A methodological approach to characterize the resilience of aquatic ecosystems with application to Lake Annecy, France

Jean-Louis Pinault, F. Berthier

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J.-L. Pinault[1] and F. Berthier[2,3]

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[1] We propose a methodological approach to characterize the resilience of aquatic ecosystems with respect to the evolution of environmental parameters as well as their aptitude to adapt to forcings. This method that is applied to Lake Annecy, France, proceeds in three stages. First, according to the depth, variations of physicochemical parameters versus time are separated into three components related to (1) energy transfer through the surface of the lake, (2) the flow of rivers and springs that feed the lake, and (3) long-term evolution of the benthic zone as a consequence of mineral and organic matter loads. Second, dynamics of the lake are deduced by analyzing the physicochemical parameter components related to the three boundary conditions. Third, a stochastic process associated with the transfer models aims to characterize the resilience of the lakes according to forcings. For Lake Annecy, whose dynamics are representative of oligotrophic stratified lakes controlled by decarbonation processes where turnover and mixing occurring once a year in winter, the major consequence is the impoverishment of dissolved oxygen in deep water in autumn due to a temperature increase of the surface water in summer. The simulation raises relevant questions about whether a connection exists between physicochemical parameters and global warming, which should not induce harmful consequences on water quality and biodiversity in deep water. This methodological approach is general since it does not use any physical conceptual model to predict the hydrosystem behavior but uses directly observed data.

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1. Introduction

[2] The increasing input of anthropogenic nutrients and chemicals into aquatic ecosystems and their effect on water quality is a growing global environmental problem, and the importance of improving our knowledge of the surface geochemical cycle of these substances is therefore increasing [*De Vitre et al.*, 1988; *Balistrieri et al.*, 1994; *Taillefert et al.*, 2000; *Ramstedt et al.*, 2003; *Teubner*, 2003; *Cioni et al.*, 2003; *Faurie et al.*, 2003]. These systems are studied extensively because they strongly affect the economic development of any given area. Diagenesis in the benthic boundary layer and transport processes and biogeochemistry have been studied and modeled in lakes [*Boudreau*, 1987; *Boudreau and Taylor*, 1989; *Boudreau*, 1996]. Mathematical modeling of physicochemical parameter evolution has received considerable attention [*Ulrich et al.*, 1995; *Thébault*, 2004]. This includes reactive transport models to determine the importance of the dynamics of major redox species [*Taillefert and Gaillard*, 2002] and the distribution of metals [*Buffle et al.*, 1989; *Gassama et al.*, 1994; *Zwolsman et al.*, 1997]. Water quality problems in many lakes are closely related to the total phosphorus concentration and several phosphorus models have been developed [*Span et al.*, 1993; *Seo and Canale*, 1996]. Temperature and dissolved oxygen content are two of the principal factors governing water quality in lake hydroecosystems [*Antonopoulos and Gianniou*, 2003]. In stratified lakes, the main sources of oxygen, which are exchanges with the atmosphere and photosynthetic activity of plankton, are confined to the epilimnion. Below the thermocline, dissolved oxygen is consumed by the respiration of organisms living in the hypolimnion (fish, zooplankton, phytoplankton, bacteria) and the oxidation of the large quantities of organic matter that accumulate on the lake bottom during the productive seasons, mainly in spring and summer. Changes in dissolved oxygen cycling patterns have been shown to be a possible indicator of biodegradable organic pollution [*Ansa-Asare et al.*, 2000]. Moreover, these hydrosystems are subject to global warming the consequence of which on biological and physicochemical cycles are to be carefully studied.

[3] The characterization of the resilience of aquatic ecosystems allows understanding their behavior with respect to the evolution of environmental parameters as well as their aptitude to adapt to forcings. Thus we propose a method to

[1]Water Division, Bureau de Recherches Géologiques et Minières, Orléans, France.

[2]Regional Geological Department, Bureau de Recherches Géologiques et Minières, Clermont-Ferrand, France.

[3]Now at Saint-Jorioz, France.

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predict physicochemical parameters and to simulate their behavior that proceeds in three stages:

[4] 1. Physicochemical parameters are predicted by separating their variations into components associated with mass transfer and energy transfer at the interface between surface water and atmosphere, the mass transfer and energy transfer from streams and springs feeding the lake, and the interactions between lake water and sediments in the benthic zone. These three boundary conditions allow modeling of the physicochemical parameters at every depth from linear models. Instead of modeling physicochemical parameters according to depth and time, they are processed independently at every depth to be separated into components according to time. This inverse approach does not relay on a numeric limnologic model, i.e., a physical conceptual model, to predict the behavior of physicochemical parameters, but uses directly observed data of streamflow, surface water temperature and physicochemical parameters at the bottom of the lakes. In this way, the method enables a realistic and an exhaustive description of lake dynamics since the interactions of the water lake with the external environment are deciphered implicitly from the input data. Only the streamflows are measured outside the lakes; both energy and mass transfer through the surface as well as interactions with the benthic zone are deduced from inner parameters. Thus the influence of meteorological conditions is reflected by the surface water temperature, which includes the action of the wind and radiations. Actual exchanges with the benthic zone are conveyed by the physicochemical parameters in deep water, which includes diagenesis in the benthic boundary layer and transport processes and biogeochemistry.

[5] 2. Dynamics and conceptualization of functioning are directly deduced from inverse modeling methodology, by analyzing the components of physicochemical parameters related to the three boundary conditions.

[6] 3. A stochastic process is developed to simulate the behavior of the lakes by forcing input conditions. The surface water temperature as well as the streamflows are simulated by using the Markov chain Monte Carlo and simulated annealing, which is an extension of a method that is commonly used to generate precipitations from the Hastings-Metropolis algorithm [*Metropolis et al.*, 1953; *Hastings*, 1970; *Bardossy*, 1998]. The evolution of the benthic zone being supposed stationary, the calibration of the surface water temperature simulator as well as the streamflow simulator enable the estimation of critical parameters according to their return period.

[7] This methodological approach is applied to Lake Annecy, France, that has been the focal point of numerous research and applied studies involving specific biological analyses [*Domaizon et al.*, 2003] and of internal physicochemical processes [*Loireau et al.*, 2003]. These have enabled short-to long-term reconstruction of past lake behavior, due to anthropogenic and other effects [*Berthier*, 2000]. Lake Annecy has been scientifically characterized since the middle of the 19th century [*Forel*, 1883; *Imhof*, 1883; *Hubault*, 1949; *Balvay*, 1967, 1978]. Although the lake was oligotrophic up until the 1940s, its water quality degraded from the mid-1940s to the 1960s as human activity around the lake increased, in spite of the relatively low population in the catchment area. In the sixties, degradation ceased when a sewer system was installed around the lake and domestic wastewater is now piped to a sewage treatment plant in Annecy, outside of the lake's catchment. The transparency of the lake began improving during the seventies as the thermocline steadily deepened. Since then, a tendency toward oligotrophication has been observed, which validates efforts to improve the water quality. Presently, the summer thermocline is between 6 m and 10 m deep. Between 1966 and 1980, lake water was systematically sampled at various locations and depths and analyzed for physicochemical properties, nutrient concentrations, plankton abundance and diversity in order to determine and monitor water quality. Monthly monitoring began in 1987, and the first multichannel profiles were done for pH, temperature, conductivity and dissolved oxygen. Since then, systematic recording of physicochemical parameter profiles has provided pertinent information concerning lake dynamics. New probes now enable us to measure additional parameters such as light attenuation (data representing transparency) and chlorophyll *a* concentration versus depth.

2. Geological and Hydrogeological Settings

[8] Lake Annecy (Figure 1) is located on the western edge of the Alps. Its catchment extends into the northern part of a transverse valley that separates the Bornes massif to the north and the Bauges massif to the south. The catchment covers a surface area of 278 km^2 at an altitude between 446.97 m (altitude of the lake) and 2357 m. The lake has a surface area of 27 km^2 and an average depth of 41 m. It is made up of two basins, the "Grand Lac" and the "Petit Lac". The larger northern basin (the Grand Lac) accounts for about 78% of the entire lake area and volume.

[9] The lake is fed by numerous tributaries and a small amount of groundwater inflow. The major tributaries are located in the south. (1) The Eau Morte flows into the southeastern end of the Petit Lac. (2) The Ire flows into the southern tip of the Petit Lac. (3) The Laudon flows into the left bank of the Grand Lac at Saint Jorioz.

[10] The Boubioz sublacustrine spring at the maximum depth of the lake, i.e., 82 m, represents the principal groundwater inflow. The Thiou (3.5 km long) is the natural outlet and flows to the Fier River.

[11] The lake's residence times, defined as the ratio of the cumulated annual inflow to the total volume, are 5.6 years for the Petit Lac and 79 years for the Grand Lac. These very different residence times result in different behavior as concerns the oxygenation of deep water. Owing to the river water's high carbonate concentration and conductivity, the lake water has relatively high pH values.

[12] The Lake Annecy depression is the result of early Cretaceous tectonics, although its present shape results from Quaternary glacial digging [*Benedetti-Crouzet*, 1972; *Beck et al.* 2001]. Glacial tongues followed the paleogeographical and structural discontinuities that separated the Bauges Massif to the southwest and the Bornes massif to the northeast. The axis of the Entrevernes syncline, located in the Bauges massif, deepens in the vicinity of the valley, lowering the massive Cretaceous limestone outcrops to the level of the lake. This caused the division of Lake Annecy into the Grand Lac to the north and the Petit Lac to the south. When the last glacier receded about 15,000 years ago [*Negrel et al.*, 1997; *Brauer and Casanova*, 2001], the lake

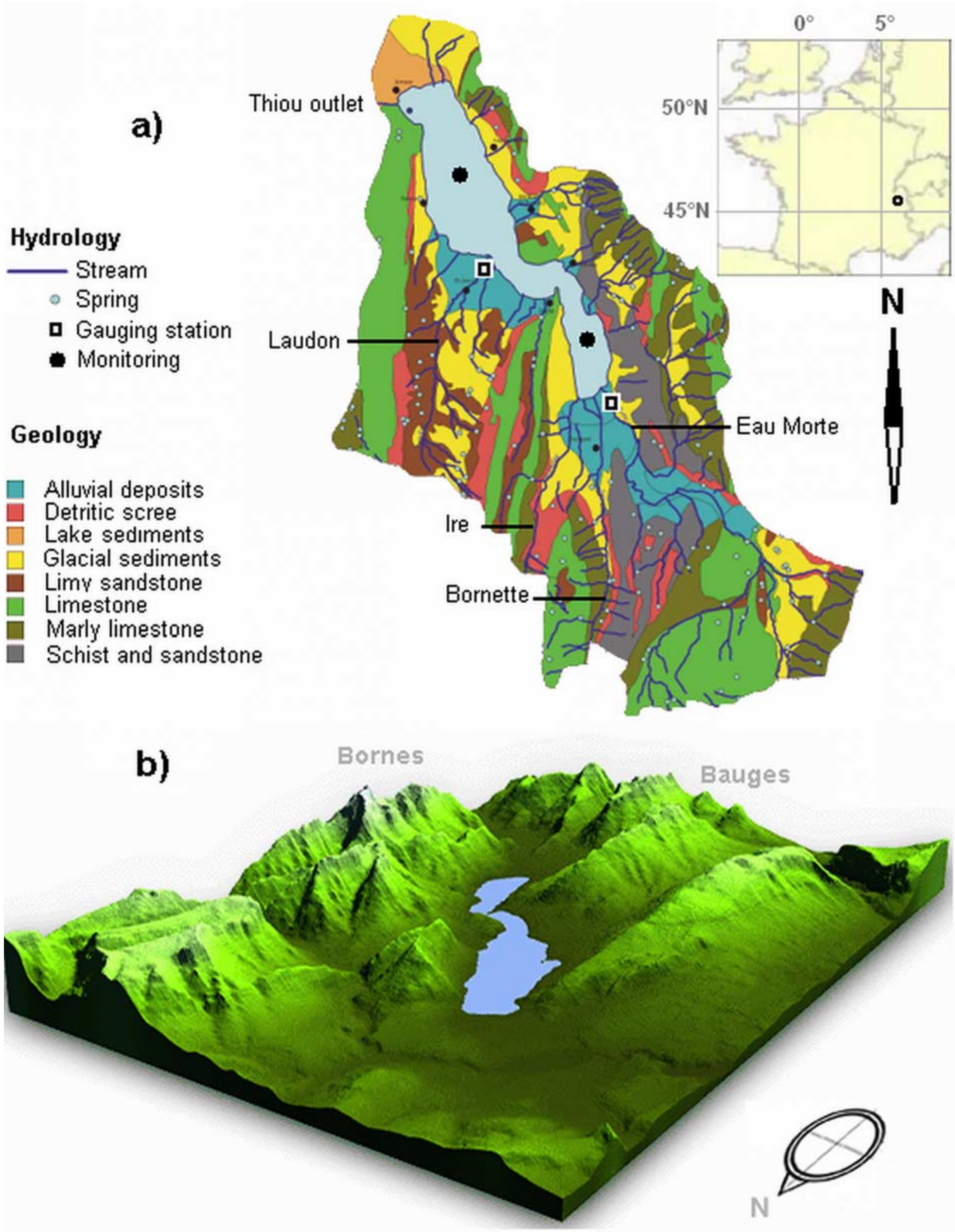

Figure 1. Hydrogeological and geological setting of Lake Annecy: (a) catchment and location of the study area and (b) topography (modified after *Berthier* [2000]).

was larger than it is today and the level of the lake has fluctuated with postglacial climate variations [*Nicoud and Manalt*, 2001; *Magny et al.*, 2001; *Loireau et al.*, 2003].

[13] Being located in Jurassic and post-Jurassic formations, the catchment is 33% limestone and 30% marl. Quaternary moraines and alluvial deposits along the tributary valleys and on the banks of the lake cover 31% of the catchment. Sandstone deposits in the Laudon valley make up the remaining 6%.

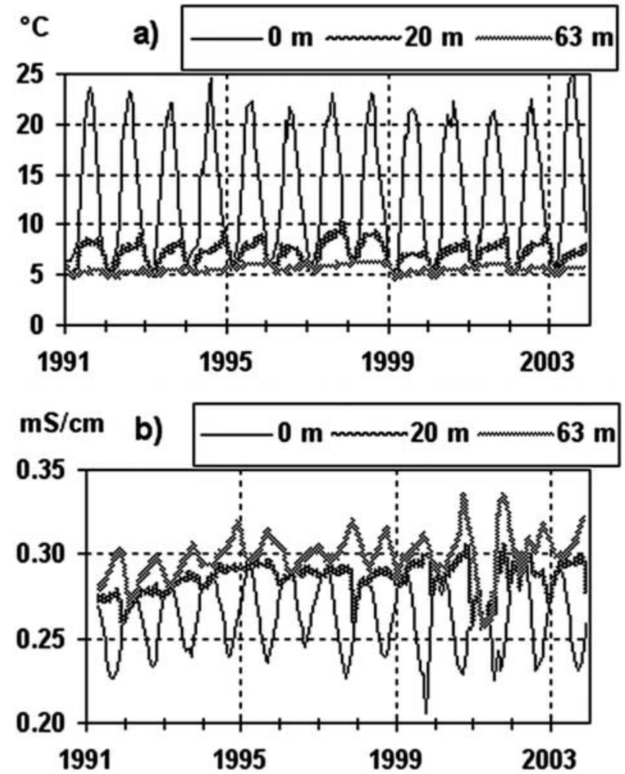

Figure 2. Representation of (a) temperature and (b) conductivity at different depths (Grand Lac). The turnover occurs once a year in spring, which induces mixing of the lake; otherwise the shallow and the deep convection cells are isolated (monthly sampling rate).

[14] The catchment is influenced by both oceanic and continental climates. Average precipitation is about 1.3 m a year. Because of to the abundant rainfall and low temperatures, there is snow in the basin in winter.

3. Lake Dynamics

[15] In summer, the shallow lake water warms up. Since the deep water is colder, and therefore denser, there is little or no mixing of deep and surface waters (Figures 2 and 3a). Since the oxygenation of the lake is due mainly to the photosynthetic activity of plankton and dissolution of atmospheric oxygen, the deep water is poor in oxygen and there are few if any living organisms (Figure 3b). In winter, on the other hand, the shallow water cools and its density increases until the balance is disrupted and the lake water mixes. The lake "turns over", the deep water is oxygenated, and living organisms return to the deep. The oxygenation of deep water in winter and in spring is strengthened by inflows. The turn over and mixing is essential to the physicochemical equilibrium of the lake. The lake water mixes each year in February, March or early April when the temperature of the shallow water drops to around 4°C and it becomes denser than the deeper water (Figure 2). Mixing is efficient since all geochemical parameters are then evenly distributed with depth. The geochemical parameters of the deep water are periodically reset to values that vary little from year to year, whereas the autonomous functioning of deep water causes significant variations in water properties. The turn over creates a memory effect since any long-term evolution of water properties affects the entire lake. Lake Annecy, for which the stratification maintains a stable cool temperature in the hypolimnion as a result of both density effects and decarbonation processes, stands out from published limnology works by *Imberger and Patterson* [1990] and *Wetzel* [2001] where the observed lakes undergo four stages, spring turnover, summer stratification, fall turnover and winter stratification. Moreover, the turn over occurs in Lake Annecy almost at the same time from year to year, which proves that mixing is not sensitive to sustained winds, as mentioned in these papers. In Lake Annecy, turn over seems to be entirely controlled by air temperature and water temperature of inflows.

[16] Conductivity represents for the most part the total concentration of bicarbonate and calcium (Figure 3c). In winter, when the lake is mixed, it is between 0.28 and 0.30 mS/cm, which corresponds to moderately mineralized water. In summer, when the lake is stratified, it is around 0.25 mS/cm in the epilimnion and about 0.29 mS/cm in the hypolimnion and remains almost constant throughout the year. Dissolved oxygen (DO) reaches a maximum and is

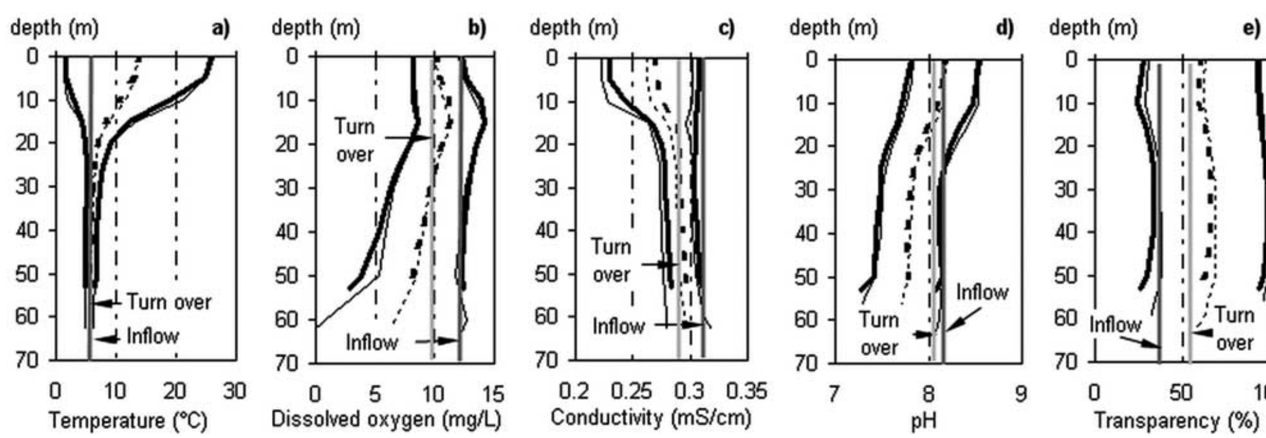

Figure 3. Geochemical parameters versus depth: (a) temperature, (b) dissolved oxygen, (c) conductivity, (d) pH, and (e) transparency. Mean values (thin dotted line for the Grand Lac and thick dotted line for the Petit Lac) and the envelope are defined from the mean plus or minus the standard deviation (thin line for the Grand Lac and thick line for the Petit Lac).

even oversaturated a few meters below the surface where phytoplankton development conditions are optimal (Figure 3b). The dissolution of atmospheric oxygen is maximal in winter when surface water is cold. It decreases with depth, due to the respiration of organisms as well as the oxidization of organic matter, and the minimum value is reached in the benthic zone where organic matter accumulates. Lake Annecy is fed by tributaries that drain calcareous formations and therefore has an alkaline pH (Figure 3d). The pH is higher than the average value (about 8) in the epilimnion when phytoplankton develops, due to the alkalinization of shallow water when there is photosynthesis. It is around 7.5 in the hypolimnion, the minimum value being reached in the benthic zone. Transparency is highly variable from year to year (Figure 3e). It is generally low in deep water, particularly at the contact of sediments.

[17] The maximum streamflow in tributaries is reached in winter due to abundant rainfall and snowmelt. The geochemical properties of Eau Morte River, which contributes about 40% of the tributary inflow, are considered to be representative of the other tributaries (Figure 3). Conductivity, which is governed mainly by calcium and bicarbonate ions, is always higher than the highest values measured in the lake (calcium concentration is about 80 mg/l). It is about 0.32 mS/cm (at 25°C) during high-flow stages, while the DO content is near the saturation value. Although the river water is cold in winter (about 6°C), temperatures can rise to more than 10°C in spring. River pH values are between 7.5 and 8.4 and the difference between river and lake values is small and may be inverted depending on the depth in the lake and the season.

[18] Thanks to lake development efforts and the new sewer system around the lake, eutrophication has stopped and quality indicators show that nutrients are globally decreasing [*Syndicat Intercommunal du Lac d'Annecy*, 1998]. In particular, the nitrate concentration has stabilized since 1993 at around 250 μgN/L, twice the 1968 level, and the phosphate concentration, after increasing sharply during the seventies, has been decreasing since 1988 and is now between 2 and 8 μgP/L, which is well below values in Lake Geneva (45 μgP/L) and Lake Bourget (about 60 μgP/L [*Span et al.*, 1993]). The oxygenation of deep water has improved since the mid-1990s (2 to 4 mg/L of DO), whereas anoxic conditions were observed in summer 1990. Lake transparency has been improving since the end of the sixties, which indicates a drop in algae populations. Diatom algae replaced the cyanobacteria as early as the sixties and the populations of both phytoplankton (about 2 μg/L achlorophyll *a*) and zooplankton have stabilized. Populations of carnivorous fish such as trout have grown since the lake water quality stabilized. Nevertheless, there were algae blooms in 1995 and 1997 for no apparent reason, which proves that the ecological balance of the lake is still fragile.

[19] Carbon dioxide production from organic matter produces protons according to the simplified exothermic reaction (1), as well as reactions (2) and (3):

$$CH_2O + O_2 \rightarrow CO_2(aq) + H_2O \tag{1}$$

$$CO_2(aq) + H_2O \leftrightarrow HCO_3^- + H^+ \tag{2}$$

$$H_2CO_3 \overset{K1}{\longleftrightarrow} H^+ + HCO_3^- \overset{K2}{\longleftrightarrow} 2H^+ + CO_3^{2-} \tag{3}$$

[20] Conductivity is governed by reaction (3) such that pK_{a1} = 6.4 and pK_{a2} = 10.3 at 25°C. The pH is between 7.25 and 8.75 (Figure 3d), which corresponds to the stability domain of bicarbonate ions.

[21] Zooplankton respiration can be represented by reaction (1). The formation of carbonates (mainly calcium carbonate) causes both pH and conductivity to decrease since carbonates precipitate (decarbonation):

$$Ca^{2+} + HCO_3^- \leftrightarrow CaCO_3 + H^+ \tag{4}$$

Reaction (5) governs oxygen dissolution:

$$O_2(g) \leftrightarrow O_2(aq) \tag{5}$$

Reaction (6) governs carbon dioxide dissolution:

$$CO_2(g) \leftrightarrow CO_2(aq) \tag{6}$$

[22] Both oxygen and carbon dioxide dissolution are enhanced by low temperature. For a given temperature T, Henry's law governs the oxygen and carbon dioxide concentrations S in surface water. It gives S_{O2} =13.37 mg/L at 4°C, S_{O2} = 9.25 mg/ at 20°C, S_{CO2} = 0.99 mg/L at 4°C, and S_{CO2} = 0.53 mg/L at 20°C.

4. Inverse Modeling Methodology

[23] Several phenomena contribute to the migration of ions, DO and solid particles from the boundaries to the core of the lake: (1) river inflow, mainly when the turn over is occurring, (2) diffusion when there is a concentration gradient and convection, (3) energy transfer to and from the surface leads to the production of DO by phytoplankton and vegetation in the euphotic zone and, moreover, photosynthesis alkalinizes the shallow water, (4) the downward migration to deep water of zooplankton and its consumption of oxygen, and (5) the migration down to the benthic zone of suspended organic matter that consumes oxygen.

[24] The boundary conditions in the benthic zone depend on the evolution of physicochemical parameters in the lake. For instance, the organic matter load depends on the development of phytoplankton and zooplankton during previous years.

[25] Although the evolution of lake dynamics is dependent on the concentration of nutrients such as nitrate, phosphate and silica that are not monitored, their long-term contribution is taken into account through the DO concentration, as a global indicator of water quality. The short-term variations in nutrient concentrations are also taken into account indirectly in the models since they are subject to the contribution of tributaries and to the temperature of the shallow water, now that human activity no longer impacts water quality.

[26] Data processing is done using the TEMPO code [*Pinault*, 2001]. The transfer model architecture required for the separation is shown in Figure 4. The use of linear transfer models requires that the physicochemical parameters being modeled undergo linear processes, which is not

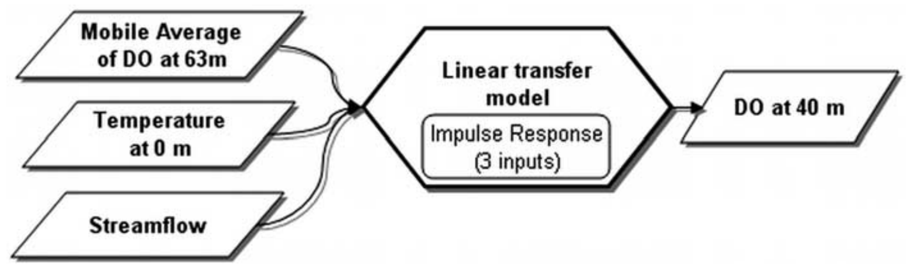

Figure 4. Flowchart of dissolved oxygen inverse modeling (Grand Lac). The raw data are interpolated and aggregated to create a continuous 15-day sampling period. The inputs of the model are the mobile average of dissolved oxygen at a depth of 63 m, the surface water temperature, and the Laudon River inflow. The output is dissolved oxygen at a depth of 40 m. Temperature and dissolved oxygen are expressed according to their reference level.

true for chlorophyll *a* that reflects the development of algae blooms whenever circumstances are favorable. Such chaotic phenomena are strongly nonlinear and, consequently, cannot be modeled using this technique.

[27] In a general point of view, the number of components is set from the inputs of the inverse models, provided they are not strongly correlated, which means separating spatial coordinates and time [*Pinault et al.*, 2001a, 2001b, 2004, 2005, 2006].

[28] Since the inverse models are not altered when input and output are multiplied by a positive number, all data are transformed to be dimensionless. The physicochemical parameters that are expressed according to time and depth are supposed to be entirely defined from three boundary conditions: (1) streamflow at the input of the lake, (2) surface water temperature, and (3) long-term variations of physicochemical parameters close to sediments.

[29] Streamflow is related to fluxes from rivers and springs at the input of the lake: thermal flux, dissolved oxygen flux, flux of conductive ions, protons and solid particles. They are assumed to be proportional to streamflow when inflow has a significant impact on the functioning of the lakes, i.e., during floods. These assumptions have been verified for each parameter whose mean value is given in Figure 3. Both Eau Morte River and Boubioz spring have been monitored, and the stability of the physicochemical parameters during the floods as well as a close correlation between temperature and conductivity of Eau Morte River and Boubioz spring were confirmed.

[30] Surface water temperature is the result of an energy balance at the interface between atmosphere and water: heating from electromagnetic wave absorption in water, heat exchanges by conduction between atmosphere and water, energy dissipation from the lake to the atmosphere, chemical and biochemical reactions in the lake as well as convection and mixing into the lake.

[31] Long-term variations of physicochemical parameters close to sediments result in long-term chemical processes in the sediments such as diagenesis, oxidation and mineralization of organic matter. They are estimated from the mobile average of the corresponding parameters measured in water, close to the sediments. The mobile average is applied with 1-year duration to filter the contribution of mass transfer and energy transfer from both the atmosphere and the rivers, which are characterized by a 1-year periodicity (Figure 5). The cross correlograms of long-term variations of dissolved oxygen, conductivity and pH to temperature in the benthic zone are shown in Figure 6a. The cross correlation is positive for conductivity and negative for pH and dissolved oxygen. This means that the temperature is controlled mainly by both the oxidation and the mineralization of organic matter according to the exothermic reactions (1) and (2). The cross correlation of dissolved oxygen to transparency is positive, which suggests that the transparency is mainly controlled by the oxidation of organic matter (Figure 6b): the higher the microorganism concentration, the lower the oxygen concentration in the benthic zone as a result of oxygen demand for the mineralization process. On the other hand, the absence of correlation between the pH and the transparency in the benthic zone shows that clay and clay minerals do not contribute significantly to the transparency of the lake. Indeed, the flocculation of clays would have been enhanced if the protons have compensated for the negative electrical charge. For the same reason, the decarbonation process that produces protons (equation (4)) has no effect on transparency.

[32] Let Q(t) be the flow of a river considered as representative of inflow from surface water and springs, $T_0(t)$ the surface water temperature and $P_b(t)$ the physicochemical parameter P observed in the benthic zone. The parameter $P_z(t)$ at depth can be written such that:

$$\Delta p_z(t) = \lambda_1.\boldsymbol{\Gamma}_1 * \mathbf{q} + \boldsymbol{\lambda}_2.\boldsymbol{\Gamma}_2 * \boldsymbol{\Delta}\mathbf{t}_0 + \boldsymbol{\lambda}_3.\boldsymbol{\Gamma}_3 * \boldsymbol{\Delta}\mathbf{p}_b + \varepsilon \quad (7)$$

where * represents the discrete convolution product $\boldsymbol{\Gamma}_1$, $\boldsymbol{\Gamma}_2$ $\boldsymbol{\Gamma}_3$ are normalized impulse responses (the area being unity) λ_1, λ_2 and λ_3 are weighting factors. Dimensionless parameters $\Delta p_z(t)$, $q(t)$, $\Delta t_0(t)$ and $\Delta p_b(t)$ are such that

$$\Delta p_z(t) = (P_z(t) - \alpha)/\overline{(P_z(t) - \alpha)} \quad (8)$$

$$q(t) = Q(t)/\overline{Q}(t) \quad (9)$$

$$\Delta t_0(t) = (T_0(t) - \beta)/\overline{(T_0(t) - \beta)} \quad (10)$$

$$\Delta p_b(t) = (P_b(t) - \delta)/\overline{(P_b(t) - \delta)} \quad (11)$$

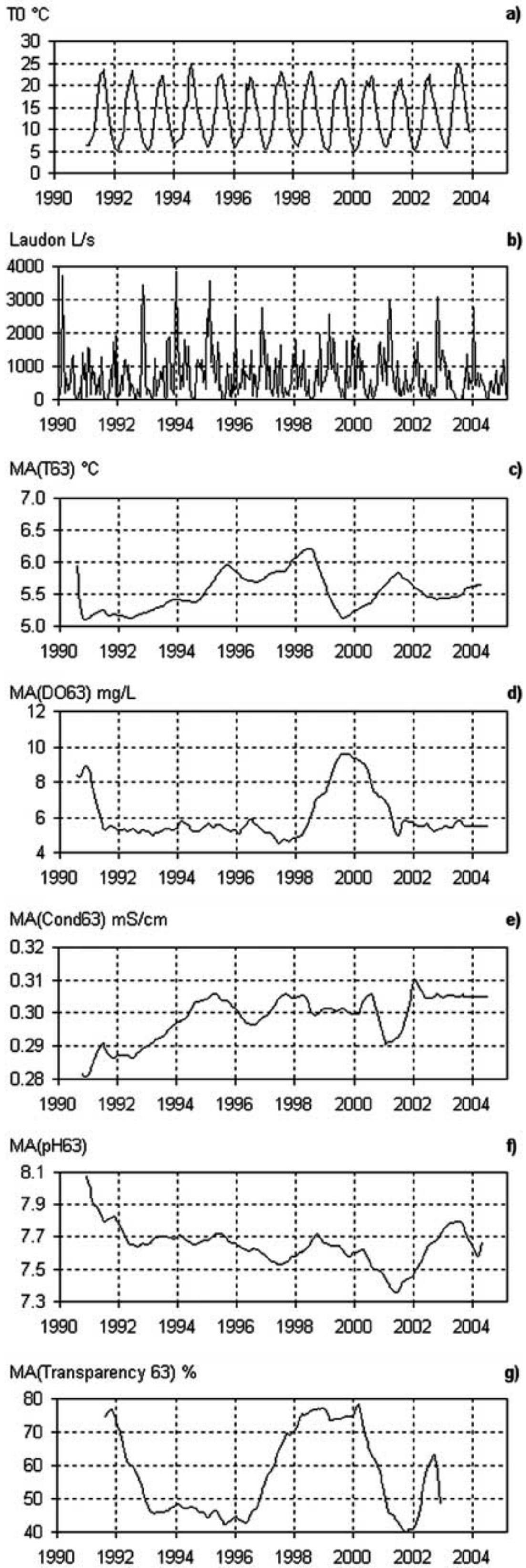

Figure 5. Representation of the boundary conditions of the linear models (Grand Lac): (a) surface water temperature, (b) Laudon flow, (c) mobile average (MA) of water temperature at 63 m, (d) MA of dissolved oxygen at 63 m, (e) MA of water conductivity at 63 m, (f) MA of pH at 63 m, and (g) MA of transparency at 63 m.

where α, β and δ are the reference levels of $P_z(t)$, $T_0(t)$ and $P_b(t)$, respectively. The symbol $\overline{X}(t)$ represents the average of the positive function $X(t)$.

[33] The terms $\lambda_1 m_{\Delta pz} \mathbf{\Gamma}_1 * \mathbf{q}$, $\lambda_2 m_{\Delta pz} \mathbf{\Gamma}_2 * \Delta \mathbf{t}_0$ and $\lambda_3 m_{\Delta pz} \mathbf{\Gamma}_3 * \Delta \mathbf{p}_b$ where $m_{\Delta pz} = \overline{P_z(t) - \alpha}$ represent the contribution to the variations of parameter $P_z(t)$ at depth z of inflow, mass transfer and energy transfer to or from the lake surface, and the contribution of the benthic zone. The random part ε, the mean of which is zero, represents erratic, complex, and usually short-term variability of the parameter P_z that is not explained by the model, including measurement errors, whether they are due to instrumentation or sampling defects.

[34] Impulse responses $\mathbf{\Gamma}_1$, $\mathbf{\Gamma}_2$ and $\mathbf{\Gamma}_3$ are defined so that

$$\begin{aligned} &\Gamma(t_i) = A.\exp\left(-\ln(2)((t_i - B)/D)^2\right) * \exp(-t_i.\ln(2)/L) \\ &\text{if } 0 \le t_i \le \tau \\ &\Gamma(t_i) = 0 \text{ elsewhere} \end{aligned} \tag{12}$$

[35] In this model, the broadening of the impulse response due to dispersive and diffusive effects is represented by the Gaussian $\exp(-\ln(2)((t_i - B)/D)^2)$ while the exponential law $\exp(-t_i.\ln(2)/L)$ points to the return to the initial state of the response. Parameter B represents the delay of the response process after a short variation (impulse) of the input whereas parameter D represents the duration of the response, L is the recession parameter, A is the normalization constant. Because of its small number of degrees of freedom (3 per impulse response), this parametric model does not need any regularization technique to be calibrated.

[36] The reference level α is estimated so that:

$$\alpha = m - \chi.\sigma \tag{13}$$

where m and σ are the mean and the standard deviation of P_z respectively. The parameter χ takes the value 2.5 while the regulation time of the parameter P_z is less than one year, which corresponds to a 160-year return period of P_z when P_z follows a Gaussian distribution. The other reference levels β and δ are estimated in the same way.

[37] Equation (7) represents the response of parameter P_z to the variations of the three boundary conditions represented by the functions q, Δt_0 and Δp_b, which are positive almost everywhere due to the definition of the reference levels. Since impulse responses and weighting factors are positive, this equation assumes that the parameter P_z reacts positively to input variations. When this is not the case, the corresponding input is replaced by its opposite in equations (9) and (10):

$$q(t) = (-Q(t) - \gamma)/\overline{(-Q(t) - \gamma)} \tag{14}$$

$$\Delta t_0(t) = (-T_0(t) - \beta')/\overline{(-T_0(t) - \beta')} \tag{15}$$

where γ and β' are the reference levels of $-Q(t)$ and $-T_0(t)$ calculated from (13) in such a way that $q(t)$ and $\Delta t_0(t)$ are still positive functions almost everywhere. The influence of the parameter P_b of the benthic zone always induces a

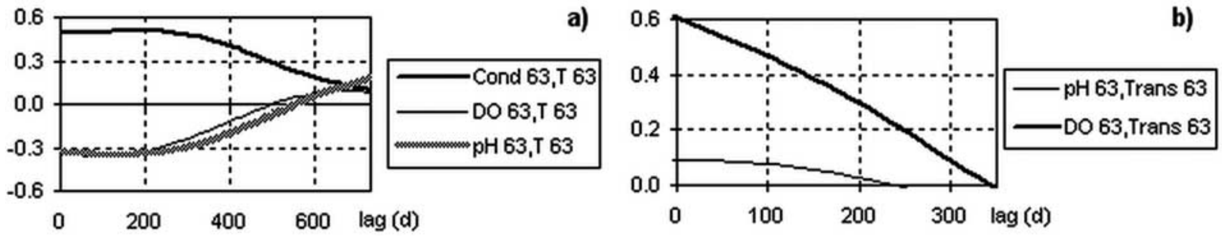

Figure 6. (a) Cross correlogram of long-term variations of conductivity, dissolved oxygen, and pH to temperature in the benthic zone. (b) Cross correlogram of long-term variations of pH and dissolved oxygen to transparency

positive response of the parameter P_z to be modeled so that this transformation is useless for this boundary condition.

[38] Equation (7) is invertible when the inputs are not strongly correlated, which assumes that the cross correlogram obtained from each pair of inputs is lower than 0.75, whatever the lag such that $|\text{lag}| \leq \tau$ where τ is the duration of impulse responses. Actually, the duration of impulse responses is always less than 250 days, which is in good agreement with the duration of the observation period (13 years).

5. An Example: Processing of Conductivity at 10 m (Grand Lac)

[39] The different steps of processing are shown in Figure 7. The inflows are positively correlated to conductivity at 10 m because the conductivity of stream water is always higher than that of lake water at this depth, particularly during floods (Figure 7a). The boundary condition at the interface represented by the temperature of water at the surface is negatively correlated to the conductivity at 10 m. This boundary condition strongly influences the behavior of the conductivity at this depth since the corresponding cross correlogram reaches -0.9 for a 40-day lag. The inputs associated with the three boundary conditions are given by equations (9), (15), and (11).

[40] The inputs are not strongly correlated with each other (Figure 7b), including the parameters related to the interface and to inflows whose periodicity is one year for both. Whereas the surface water temperature varies regularly from one year to the next, the flow of the Laudon undergoes strong annual variations depending on rain and snow fall in the catchment (Figure 5b). The interannual variability of inflows decreases their cross correlation with the surface water temperature. The parameter that is representative of the benthic zone is the mobile average of the conductivity observed at 63 m, near the bottom of the lake. The 1-year periodicity is filtered by the mobile average and only long-term variations become evident (Figure 5e). It is therefore correlated with neither the surface water temperature nor the inflows for lags of less than 150 days.

[41] Figure 7d shows the components relative to the three inputs. The strong influence of the interface is confirmed by its weight, 79%, whereas the weights associated with inflows and the benthic zone are 8% and 13%, respectively. Impulse responses (Figure 7e) reveal a rapid interaction between the interface and conductivity at 10 m, whereas the influence of the benthic zone is more delayed. The mean lags calculated from the impulse responses are the mean transit times associated with the interactions. They are 55, 36 and 79 days for interactions related to the inflows, the interface and the benthic zone, respectively.

[42] The model that uses the continuous transport equation (7) explains more than 90% of the variance of the observations (Figure 7c) although the turnover that is responsible for the homogenization of the lakes in winter occurs suddenly at the 15-day timescale fixed by the sampling step. The continuous approximation is therefore acceptable for modeling the outputs $\Delta p_z(t)$ such as the conductivity at 10 m even though these parameters vary rapidly when the turn over occurs (Figure 2).

6. Functioning of the Lakes

[43] The following calculations are done for both lakes. Although their behavior is similar, the metalimnion is shallower in the Petit Lac than in the Grand lac and the watershed area/lake volume ratio is reversed. The dynamics of the Petit Lac are therefore more closely linked to the contribution of river water and the evolution of deep water properties from eutrophic to oligotrophic conditions is less noticeable than in the Grand Lac.

[44] The separation of physicochemical parameter variations into three components related to inflows, the interface and the benthic zone are shown in Figure 8 for the Grand Lac and in Figure 9 for the Petit Lac. The inputs that are related to the inflow and the interface are never strongly correlated to the parameters P_b representative of chemical reactions in the benthic zone since the P_b parameters are processed to filter the influence of inflows and surface water temperature that both undergo a strong annual periodicity. Mean transit times of fluxes are represented in Figures 10 and 11 for both lakes.

6.1. Heat Propagation

[45] The inflows do not contribute to lake temperature, whatever the depth (Figures 8a and 9a). The contribution of the tributaries is low since there is little difference in temperature between river and deep lake water in winter when there is significant tributary inflow (Figure 3a). For both lakes, the metalimnion is a thermal barrier. Indeed, the epilimnion temperature is controlled solely by the surface water temperature, whereas the hypolimnion temperature is strongly influenced by chemical reactions in the benthic zone, the influence increasing with depth, which is particularly prominent in the Grand Lac. Heat propagation is rapid in both compartments (Figures 10a and 11a), whether induced from the surface or from the benthic zone, whereas it is delayed through the metalimnion, which acts as a

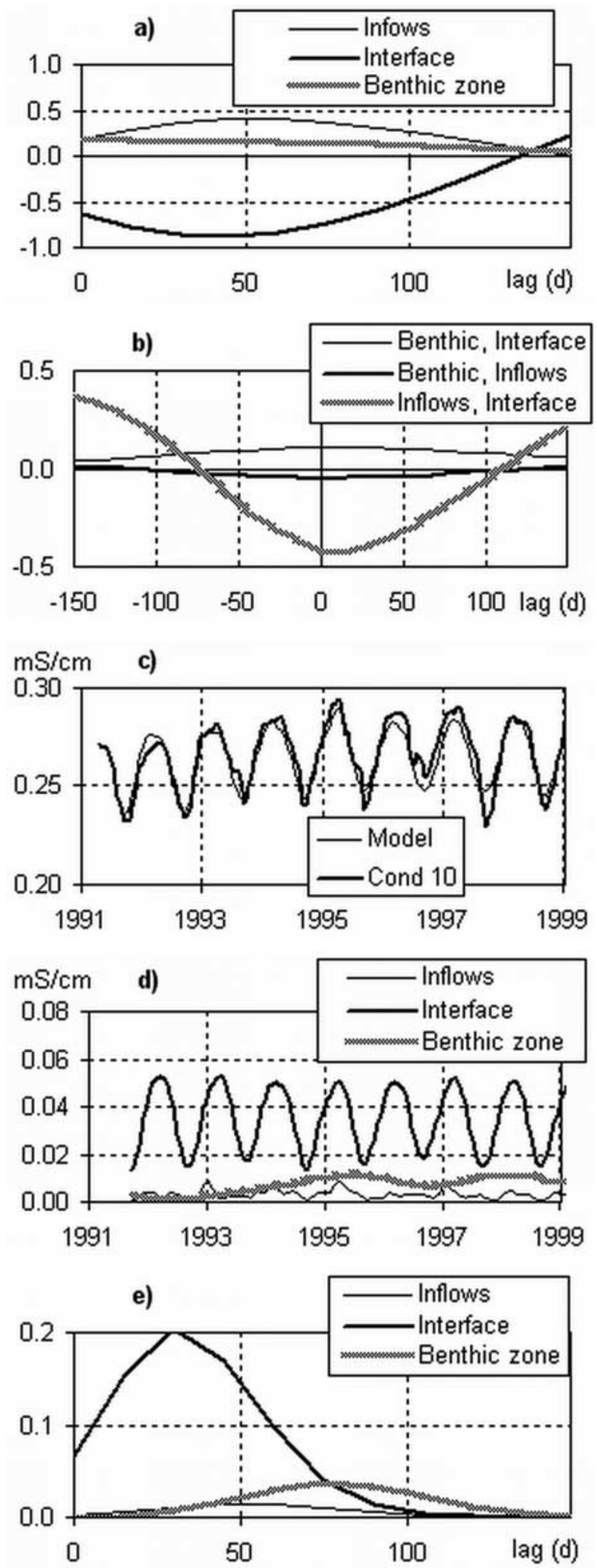

Figure 7. Processing of conductivity at 10 m (Grand Lac): (a) cross correlations between the inputs and the output, (b) cross-correlations between the inputs, two by two, (c) the model given by equation (7) and observations (more than 90% of the variance is explained by the model), (d) separation of the output, and (e) weighted impulse responses whose areas are the weighting factors given by equation (7)

thermal barrier except during turn over. The epilimnion temperature results mainly from thermal transfer through the surface, which triggers the turn over in winter. The temperature can reach 25°C at the end of summer.

6.2. Dissolved Oxygen Transport

[46] The dissolved oxygen content in deep water reflects the evolution of water quality since it depends on the organic matter load in the benthic zone. This load depends on phytoplankton and zooplankton populations, which decrease with nutrient concentrations.

[47] Tributaries contribute to the oxygenation of the lake at every depth (Figures 8b and 9b), the mean transit time of DO propagation being between 100 and 150 days (Figures 10b and 11b). During winter, DO in stream water, which is about 12 mg/L during peak flow (Figure 3b), is higher than in the lake. Nevertheless, in both lakes, the greatest contributor is the interface. The oxygenation of the epilimnion results from both the dissolution of atmospheric oxygen, which occurs mainly in winter in cold water, and photosynthesis, which is most efficient in summer when phytoplankton develops in the euphotic zone. DO migrates rapidly from the surface to deep water through the metalimnion (70 days). The forces driving the downward flux of DO are turn over and diffusion. The epilimnion does not undergo the influence of the benthic zone, as opposed to DO in the hypolimnion, which depends strongly on the oxygen demand at the bottom of the lake, the mean migration time being about 100 days in the Grand Lac and 60 days in the Petit Lac (Figures 10b and 11b). DO in the epilimnion is oversaturated in summer when the concentration reaches 13 mg/L.

6.3. Ion Transport

[48] The conductivity of tributaries, 0.32 mS/cm during peak flow, is higher than that of the lake throughout the year (Figure 3c). On the other hand, the pH of stream water, 8.2, is close to the mean value of that of the epilimnion but higher than that of the hypolimnion (Figure 3d). Made up mainly of calcium carbonate, the ions supplied by tributaries migrate slowly in the hypolimnion, the mean transit time being more than 150 days in both lakes (Figures 10c and 11c). In both lakes, the influence of the surface water temperature on conductivity and pH is the opposite of what it is in the epilimnion and the hypolimnion (Figures 8c, 8d, 9c, and 9d). In the epilimnion, the conductivity decreases and the pH increases as the surface water temperature increases. Both parameters indicate that the epilimnion is controlled by the dissolution of carbon dioxide, which is an exothermic reaction (2), whereas the hypolimnion is controlled by the decarbonation process, which is an endothermic reaction (4). The pH in the epilimnion is also controlled by alkalinization of shallow water in the euphotic zone as a result of phytoplanktonic photosynthesis. The dissolution of CO_2 in the epilimnion occurs mainly at the end of winter and the beginning of spring since the mean transit time is very short, less than 30 days (Figures 10c, 10d, 11c, and 11d) while the decarbonation process in the hypolimnion is active mainly in autumn since the mean transit time is about 50 days in the Grand Lac, a little higher in the Petit Lac. The decarbonation process in the hypolimnion is, however, strongly controlled by the benthic zone in both lakes (Figures 8c and 9c).

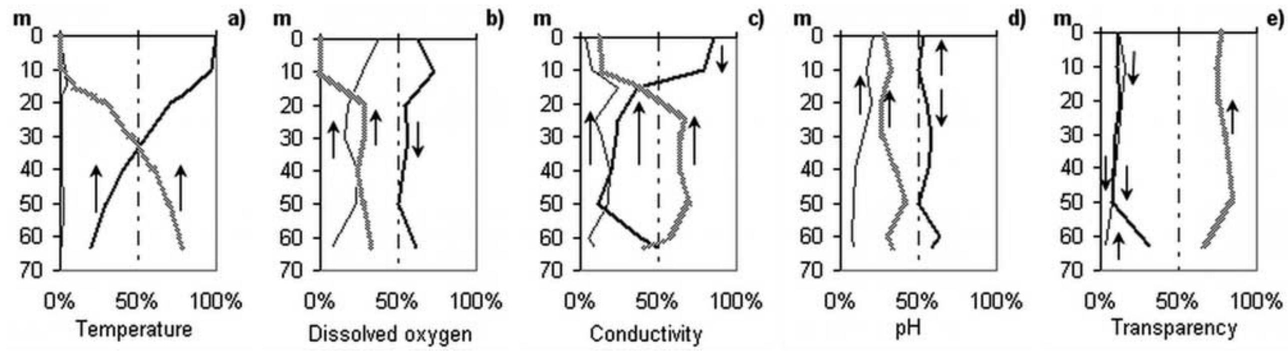

Figure 8. Separation of physicochemical parameter variations of the Grand Lac into the three components related to the three inputs (the inflows (thin black line), the interface (thick black line), and the benthic zone (thick gray line)) versus depth. (a) Temperature, (b) dissolved oxygen, (c) conductivity, (d) pH, and (e) transparency. The arrows point up or down depending on whether the parameter is positively or negatively correlated to the corresponding input.

6.4. Transport of Solid Particles

[49] For both lakes, transparency is almost entirely controlled by the benthic zone at every depth (Figures 8e and 9e) since mineralization processes are strongly controlled by the available oxygen, which depends on the organic matter load at the bottom of the lakes. Improvement of transparency is visible up to the surface when the oxygen demand of the organic matter and zooplankton is reduced.

7. Lake Annecy in the Context of Climate Changes

[50] Whereas the lake stratification maintains a stable cool temperature in the hypolimnion as a result of both density effects and decarbonation processes, the DO in the benthic zone depends strongly on the temperature of surface water in the lake and inflows (Figures 8b and 9b). An increase of a few degrees in the surface water temperature can cause a drastic decrease in DO in the benthic zone, all the more so as it is correlated with a decrease in inflow as has been observed over the last 13 years. The average maximum surface water temperature observed from 1991 to 2002 is 22.84°C, the standard deviation being 1.01°C. The surface water temperature reached 25.0°C in 2003 during a heat wave in Western Europe. Assuming a Gaussian distribution of the maximum surface water temperature, the return period for such a value is about 60 years. In the context of climate warming, such temperatures will be increasingly frequent. This could have severe consequences on the functioning of deep lakes since the DO in the benthic zone, which reaches its minimum in autumn, depends strongly on the surface water temperature in summer. According to Henry's law (5), a high surface water temperature leads to a deoxygenation of the surface water (Figure 3b). The DO at the surface of the lake may drop to 9 mg/L in summer while DO in the epilimnion exceeds 13 mg/l due to phytoplankton, inducing a steep concentration gradient.

[51] In order to evaluate the impact of global warming on the functioning of Lake Annecy, a stochastic process is developed to simulate an increase of a few degrees in the maximum surface water temperature. This process has already been developed virtually by *Pinault et al.* [2005] for simulating the influence of long-term rainfall fluctuations on the return period of groundwater-induced floods. Here the parameters to be simulated are the surface water temperature of the lakes and inflows. The direct simulation of these parameters implicitly takes into account energy transfer processes from the atmosphere to the lake including the absorption and emission of infrared radiation and heat conduction between water and atmosphere enhanced by the wind. In the same way, the simulation of inflows implicitly integrates rainfall, evapotranspiration, snowmelt and the

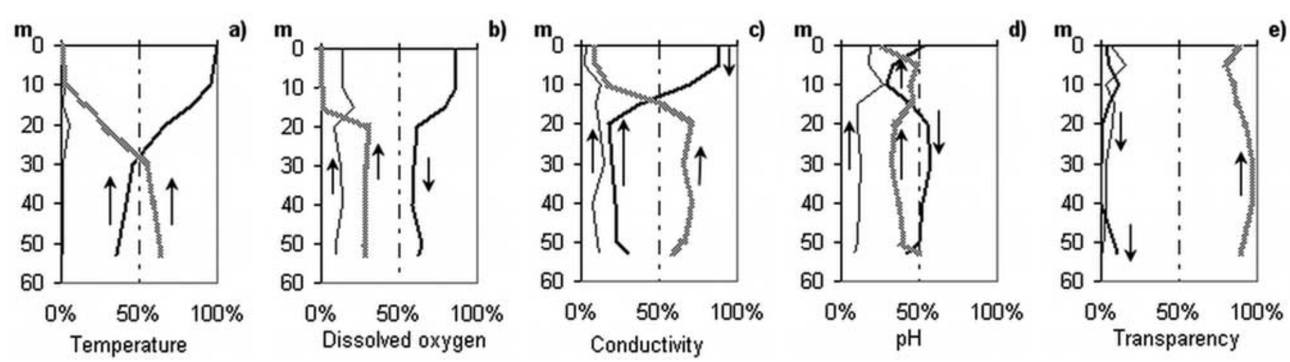

Figure 9. Separation of physicochemical parameter variations of the Petit Lac into the three components related to the three inputs. The conventions are the same as in Figure 8.

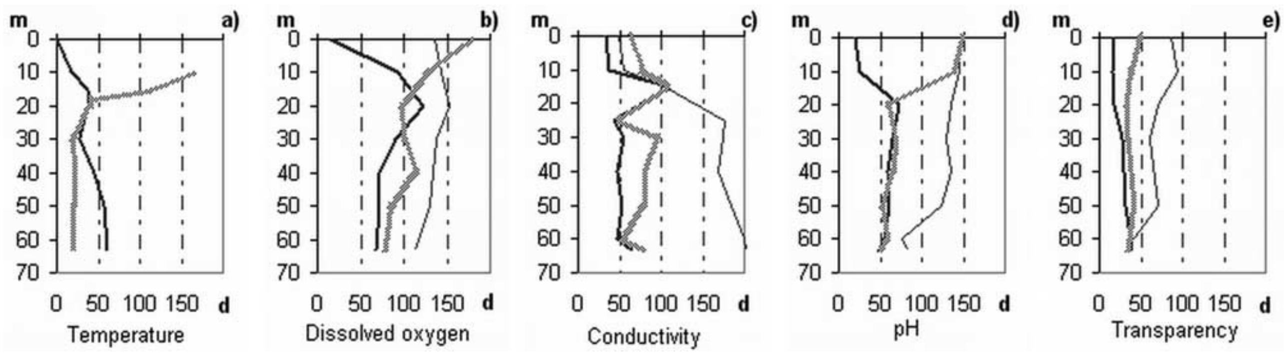

Figure 10. Mean transit times in days of interactions between the stream water (thin line), the interface (thick black line), the benthic zone (thick gray line), and the physicochemical properties of the lake water according to the depth (Grand Lac). (a) Temperature, (b) dissolved oxygen, (c) conductivity, (d) pH, and (e) transparency.

contribution of groundwater to surface water and sublacustrine springs.

7.1. Inflow Generator

[52] The inflow generator uses the Markov chain Monte Carlo and simulated annealing [*Bardossy*, 1998] from the Hastings-Metropolis algorithm [*Metropolis et al.*, 1953; *Hastings*, 1970]. It respects the following conditions deduced from the analysis of the observed streamflow series.

[53] 1. The first condition is the marginal distribution of streamflow corresponding to the sampling step Δt (15 days). The Gumbel law is used to sample exceptional events (Figure 12a).

[54] 2. The second condition is the autocorrelation function of streamflow (Figure 12b).

[55] 3. The third condition is the scaling relationship using the three first raw moments of the aggregated distribution fulfilled for k = 1, 2 and 3, Δt = 15 and 30 days

$$M_j(k.\Delta t) = k^{\lambda(j)} M_j(\Delta t) \qquad (16)$$

where the moment $M_j(k.\Delta t)$ is the sum, on the time period $k.\Delta t$, of the flow raised to the power of j. Only strictly positive values are summed in order to consider the mean flow. This scaling relationship aims to structure the duration of floods (Figure 12c).

[56] 4. The fourth condition is the probability density of the mean monthly flow (Figure 12d).

7.2. Surface Water Temperature Generator

[57] In order to accurately reproduce the nonstationarities of climatic inputs due to possible climate changes, the surface water temperature generator is coupled to the streamflow generator while the maximum surface water temperature is forced to fluctuate in the vicinity of a prescribed value within a predefined period. The deviations (noise) of temperature around the mean monthly values observed for the observation period are simulated (Figure 13a). The noise is sampled by using its marginal distribution (Figure 13b). Since these deviations are temporally structured, simulated annealing enables the observed and simulated autocorrelation functions to be as close as possible, as well as the cross-correlation noise-streamflow functions (Figure 13d). The cross-correlation noise-streamflow function is calculated for positive and negative lags in order to simulate both the causal relationship of atmospheric temperature on rainfall and the inverse. The first three moments are calculated from the absolute value of deviations (Figure 13c). Calculation of moments from the signed deviations would therefore lead to zero values when the observation period increases because the mean value of deviations tends to zero, making the exponents $\lambda(j)$ meaningless (16). Adding the simulated noise to the average

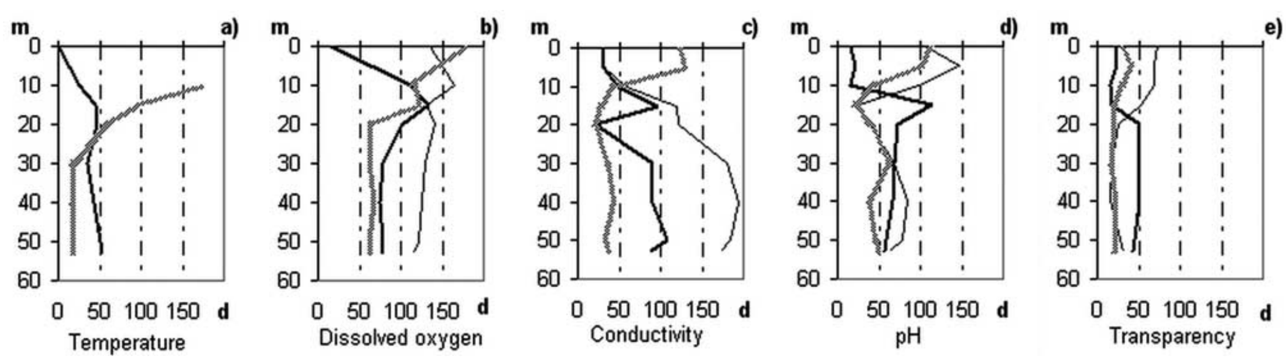

Figure 11. Mean transit times in days of interactions between the inputs and the physicochemical properties of the lake water according to the depth (Petit Lac). The conventions are the same as in Figure 10.

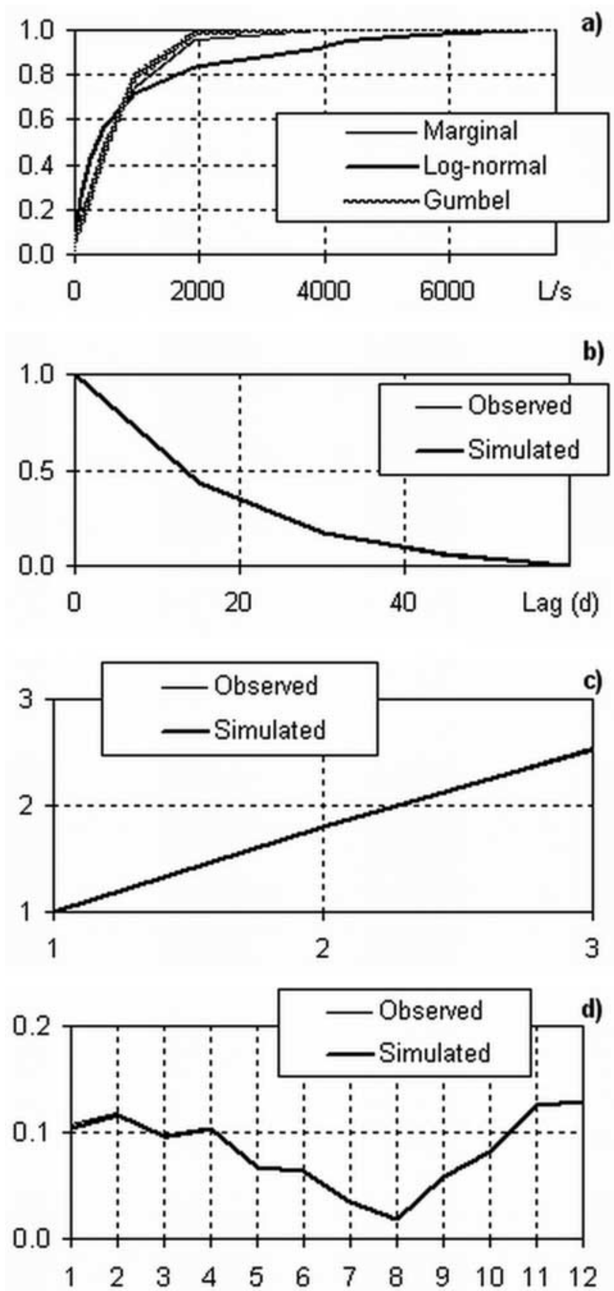

Figure 12. Some characteristic properties of the Laudon flow used as the representative inflow in the Grand Lac: (a) distribution function of streamflow and models, (b) observed and simulated autocorrelation functions, (c) observed and simulated exponents according to the order of the moments, and (d) observed and simulated monthly distribution of stream flow.

monthly surface water temperature generates surface water temperature series (Figure 14).

7.3. DO Generator in the Benthic Zone

[58] Generation of the DO in the benthic zone is done using the transfer model (Figure 4). Each realization is obtained by simulating both streamflow and surface water temperature as model inputs. The boundary condition of DO in the benthic zone for taking into account the oxygen

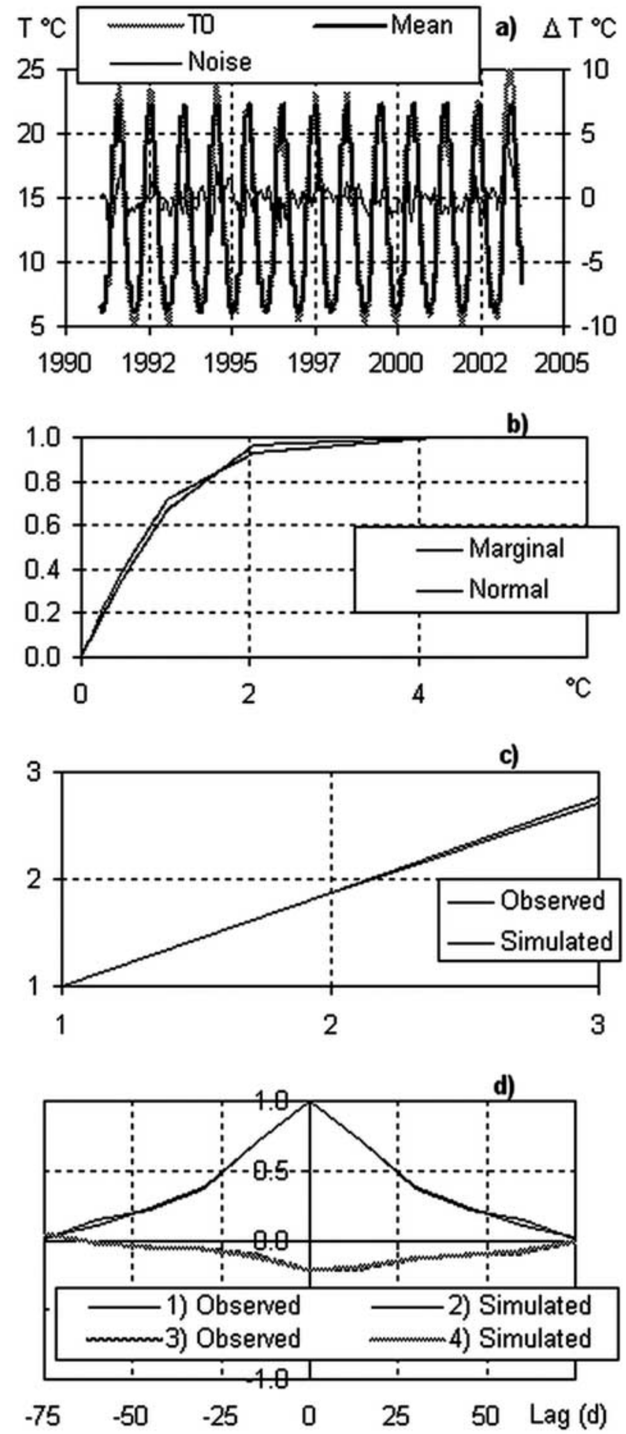

Figure 13. Some characteristic properties of the surface water temperature of the Grand Lac: (a) the observed surface water temperature, monthly mean calculated over 13 years and noise, (b) distribution function of the surface water temperature noise and the Gaussian model, (c) observed and simulated exponents according to the order of the moments, and (d) observed and simulated correlograms (1 and 2 refer to the autocorrelograms and 3 and 4 represent the crosscorrelograms between the inflow and the surface water temperature).

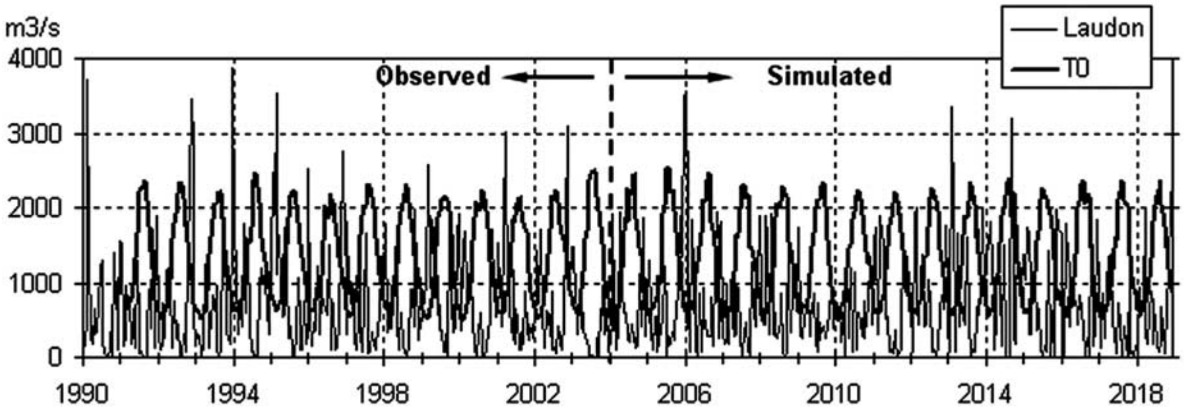

Figure 14. Observed flow of the Laudon, the observed surface water temperature of the Grand Lac, and simulated data. The simulation is done from 2004 to 2018 since the Hastings–Metropolis algorithm requires 15 years to correctly reproduce the properties of the observed data with a 15 day sampling step.

demand is set at 5.5 mg/L in the Grand Lac which corresponds to stationary conditions (Figure 5).

7.4. General Analysis of Results and Discussion

[59] The deoxygenation process of the benthic zone resulting from an increase of a few degrees in the maximum surface water temperature occurs in the Grand Lac whereas the decrease in DO concentration has no consequence in the Petit Lac since the minimum never drops to 3.5 mg/L (Figure 15). The main factor that acts in favor of a better oxygenation of the Petit Lac is its short residence time of a few years, whereas it is several decades for the Grand Lac. The maximum surface water temperature increase therefore has no consequence in the Petit Lac, the DO of which is supplied mainly from inflows, whereas the oxygenation of the benthic zone is mainly provided from exchanges between surface water and the atmosphere as for the Grand Lac. For both lakes, atmospheric oxygenation is efficient in winter due to the low surface water temperature, which enhances oxygen dissolution responsible for the high DO concentration that fluctuates around 10 mg/L in deep water in early spring. In spring and in early summer, the oxygenation of the epilimnion is due mainly to photosynthetic activity of plankton. The oxygenation of surface water in summer is all the less efficient as the surface water temperature is higher, which promotes oxygen release to the atmosphere. Thus a few degrees increase in the surface water temperature in summer could induce severe reducing conditions in the benthic zone in autumn. The simulation shows that the return period of such transient events is several ten years for surface water temperature reaching 25°C, which should not induce harmful consequences on biodiversity in deep water due to the production of ammoniacal nitrogen and phosphorus release from sediments (Figure 15). Deep water in the Petit Lac whose residence time is only a few years is mainly oxygenated by inflow and, consequently, DO in the benthic zone depends little on surface water temperature in summer. On the other hand, the lakes do not seem to be threatened by other consequences of global warming. The resilience of Lake Annecy results from the temperature of the hypolimnion that is controlled by the decarbonation process while the durability of turn over is ensured by the low atmosphere temperature in winter.

8. Conclusion

[60] A general approach was presented to characterize the resilience of aquatic ecosystems, and applied to Lake Annecy whose dynamics are representative of oligotrophic stratified lakes controlled by decarbonation processes where

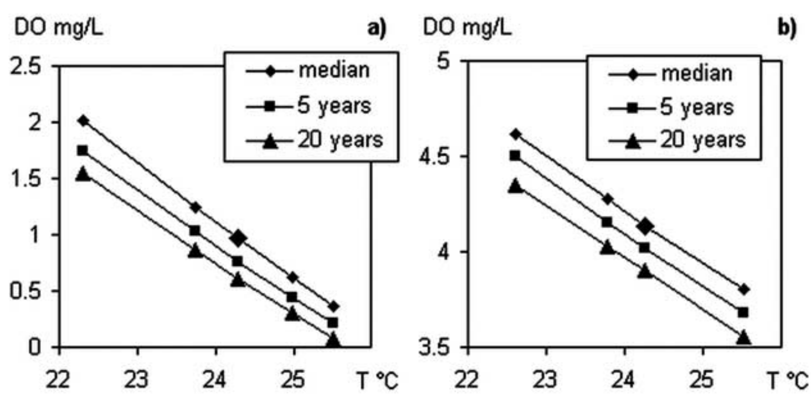

Figure 15. Influence of the maximum surface water temperature of the lakes on the minimum dissolved oxygen concentration in the benthic zone. Each curve is associated with a return period. The quantiles are calculated from 256 realizations of the stochastic processes: (a) the Grand Lac and (b) the Petit Lac.

turn over and mixing occur once a year in winter when the temperature of shallow water drops below that of deep water.

[61] The monitoring of Lake Annecy, its tributaries and springs and the separation of physicochemical parameter variations into components related to forcings has enabled the quantification of the major geochemical processes that govern lake water quality and has increased our understanding of transport phenomena and annual cycles. The stochastic processes associated with the transfer models aimed to characterize the resilience of the lakes, the major threat of which is the impoverishment of dissolved oxygen in deep water in autumn due to a temperature increase of the surface water in summer, in the context of global warming. The simulation of DO in deep water of the Grand Lac and the Petit Lac was carried out by generating surface water temperature and inflows, stationarity being assumed as for the interactions of deep water with the benthic zone. No assumption was expressed about climate change but the DO in deep water was represented according to the maximum surface water temperature reached in summer, taking the surface temperature that was reached during the heat wave of 2003 as a landmark. The variability of the surface water temperature as well as the inflows, both being coupled, was conveyed through the return period of DO. The simulation raises relevant questions about whether a connection exists between physicochemical parameters and global warming, which should not induce harmful consequences on water quality and biodiversity in deep water.

[62] This methodological approach is general since it does not use any physical conceptual model to predict the hydrosystem behavior, but uses directly observed data. In this way, the method enables an exhaustive description of aquatic ecosystem dynamics since the interactions with the external environment are deciphered implicitly from the input data.

[63] **Acknowledgments.** This work was done within the framework of BRGM's research programme "Monitoring of hydrosystems." The monitoring campaigns were originally financed by Syndicat Intercommunal du Lac d'Annecy, the Lake Annecy watershed management board in charge of activities aimed at improving water quality given the considerable scientific and economical interests linked to water management and tourism. Profiles, water sampling, chemical analyses, and biological counting are now done by the INRA (National Institute of Agronomic Research). We appreciated the contribution of the two anonymous reviewers as well as the Associate Editor, who significantly improved the understanding of the paper.

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F. Berthier, 80 route des Marterayes, F-74410 Saint-Jorioz, France.

J.-L. Pinault, Water Division, BRGM, 3 avenue Claude Guillemin, F-45060 Orléans cedex, France. (jl.pinault@brgm.fr)