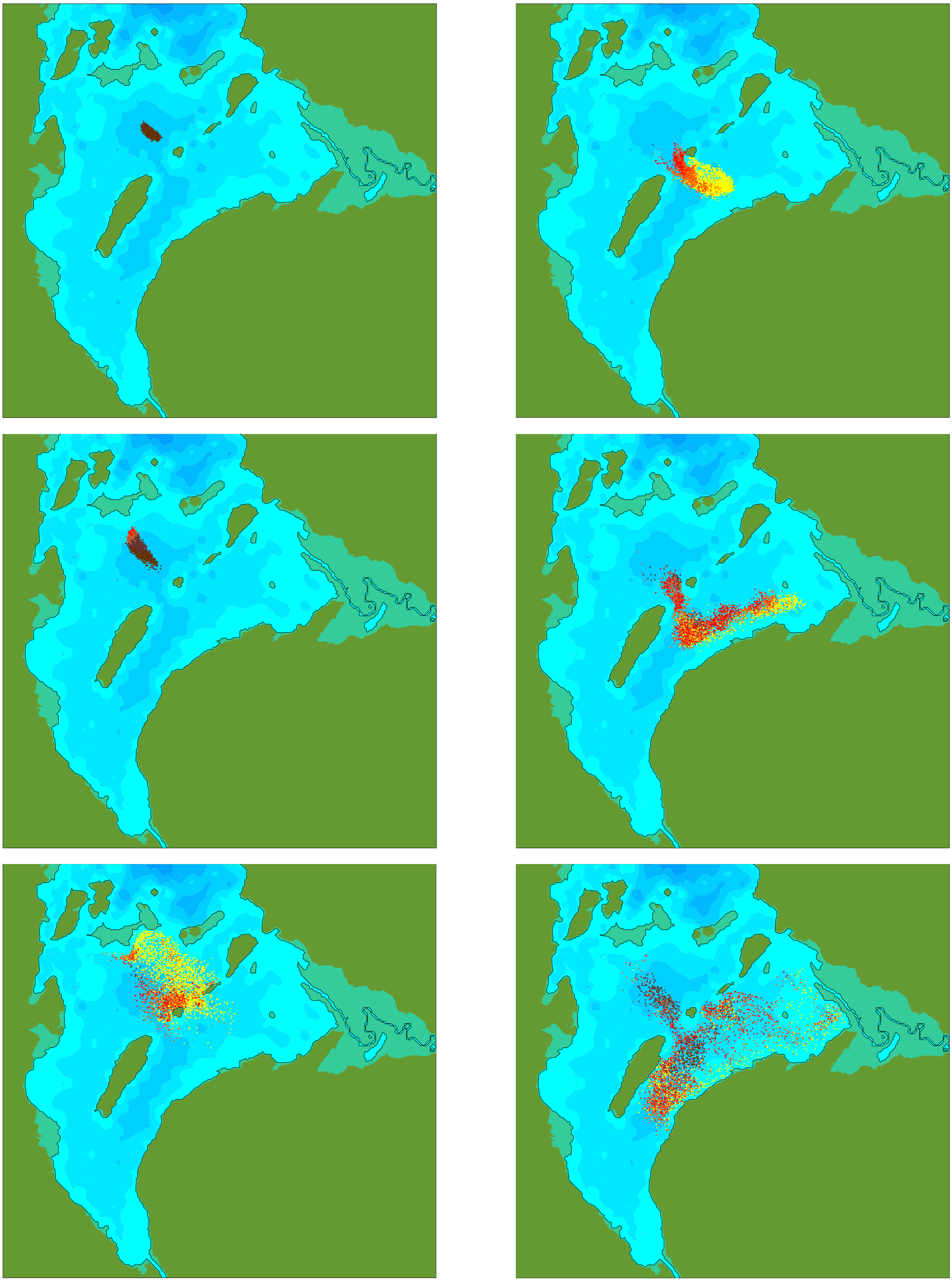

Fig. 6.8: Distribution of marked water (near-bottom origin on the left – near-bottom on the right) after one, two and three days (from top to bottom)

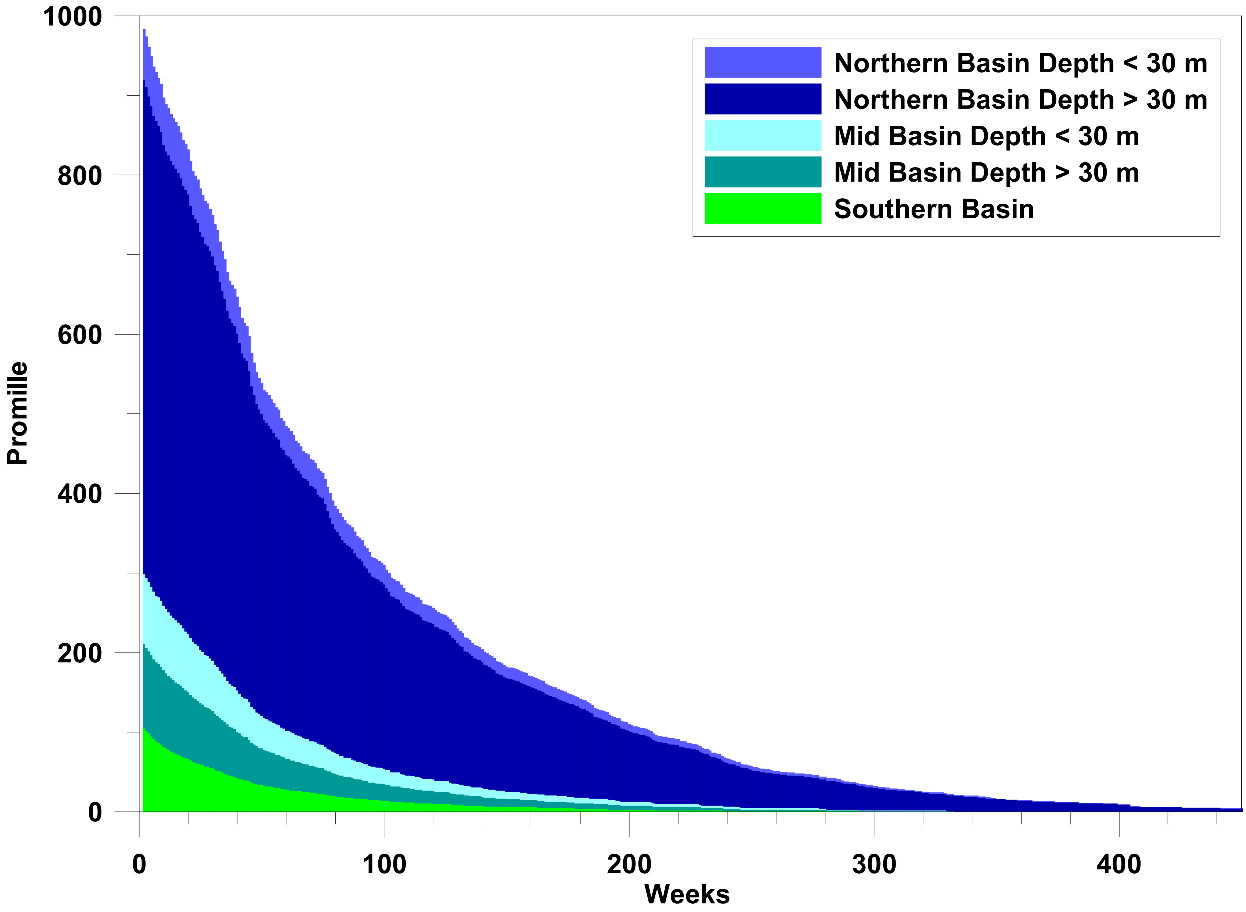

Fig. 6.9: Distribution of water in Loch Lomond over time depending on original position in June 1966 – water originally marked in the whole lake

Fig. 6.9 shows the fate of different lake water bodies over time. For simplicity only five lake compartments were discriminated, these were defined by the three lake basins and additionally for the two deeper basins the vertical water column was separated by an arbitrarily chosen 30 m division. This was chosen because the summer thermocline tends to be strongest around this water depth in Loch Lomond.

The different residence behaviour of the southern and northern basins is quite obvious. Each numerical particle can be traced over time and the time it is leaving the lake can be computed easily. By averaging the individual residence times of tracers it is possible to derive a statistically significant value for a pre-defined tracer ensemble e.g. water marked in the hypolimnion of the northern basin. According to the model results the mean residence times of the five different lake regions chosen vary dramatically. The values range from less than 6 months (South Basin) and more than 4 years (deep sections of the North Basin). This indicates the usefulness of the chosen method providing a very detailed information also for water quality questions in lakes.

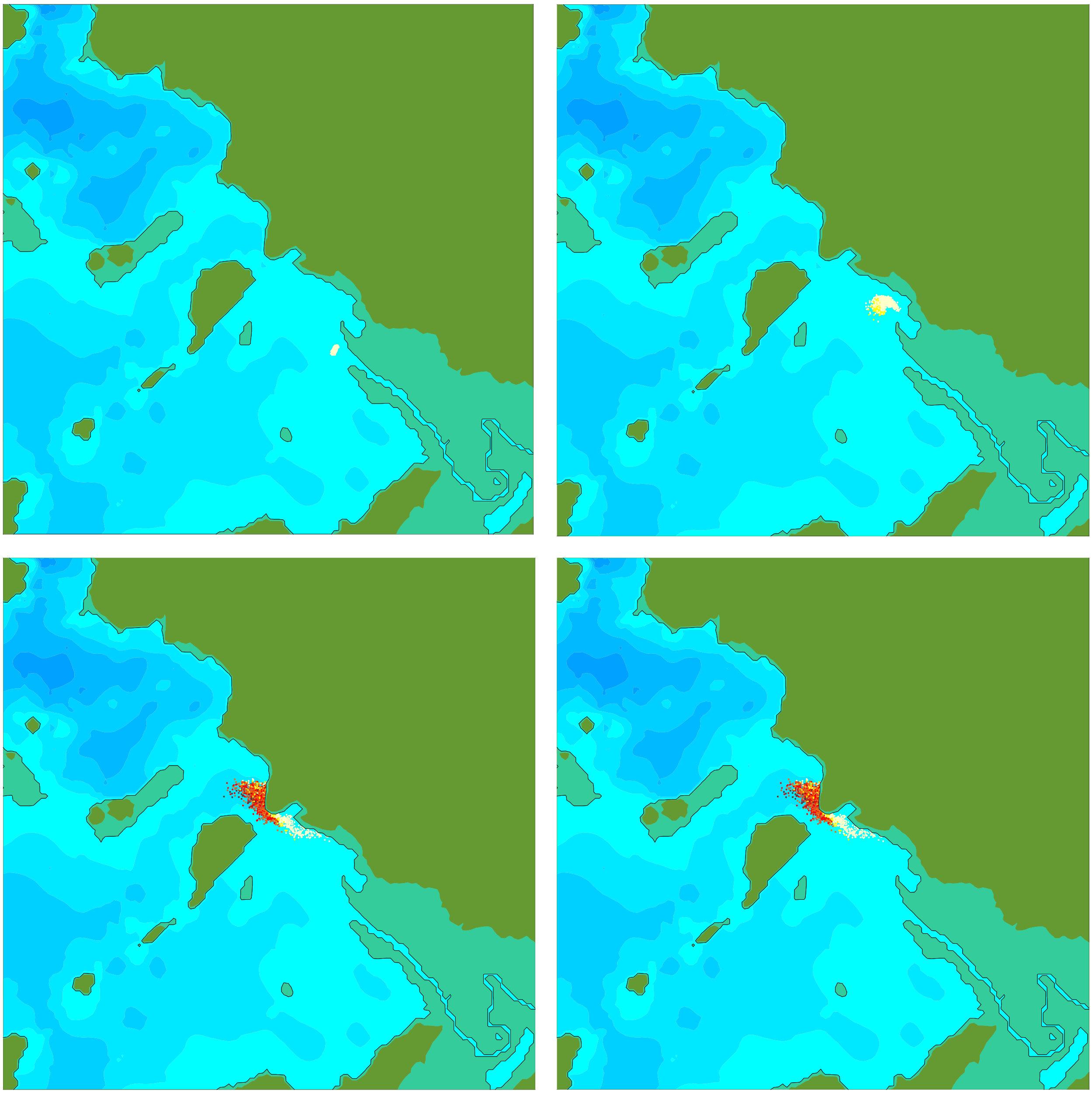

Fig. 6.10: Pathway of water particles marked at the mouth of the River Endrick – snapshot distributions 8 hrs, 16 hrs., 36 hrs and 72 hrs after entry into the lake for southwesterly winds

The same method can be used also to investigate the fate of water entering the lake from different tributaries (or indeed by direct rainfall on the lake surface). Fig. 6.10 shows model results when focussing on the fate of river water from the main tributary of Loch Lomond. Steady state calculations with different main wind directions had already provided hints that depending on the lake circulation pattern during inflow the residence time of Endrick water in the lake may vary between a few days and a few years.

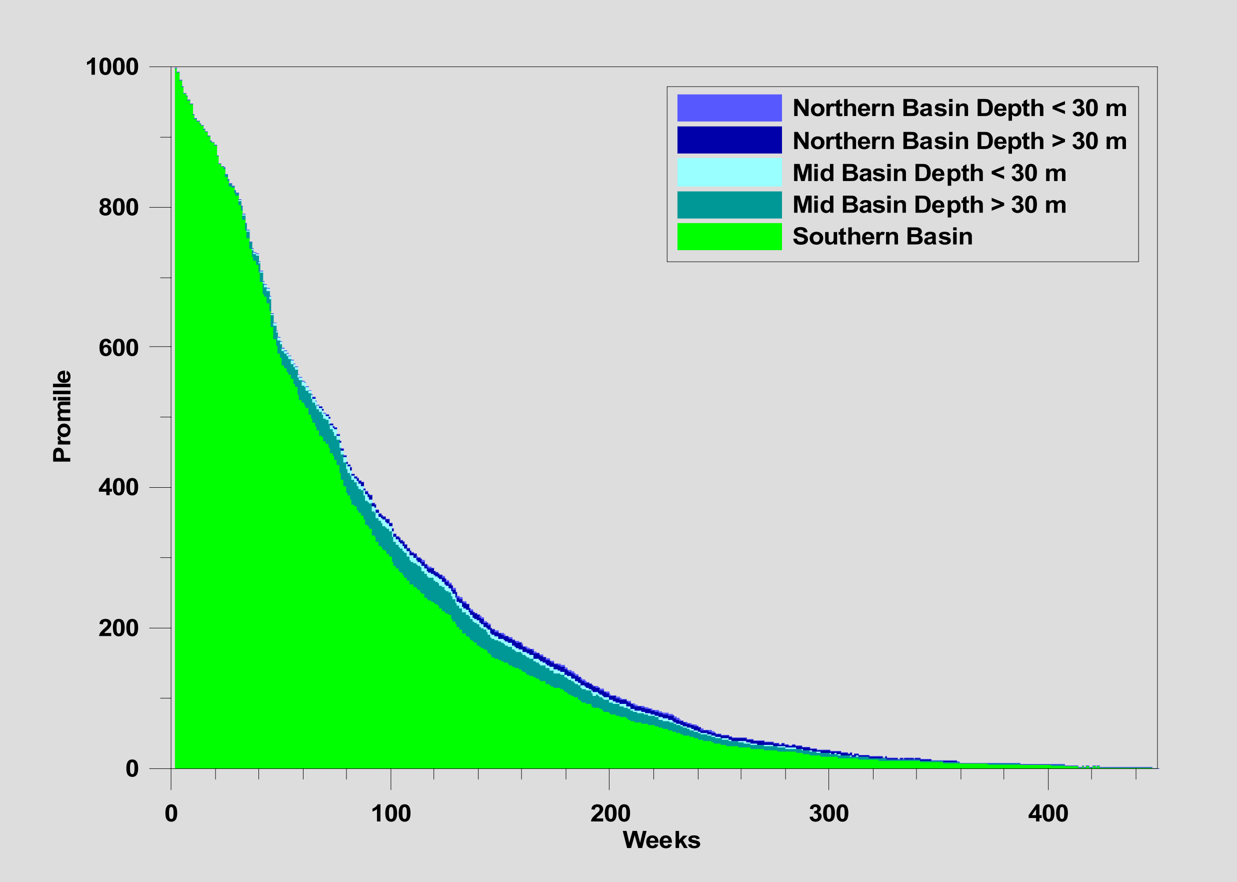

Fig. 6.11: Volume of River Endrick Water (released during June and July 1966) staying in different regions of Loch Lomond over time

This fact taken into account the river water was marked over a time period of two months were the lake circulation was changing very rapidly over time. In fig. 6.11 the remaining volume of water over time is shown for this specifically defined River Endrick inflow - with additional information on how much has left the lake and where the remaining water stays at a given time. Much of the water stays in the southern basin but the small portion which succeeds to enter the mid basin stays there for a relatively long period.

This second example shows a flushing pattern which is very important for Loch Lomond water quality. The relatively nutrient rich water of the River Endrick influences mainly the southern part of the lake, the remaining water in Loch Lomond is predominantly originating from the mountain streams which have a very low nutrient content. This is the reason why nutrient levels in the deep northern part are distinctly lower than in the south.

6.4 CONCLUSIONS

The described model investigations did show the value of using special modelling techniques to obtain a better insight into the transport and dispersion of water masses in large waterbodies like Loch Lomond. The knowledge about these hydrophysical phenomena in deep lakes are a prerequisite to know better the retention time within confined lake compartments or simply fate of river water over a considerable length of time. Loch Lomond with its three distinct sub-basins proved to be a very good shwocase.

The work included a.o. the following main features:

- Wind-driven currents on Loch Lomond (derived from EUROLAKES work package WP 2) have been simulated for all available typical wind fields and associated exchange transport between 1D lake basins were computed. Here very strong upwelling/downwelling events have been recognised.

- 1D computations were done to refine stratification information for wind-driven and density currents in 3D as basis for tracer simulations.

- Specific emphasis was laid upon investigations on the lifetime of water bodies (e.g. flushing within epilimnion).

- Ultimately long-term tracer simulations (> 8 years) were done to derive residence times for individual basins and epilimnion / hypolimnion. Here tracer methods have been used to calculate residence times in different basins by means of combination of typical current fields and meteorological time series from 1966-1976.

In case of Loch Lomond the usefulness of the traditional rule of thumb to derive a mean residence time has proved to be rather doubtful. Depending on the origin of the water (location of tributaries, rainfall) and the local meteorological/hydrological conditions water may have residence times in Loch Lomond between a few days and more than a couple of years.

7 TOWARDS AN IMPROVED METHODOLOGY FOR COMPUTING RESIDENCE TIMES

In the case of deep large lakes like the ones investigated in EUROLAKES the usual concept of residence times is not applicable. In these large waterbodies many physical phenomena interact and produce very variable hydro- and thermodynamical conditions which govern the movement, mixing and dispersion of water and therefore influence the time in which certain defined water masses stay in different locations or where they are subject to similar environmental conditions (like the euphotic zone or in the deep hypolimnion). This fact points to the necessity to go a step forward from a space and time integrated concept of residence times which has so far dominated lake research.

The results of the investigations presented in this report have pointed to two different avenues to improve methodologies for computing residence times taking deep large lakes as case studies:

1. Detection and interpretation of the temporal and spatial distribution of tracers in the field (like e.g. rare elements, radioactive material, a.o.). This has to be combined with the use of models as measurements can only be done in a finite number.

2. Investigation of the probable hydrophysical variability of the given lake with a full three-dimensional model taking into account the variability of the given morphological, hydrological and meteorological conditions which govern the dynamics of the waterbody. This model, however, has to be validated by dedicated measurements. If certain spatial generalisations are found to be allowable these may feed into specially constructed two-dimensional or one-dimensional model tools. These will be more suitable to be refined for the objectives of water quality and even ecological objectives.

In both methodologies a sophisticated approach has to be chosen where field observations and model investigations have to go hand in hand.

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