

CHAPTER 1

“Longitudinal circulation patterns in the Sau Reservoir”

Review and updating from:

Armengol, J.; García, J. C.; Comerma, M.; Romero, M.; Dolz, J.; Roura, M.; Han, B-H.; Vidal, A. and Šimek, K. (1999). Longitudinal processes in canyon type reservoirs: the case of Sau (N. E. Spain). Theoretical Reservoir Ecology and its Applications. J. G. Tundisi and M. Straškraba. Leiden, International Institute of Ecology. Brazilian Academy of Sciences and Backhuys Publishers: 313-345.

ABSTRACT

The longitudinal circulation of the River Ter across the Sau Reservoir is the result of the difference between inflow and epilimnion water temperatures along the year. Horizontal patterns of stratification and river circulation in this reservoir can be combined to explain its hydrodynamics. Therefore, from these observations, an empirical annual pattern of longitudinal circulation in the Sau Reservoir was obtained for the 1996-2000 period. The general river circulation model is characterized by underflow in winter, overflow-interflow in spring and interflow in summer-autumn.

Calculations of the “Plunge point” position on the longitudinal axis allowed us to locate the border between riverine and lacustrine zones of the reservoir during the periods of interflow and underflow. This was useful to calculate the percentage of mixing between river and reservoir waters.

Key words: reservoir, circulation patterns, plunge point

INTRODUCTION

Environmental variables in river valley reservoirs change following the longitudinal axis of the reservoir, in response to water circulation induced by the river inflow (HEZLAR and STRAŠKRABA, 1989; KENNEDY *et al.* 1990, FORD, 1990). Because the inflow density usually differs from the density of the reservoir water surface, rivers enter and move through reservoirs as density currents (FORD, 1990). Density differences can be caused by temperature, total dissolved solids, and suspended solids.

Changes in river water temperature and in the water column of the reservoirs have a delay in time and this allows the existence of temporal water circulation patterns in the reservoirs (STRAŠKRABA *et al.*, 1993). In some cases, as in the Sau Reservoir, water circulation is also modified by the use of selective outlets (IMBERGER, 1979; SALENÇON and THÉBAULT, 1997), making it possible to release water from different depths. In addition, in the Mediterranean region, variability of rain distribution and intensity introduces strong changes in the river inflow (ARMENGOL *et al.*, 1999). This change in the inflow disrupts the gradients developed during periods of more regular water circulation (KENNEDY and WALKER, 1990; KIMMEL *et al.*, 1990).

The River Ter, main tributary of the Sau Reservoir, is highly polluted and has high nutrients loads, mainly of ammonia and soluble reactive phosphorus (VIDAL and OM, 1993; ARMENGOL *et al.*, 1994), but also particulate and dissolved organic matter (ŠIMEK *et al.*, 1998). These high inputs allow the development of microbial, phytoplankton and zooplankton communities along the horizontal axis of Sau (ŠIMEK *et al.*, 1998, ŠIMEK *et al.*, 1999, ARMENGOL *et al.*, 1999, COMERMA *et al.*, 2001).

In the reservoir, the movement and mixing of dissolved and particulate matter coming from the river will result from factors described above and will influence changes in its biological communities and

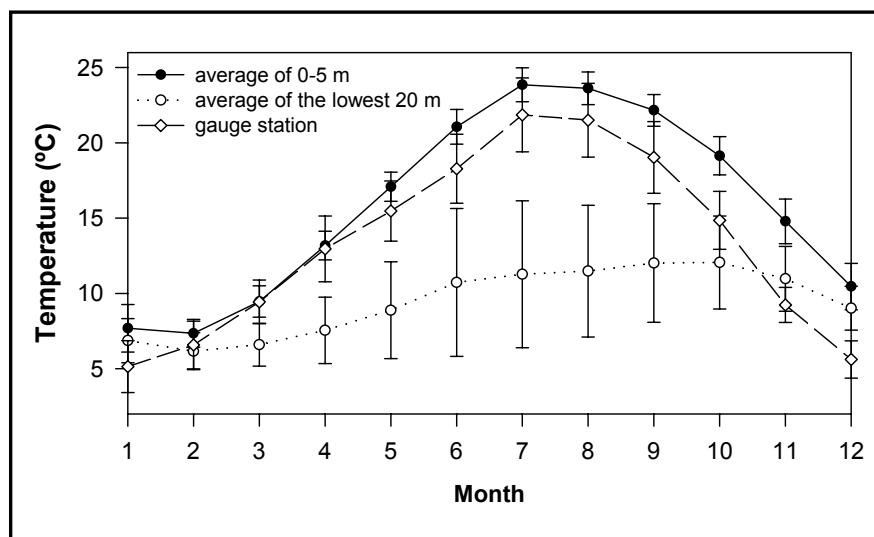
processes. The aim of this chapter is to introduce reservoir transport mechanisms that impact water quality and to identify the general pattern describing longitudinal water circulation in the Sau Reservoir.

RESULTS AND DISCUSSION

The annual pattern of longitudinal water circulation

Because inflow water densities (i.e. temperatures) are continuously changing, the depth at which an intrusion moves through a reservoir will also change (FORD, 1990). An empirical annual model of longitudinal water circulation was deduced from monthly average temperatures at surface and bottom of the Sau Reservoir and at the gauge station in the River Ter for the 1964-85 period (Fig. 1.1). A clear seasonal pattern of longitudinal water circulation can be identified from the comparison of these three series.

Figure 1.1
Monthly average temperatures at surface and at bottom waters of the Sau Reservoir and at the gauge station in the River Ter during 1964-85 period.



The River Ter cools down to temperatures below those of bottom waters in Sau by mid-November, coinciding with early snowfalls in the

Pyrenees or with typically Mediterranean seasonal autumn floods. From this moment and during winter, the inflow temperature is colder than that of the bottom of Sau, which is fully mixed at this moment, producing the **deep circulation** of the river through the reservoir. Deep circulation of the river remains until February, when river temperatures rise faster than those of surface waters in the reservoir (i.e. the “**superficial circulation period**”). The effect of this circulation is an injection of nutrient-rich water coming from the river into the photic zone of the reservoir. In this period we have observed spring phytoplankton blooms (ARMENGOL *et al.*, 1999) as is often the case of reservoirs with similar water circulation patterns (VYHNÁLEK *et al.*, 1994). At the beginning of spring, surface temperatures of Sau can achieve higher values than those in the river, which progressively sinks to levels below the photic zone. An **intermediate circulation** of the river in the reservoir characterizes the transition between spring and summer. During summer, the river progressively sinks down to the level of the thermocline and contributes to the thermal stability of the water column in the reservoir. This situation persists until the end of summer. The river then starts to become colder than the reservoir and deep circulation starts again, closing the annual cycle of river-reservoir interaction.

Interannual variability in Mediterranean regions is large. Thus, the annual pattern of water circulation described can be very different from year to year. The time of first snowfalls in the Pyrenees determine the rapid lowering of river water temperatures.

By contrast, temperate winters will reduce the period of deep circulation. Cold springs with fluctuating temperatures can modify the intermediate circulation and thereby influence the moment in which the thermocline forms. Rain has an important effect on the hydrological regime and can modify the hydrodynamics of the reservoir. For large periods of time (i.e. months to years), residence time can be used as a good descriptor of reservoir's hydrodynamics. Shorter periods (i.e. days to weeks) can see immediate effects by floods. Floods are quite frequent in the Mediterranean climate and can take place at any time of the year. In the past years (1996-2000), main floods occurred between autumn and winter (Fig. 1.9b), when, because of the weak stratification, floods

could accelerate water mixing.

Sampling was conducted in the 1996-2000 period. In Figure 1.2 interannual differences in the circulation and thermal patterns of the reservoir are shown.

Figure 1.2
Monthly temperatures at surface and bottom waters of the Sau Reservoir and at the gauge station in the River Ter throughout 1996-2000.

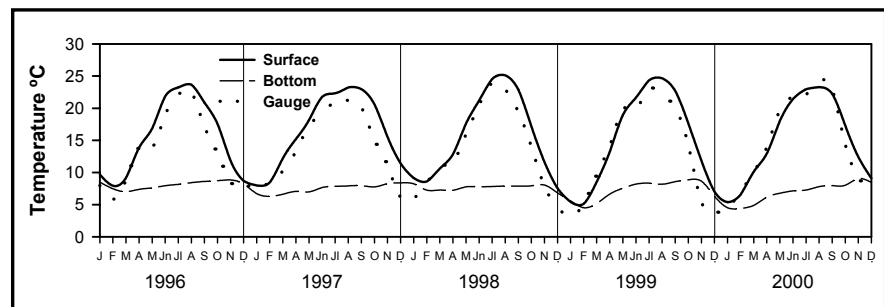
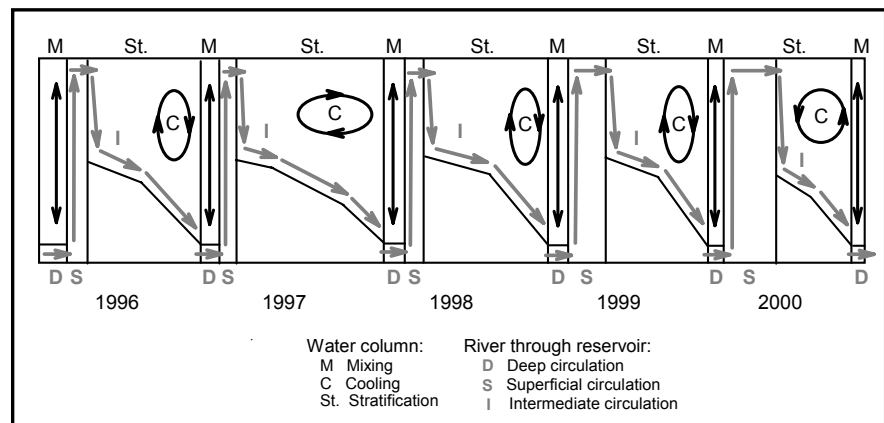


Figure 1.3
Empirical model for the annual water circulation pattern (1996-2000), compared with the observed vertical stratification at station 1.



All three circulation patterns (i.e. deep, superficial and intermediate) described above happened in succession in every year. Differences between years were mainly in the duration of circulation patterns, conditioned by climatology and water reserve. Observe years 1999 and 2000, with a long superficial circulation period of the river through the reservoir. Both were dry years and the reservoir had low water levels (i.e. 53.6hm^3 and 62.8hm^3 , respectively) in comparison with preceding years (i.e. around 115hm^3). Proportionately to the volume, the total length of the reservoir was less during the 1999-2000 period (i.e. around 10km) than during the 1996-1998 period (i.e. around 18km). Longitudinal circulation varied strongly in the shorter reservoir and the importance of

this axis in reservoir processes was reduced.

Taking all dates together we constructed an empirical model (Fig. 1.3), where stratification and cooling processes and also river flows through the reservoir are described in each year. We consider that, in absence of floods or snowfall in the Pyrenees, overflow can take a long period.

Seasonal patterns of stratification and river circulation

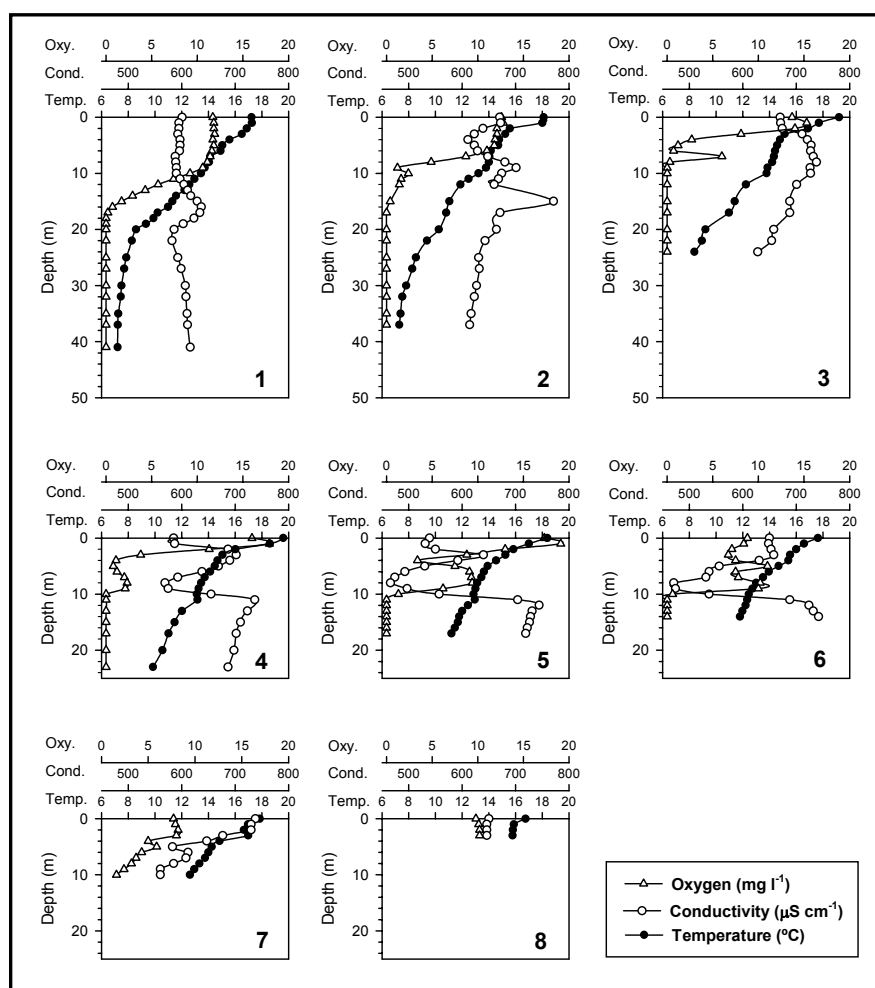
The reservoir is relatively narrow (max. width is 1.5km) and the cliffs that surround it reduce meteorological forcing, especially the effect of the wind. In these conditions the intrusion of the river into the vertical density profile is maintained in most of the length of Sau. We used a combination of temperature, conductivity and oxygen profiles (Figures 1.4 to 1.6) to characterize river circulation patterns and their seasonal variability.

In spring, small changes in air temperature produced by changes in meteorological conditions are enough to produce fluctuations in the river temperature, causing the river to move up and down in the water column. The evidence of these movements can be appreciated by the step profiles of conductivity. These have a more conservative behaviour (i.e. by Fick's law) than temperature (i.e. by Fourier's law) in identical hydrographic conditions (MARGALEF, 1983). In profiles measured in May 1998 (Fig. 1.4) it is possible to see that the more saline river water moved over the bottom downstream to station 5 and then circulated at intermediate depths reaching station 1. In this case, steps in figures were the marks of past similar situations, but with different river temperatures. Thermal stratification is weak during spring. This situation is maintained by the vertical component of water movement induced by the river, and this prevents the formation of secondary thermoclines and the gain of thermal stability.

Summer circulation of the river takes place in more stratified conditions, as we can see in the profile measured the first of September 1998 (Fig. 1.5). The thermocline was situated at 14m depth, just where

the river water was flowing. Until station 4 it was possible to see a large increase of oxygen and conductivity, because in this period the water coming from the river had more oxygen and dissolved salts than the reservoir. Oxygen is consumed very fast by the biological activity of organisms using the allochthonous organic matter transported by the river. In addition, the autochthonous primary production will sink from the epilimnion.

Figure 1.4
Temperature, conductivity and oxygen profiles along the main axis of the Sau Reservoir in spring 1998. Sampling points are ordered from the dam (1) to the river (8).



In the upper part of the epilimnion a secondary stratification can be appreciated in the oxygen profile, which defines the mixing depth. In this very stable profile there is not enough kinetic energy to mix the superficial

water, oversaturated with the oxygen produced by photosynthetic activity, with the anoxic water situated above the thermocline.

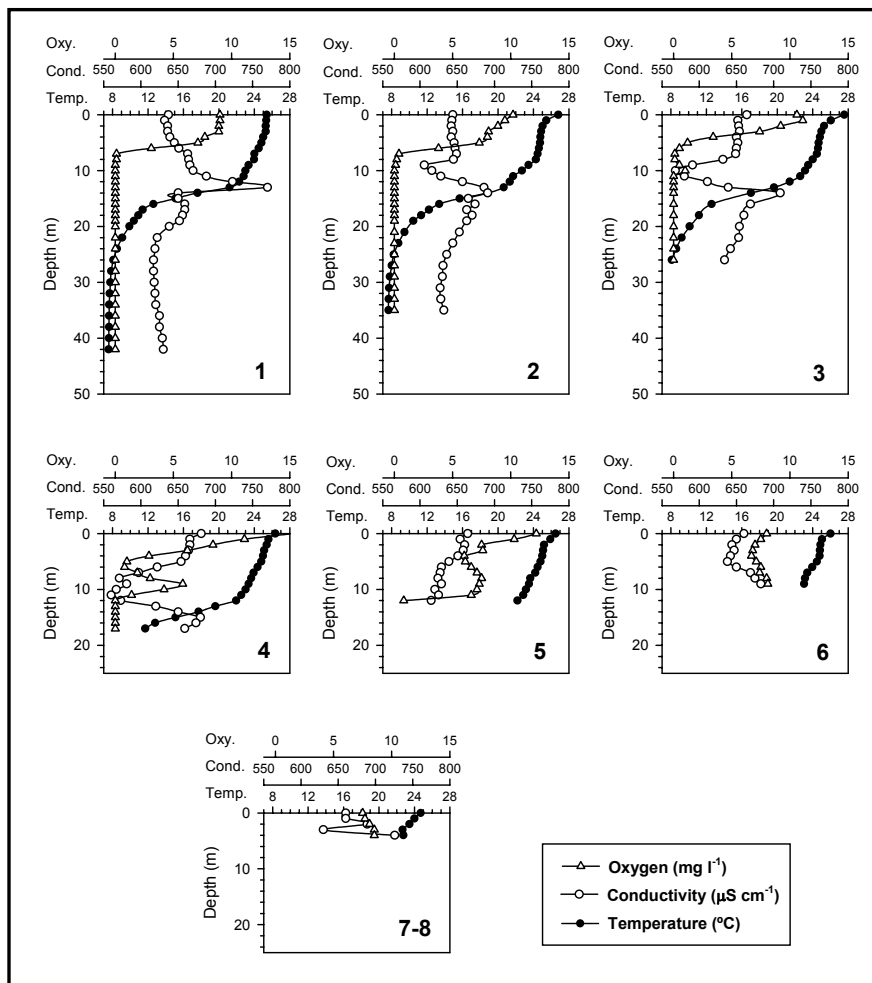
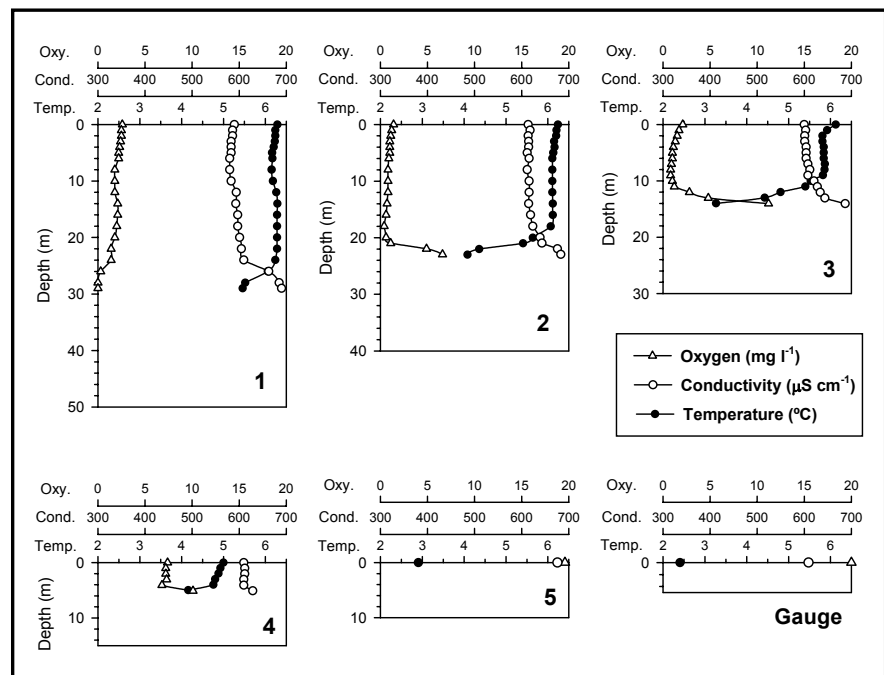


Figure 1.5 Temperature, conductivity and oxygen profiles along the main axis of the Sau Reservoir in summer 1998. Sampling points are ordered from the dam (1) to the river (7-8).

Overturb starts in autumn, with variable rapidity depending on weather conditions. The mixing of the epilimnion with the hypolimnion takes place by means of the cooling effect of the river and wind has generally small influence on mixing. We have seen that at the end of summer the circulation of the river defines the thermocline. The progressive cooling of the river in autumn produces the sinking of the thermocline. This process is usually very slow and is only accelerated by snowfalls in the Pyrenees and fast floods (cf. Fig. 1.9b). Then, overturn of

the water column is complete and deep circulation of the river occurs (Fig. 1.6, data from December 1998). Very cold water from the river, with higher oxygen concentrations than upper layers of the reservoir and, sometimes, with water of low conductivity, circulates at depth.

Figure 1.6
Temperature, conductivity and oxygen profiles along the main axis of the Sau Reservoir in winter 1998. Sampling points are ordered from the dam (1) to the river (6).



Interannual differences in this pattern are closely related to the temperature of river water. Two things are important to explain why is the river so determinant, the first one is the extremely uniform characteristics of the channel part of the reservoir, while the second is the small influence of wind. Sau is a typical canyon reservoir (see Figure I.1). Relatively high mountains reduce wind speed on the reservoir, and because of this also the importance of the wind-induced turbulent kinetic energy.

A summary is shown in Figure 1.7 of the average annual cycle of river water circulation inside the water column of the reservoir.

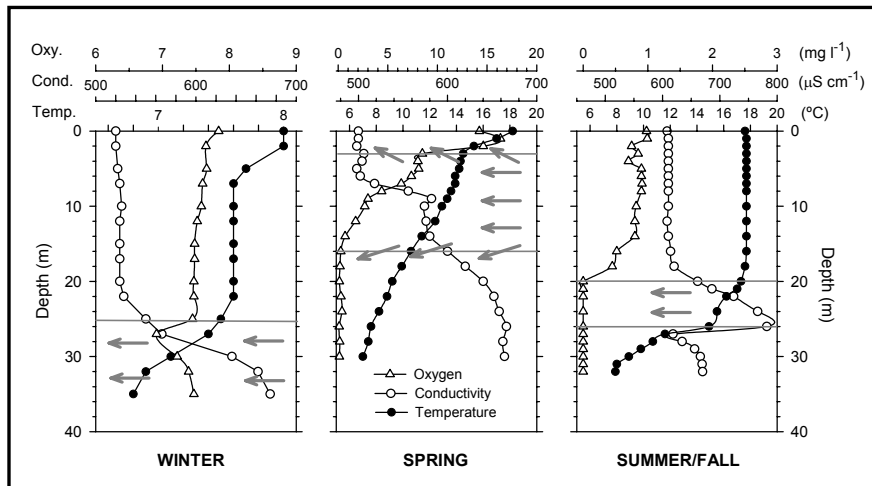


Figure 1.7
Seasonal patterns of stratification and river circulation. The grey arrows show the level of the river circulation and the water mixing between the river and limiting water levels.

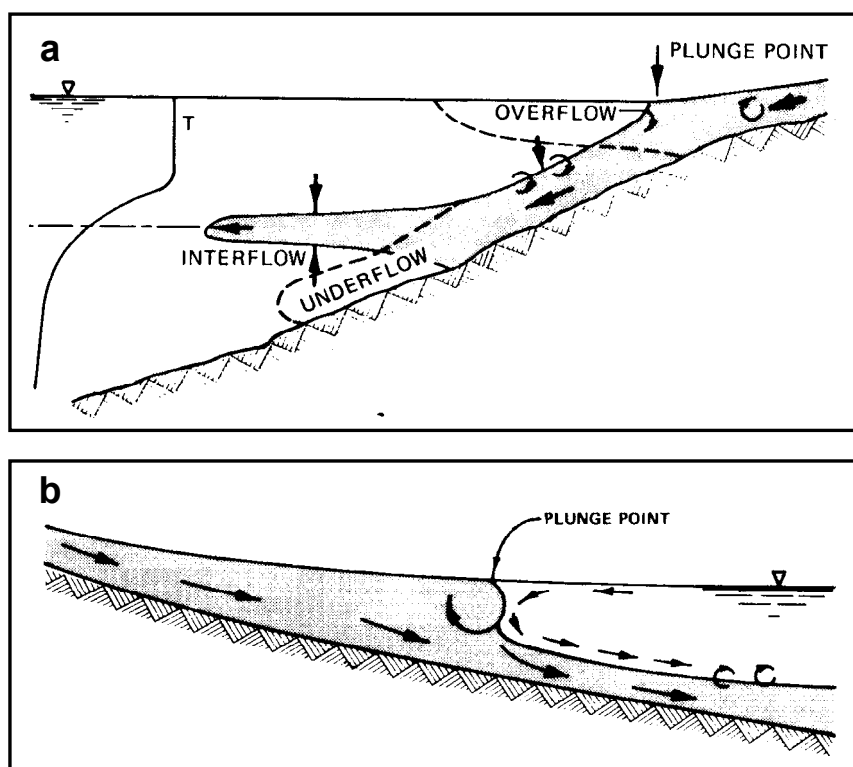
In spring, stratification is weak and the circulation of the river produces waves according to air temperature fluctuations, maintaining this situation. The transition towards summer means that each time these fluctuations are reduced, river and thermocline are at the same depth. With autumn, river temperatures decrease and its waters sink very slowly until first snowfall in the mountains or storms in the plains, when sinking precipitates.

The horizontal patterns of the Sau Reservoir and the “Plunge Point”

During inter and underflow, the “plunge point” defines where the intrusion of the River Ter takes place in the reservoir, and the limit of lacustrine conditions in Sau. In the classical view of KIMMEL and GROEGER (1984) the plunge point is the border between the riverine and the lacustrine zones of a reservoir. This means that the inflowing dissolved and particulated materials transported by the river interact with the epilimnion water resulting in an exchange of compounds between them. During the stratification period this is one of the main ways by

which organic matter and nutrients are introduced into the epilimnion and longitudinal processes along the reservoir are maintained (FORD, 1990). A schematic description of these processes is shown in Figure 1.8 a and b. Different types of river flow described above for the Sau Reservoir are also represented.

Figure 1.8
Schematic drawings representing kinds of inflow circulation, from FORD (1990).
a) Different density inflows to impoundment.
b) Pooling at the plunge point.



The position of the plunge point in Sau was calculated by means of the model developed by IMBERGER (1979) and according to the theoretical background even in IMBERGER and PATTERSON (1981).

In order to use the model of Imberger, we assumed a small slope of the river bed (i.e. 0.0035) producing significant shear. We also assumed that flows with high entrance Froude numbers (F_i) were very limited in the considered period of time. Under these assumptions and according to this model, the plunge point (L_o) can be calculated by the equation,

$$L_o = h_o / \tan\varphi \quad \text{Equation 1.1}$$

where h_o is,

$$h_o = \left[\frac{2Q_o^2}{F_i^2 \Delta\rho \tan^2\alpha} \right]^{1/5} \quad \text{Equation 1.2}$$

and F_i is,

$$F_i^2 = \frac{\sin\alpha \cdot \tan\varphi}{C_D} \left(1 - 0.85C_D^{1/2} \sin\alpha \right) \quad \text{Equation 1.3}$$

The definitions of the terms in Equations (1.1-1.3) are shown in Table 1.1. The extremely uniform morphology of the reservoir down most of its length allowed us to maintain a constant bed slope value (0.0035) and incur in little error. The calculated half angle of the river valley is 85° and the bottom coefficient drag was set at a value of 0.016.

Term	Definition
L_o	Distance of the plunge point from the river gauge
h_o	Depth of the water column at the plunge point
φ	Slope of the stream bed (in degrees)
α	Half angle of stream bed
F_i	Internal Froude number
ρ_o	Density of the river water
ρ_s	Density of surface water
C_D	Drag coefficient of stream bed set as 0.016
$\Delta\rho$	Relative density = $(\rho_o - \rho_s) / \rho_o$
Q_o	Daily inflow (data in Fig. 1.9b)

Table 1.1
Definitions of terms used in IMBERGER and PATTERSON's model (1981) for calculation of the plunge point position.

In a first step we calculated two empirical equations for the 1997-98 period, relating the daily temperatures of the river at the gauge station and at the surface of Sau (ARMENGOL *et al.*, 1999) with the daily average temperatures of the air measured at the meteorological station of Sau. Using the data from June 1997 to December 1999, statistically significant equations obtained were very close to those published by ARMENGOL *et al.* in 1999, i.e.

$$T_{\text{gauge}} = 1.21 + 1.003T_{\text{air4d}} \quad r^2 = 0.95 \quad n = 31 \quad \text{Equation 1.4}$$

$$T_{\text{sup}} = 4.31 + 0.94T_{\text{air7d}} \quad r^2 = 0.87 \quad n = 57 \quad \text{Equation 1.5}$$

where T_{gauge} and T_{sup} are temperatures at the gauge station and at the 0-2m water level of Sau respectively, while T_{air4d} and T_{air7d} are average daily temperatures of the air in the last 4 and 7 days before measurement of the water temperature. These results have been extended to all the considered period (starting when meteorological station was installed, in May 1997) in order to calculate the densities of the river and of the reservoir water. For the calculation of densities the KRAMBECK *et al.* (1992) transformation was used, assuming a negligible effect of salinity on density.

Results obtained can be seen in Figure 1.9. against water level changes. This effect is very important because the considered period covers the transition between “normal” to “dry” years from the hydrological point of view. In addition to the parameters used in the IMBERGER and PATTERSON (1981) model, we have to consider water level fluctuations as a factor in the movement of the plunge point towards the dam. Because this movement takes place in a very uniform canyon, the morphometrical parameters used in the model are not affected and we only need to know the position of the plunge in each period of time. For instance, during most of 1997, the plunge point was situated between stations 8 and 7, while in 1998 it was somewhere between stations 7 and 5 (Fig. 1.9).

Our results show that the displacement of the plunge point is more

sensitive to changes in water flow than to temperature changes as was also found by KENNEDY and WALKER (1990) in reservoirs of the United States. In Sau, results fall into two extreme situations. The first is during spring overflow, when the temperature of the river is higher than that of the reservoir and there is no plunge point. The second situation occurs when there is a large flood and the reservoir is in a phase of turbulent mixing.

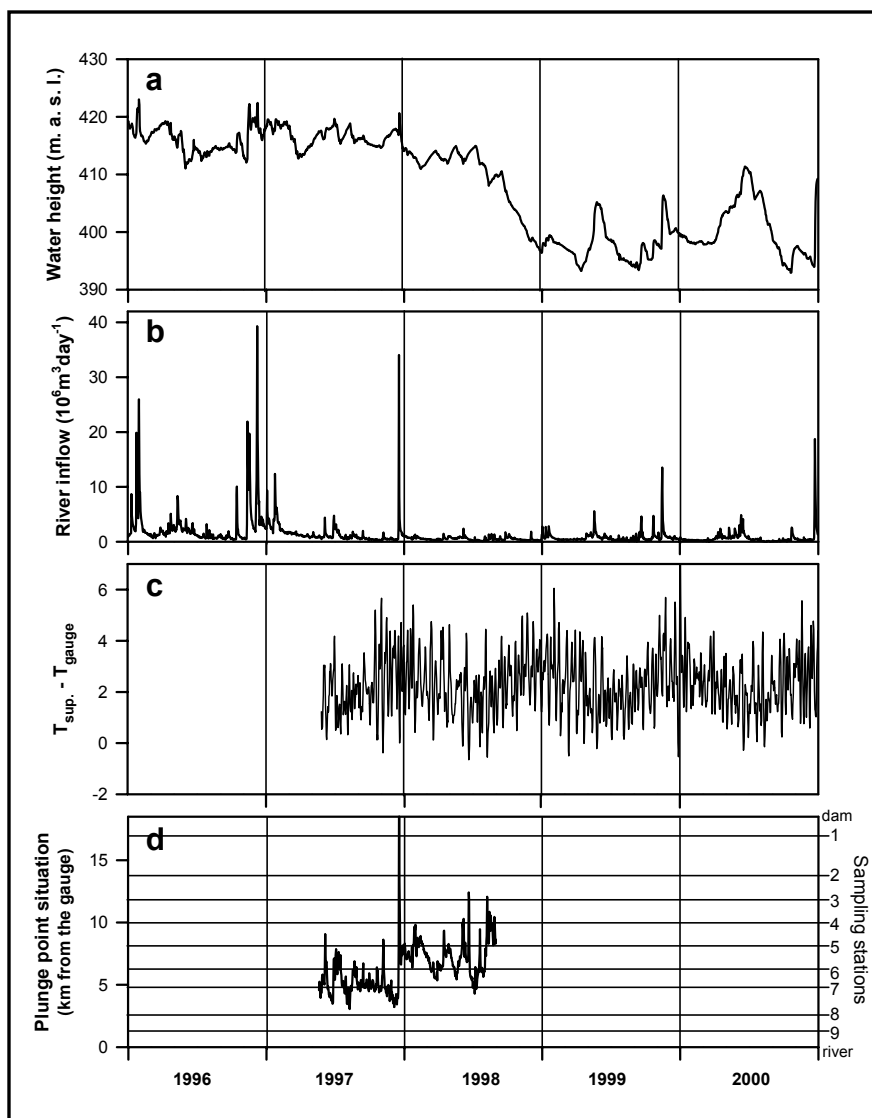


Figure 1.9

Data from 1996 to 2000:

a) Daily changes in water height.

b) Daily inflows of the River Ter.

c) Daily temperature differences between the surface of Sau ($T_{sup.}$) and the gauge station at the River Ter (T_{gauge}). Values were calculated from equations 1.4 and 1.5.

d) Location of the plunge point in the Sau Reservoir for 1997-1998 period. Location of sampling stations is also shown.

The plunge point locates the main point of mixing between river and the epilimnion water body. Using conductivity and chloride concentration as tracers of each water type it was possible to calculate by a mass balance (Equation 1.6) the amount of river water mixed with the epilimnion. We constructed several systems of equations with two factors, where x and y were the percentages of river and reservoir waters, respectively, making up water at the plunge point on each sampling occasion. The known variables were conductivity or chloride concentration in the river (C_R), in the reservoir epilimnion (C_E), and at the plunge point (C_P),

$$\left. \begin{array}{l} C_R \cdot x + C_E \cdot y = C_P \cdot (x + y) \\ x + y = 100 \end{array} \right\} \text{Equation 1.6}$$

In following chapters we will use the plunge point and the percentage river water mixed at the plunge point to describe biological events through the main axis of the Sau Reservoir.

CONCLUDING REMARKS

The course of the river through the reservoir guides the annual longitudinal pattern of circulation in the Sau reservoir. Temperature, dissolved oxygen concentration, and conductivity at the inflow, related to those in the reservoir, are the main factors describing processes. We have observed three patterns of river circulation throughout the year: underflow in winter, overflow or interflow in spring, and interflow following the thermocline in summer/autumn (cf. Figures 1.3, 1.7 and 1.8).

We have created a highly useful empirical model to frame biological sampling aimed towards a general goal, explained in next chapters. By using the location of the plunge point we were able to calculate river water mixing with reservoir waters.

CHAPTER 2

“Effects of water circulation on nutrient dynamics”

Review and updating from:

Armengol, J.; García, J. C.; Comerma, M.; Romero, M.; Dolz, J.; Roura, M.; Han, B-H.; Vidal, A. and Šimek, K. (1999). Longitudinal processes in canyon type reservoirs: the case of Sau (N. E. Spain). Theoretical Reservoir Ecology and its Applications. J. G. Tundisi and M. Straškraba. Leiden, International Institute of Ecology. Brazilian Academy of Sciences and Backhuys Publishers: 313-345.

ABSTRACT

We observed decreasing chemical gradients from river to dam in the epilimnion of the Sau Reservoir, caused by the inflow of River Ter, a river highly polluted with organic matter. Sau works as an efficient purification system, improving water quality from inflow to outflow. The efficiency of this system depends on nutrient loads, nutrient concentrations in the reservoir, sedimentation rates, biological activity and water flow. Water flow in the reservoir, flowing in bottom (underflow), middle (interflow) or top layers (overflow) through greatly influences the degree of mixing between river and reservoir waters.

Key words: reservoir, water chemistry, and nutrient dynamics

INTRODUCTION

Horizontal environmental gradients are common in river valley reservoirs. These gradients are controlled by water circulation (hydrology), abiotic (sedimentation, precipitation, etc.) and biotic (production, grazing, migration) processes and their varying intensity along them (FORD, 1990). It has been accepted that in long and narrow reservoirs this horizontal transformation is progressive. Thus, reservoirs can be considered as reactors or chemostats (UHLMANN, 1972; MARGALEF, 1983). According to a chemostat model, water inflow is generally rich in salts (i. e. conductivity is high), in nutrients (nitrogen and phosphorus) and the transport power of water is high, bringing in large amounts of particulate matter (clay, organic remains). All these characteristics change as the water flows through the reservoir towards the dam. This model has been considered oversimplistic because it ignores vertical gradients and convective processes (MARGALEF, 1982). Nevertheless, it can be used when an homogeneous mass of water is considered (e. g. one given depth).

The annual pattern of longitudinal circulation caused by the highly polluted River Ter in the Sau Reservoir has been characterized by ARMENGOL *et al.* (1999). There are three periods when the river clearly overflows (spring), interflows (summer-autumn) and underflows (winter) through the reservoir. Each period contributes in a different manner to mix river and reservoir waters. The proportion of river water mixed with the epilimnion decreases from over- to underflow. We hypothesized that this mixing of the inflowing water with the reservoir water body at the plunge point might have a significant effect on overall reservoir water quality.

The aim of this chapter is to investigate the longitudinal rate of change in chemical water composition and to explain changes in terms of inflake processes. We have used a first order decay model to describe the dynamics of processes, on the assumption hydrological conditions were fairly constant. Thus, in the present chapter we used a simple approach

to following the rate of change of several conservative (carbonate alkalinity, chloride concentration and conductivity) and non-conservative variables (turbidity and concentrations of particulate material, silicate, soluble reactive phosphorus, ammonium, total phosphorus and total nitrogen) in the epilimnion of the reservoir.

RESULTS AND DISCUSSION

The reservoir as a “water purifying plant”

It is well known that reservoirs exhibit marked longitudinal chemical gradients (THORNTON *et al.*, 1990), with water quality improvements from the river to the dam. Various processes affect nutrient distribution and availability in reservoirs: nutrient loading (external and internal), sedimentation, flow, mixing, and discharge (KENNEDY and WALKER, 1990). Depending on these factors, reservoirs are more or less efficient “water purifying plants”.

This water purifying activity is examined, considering the case of the Sau Reservoir in July 1996. High nutrient loads, relatively constant inflow and outflow, interflow river circulation, and high biological activity due to hot temperatures were typical during the studied period. We will examine the factors describing these conditions in detail.

The thermal and hydrographic situation can be deduced from the vertical profiles of temperature, conductivity, turbidity, and oxygen saturation, measured at different points along the longitudinal axis of the reservoir (Fig. 2.1).

The reservoir was stratified in July 1996, with an oxygen-oversaturated epilimnion and an anoxic hypolimnion. The river Ter flowed into the Sau Reservoir to the plunge point, where water remained relatively stagnant, and debris transported by the river accumulated, separating water laden with debris brought in by the river from the cleaner reservoir water.

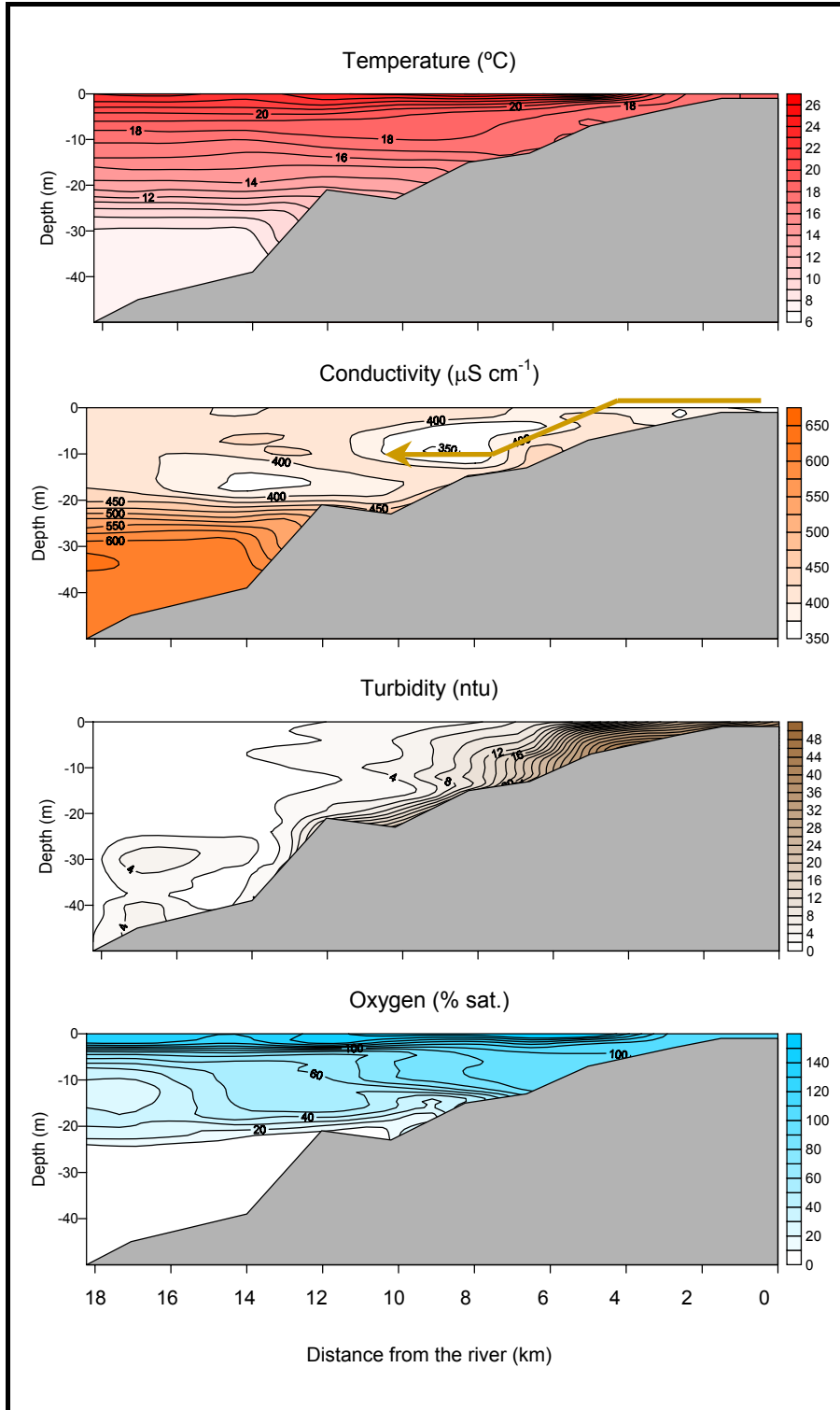


Figure 2.1
Longitudinal profiles of temperature, conductivity, turbidity and oxygen saturation in the Sau Reservoir (July 1996). The arrow shows the direction of progression of the river through the reservoir.

The plunge point was situated between stations 8 and 7 (4.3 km from the river). The river sank here and progressed through Sau as an interflow, tentatively situated at 10 m depth. At the plunge point, the river water volume inflowing to the epilimnion of the reservoir was estimated to be *circa* 24% of the total epilimnetic water volume.

Turbidity and percentage of oxygen saturation changed along the reservoir, showing the change in intensity of inlake processes such as primary production and sedimentation. For instance, sedimentation was fast (Fig. 2.1) and, at the downstream station 6, the surface water had relatively small amounts of the particulate matter transported by the river. Between stations 7 and 6, the percentage of oxygen saturation and pH (data not shown) were higher than at the other sites, suggesting that primary production was higher there. Higher phytoplankton productivity and biomass were generally found here. This could be explained by the co-occurrence of high concentration of nutrients (see Fig. 2.2), decreasing flow velocity, and no light limitation by river detritic material (KIMMEL et al., 1990).

Because of the homogeneous hydrographic conditions in the epilimnion, the stable weather during this sampling week, and the uniform morphology of the basin, the epilimnion worked as a chemostat, with a piston flux of water. UHLHMAN (1991) compared the mode of functioning of lakes to a chemostat, because of their homogeneity and differentiated inflow and outflow.

Chemical analyses were done on integrated water samples (0-5m), which were collected from the nine sampling stations (cf. location of stations in Fig. 1.1). Results obtained (Fig. 2.2) showed that most of the studied variables had the same pattern of change, which can be described by a first order decay model (as proposed by KENNEDY and WALKER, 1990). According to this model, concentration of a compound at a site x of the reservoir can be described by the equation,

$$C_x = C_0 e^{-rx} \quad \text{Equation 2.1}$$

where C_0 and C_x are the values of the variable C at the river and at the point x , respectively; x is the distance from the river (km); and r is the rate

of change of each variable along the reservoir.

"Distance from the river" (i.e. space) acts as a surrogate measure for time, because water is assumed to flow at a constant velocity and as a single mass through the reservoir. Efficiency measured how fast were processes reducing concentration of several compounds along the longitudinal axis of the reservoir.

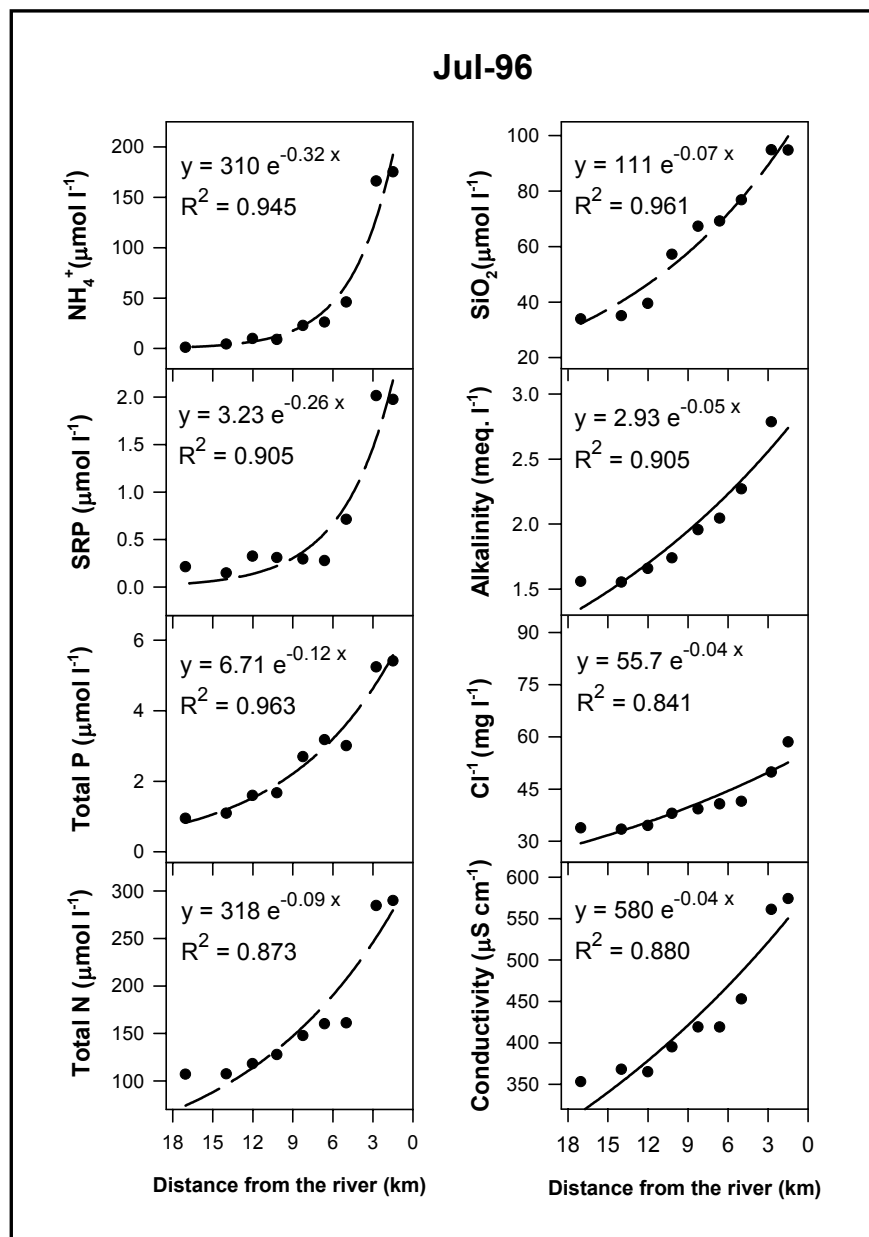
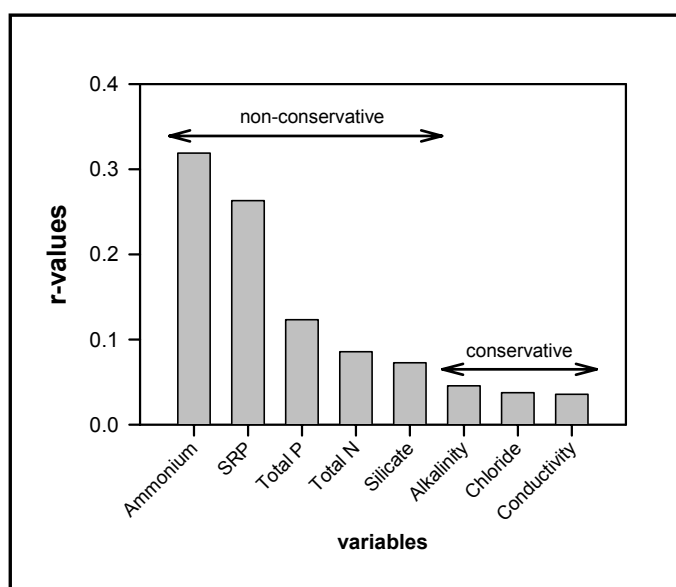


Figure 2.2
Decreasing concentrations of several variables (NH₄⁺, SRP, Total P, Total N, SiO₂, alkalinity, Cl⁻¹ and conductivity) through the epilimnion of the reservoir in July 1996. A first order decay model was applied ($p \leq 0.001$). Conservative variables (continuous lines) decreased more slowly than non-conservative variables (broken lines).

Significant rates of change of the studied are shown in Fig. 2.3. Surface water circulation in Sau lead to the loss of dissolved and particulate components, similarly to what happens in a chromatograph, in which components migrate at different speeds. The rate of change of a variable indicates the intensity of reservoir processes in retaining or transforming it.

Figure 2.3
Rates of change (r) from first order decay models applied to ammonium, SRP, Total P, Total N, silicate, alkalinity, chloride and conductivity.



Chloride, conductivity and alkalinity are considered conservative or *quasi* conservative variables. This can be easily seen from their low rates of change ($r \sim 0.04$, Fig. 2.3). These variables decreased slowly, mainly by dilution, although alkalinity had a higher rate of change, as corresponds to a variable affected by the balance production/respiration.

Nutrients are considered as non-conservative variables because they are strongly affected by biological activity. The effect of the latter can be estimated once the effect of dilution is subtracted, for example by taking chloride concentrations as a blank.

Nitrogen is of special interest in Sau, because of the intensive farming and large numbers of livestock in its catchment. In upstream reaches of the River Ter, primary sewage treatment produced a reduction

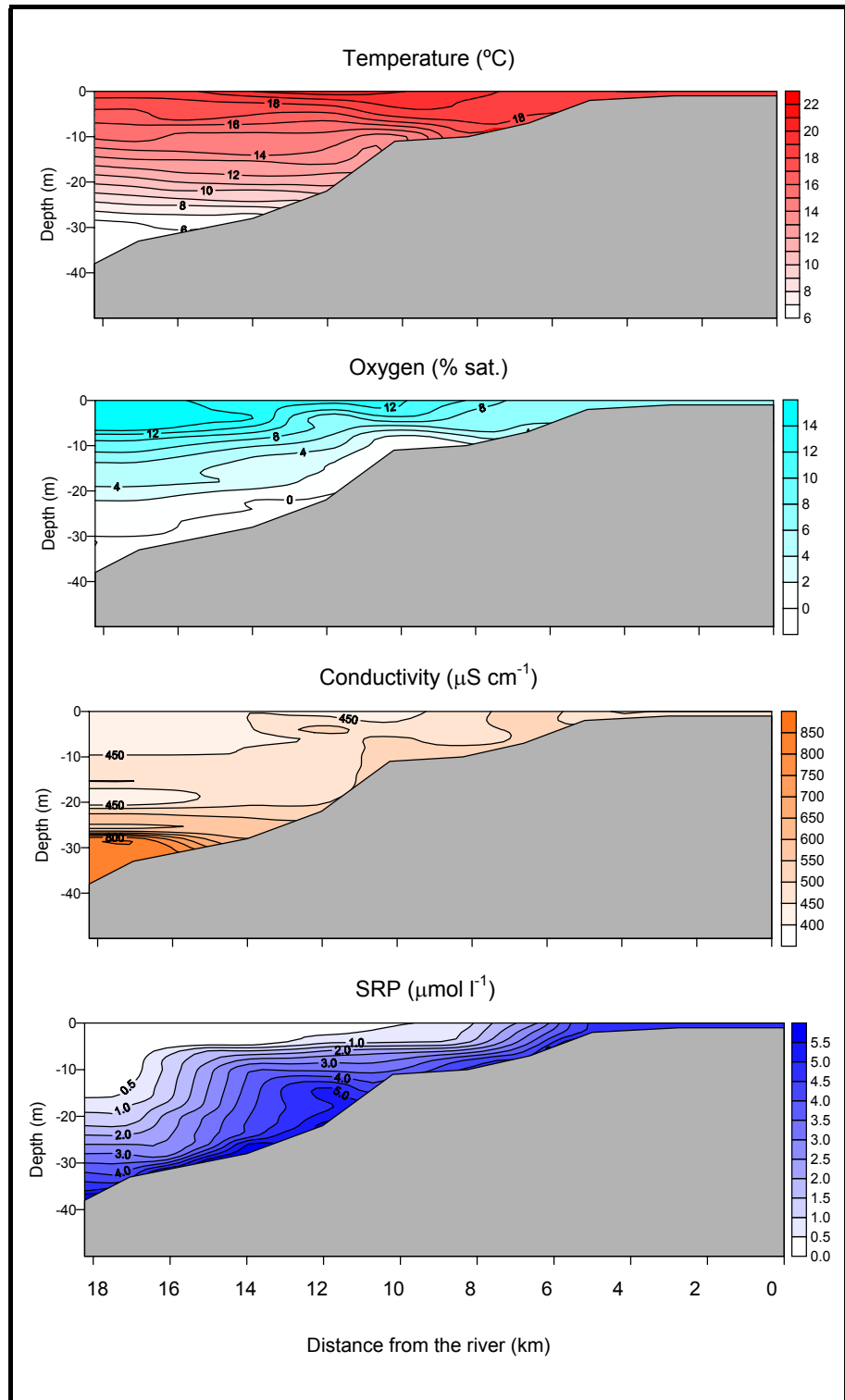
in the phosphorus loading to Sau. However, the process has not been very efficient in eliminating nitrogen. The average loading (1965-1999) was $4.63 \cdot 10^3$ kgN day⁻¹. Most of this nitrogen was in the form of ammonium or as particulate organic matter. The rate of change of the ammonia ($r=0.32$) was the highest of measured variables (Fig. 2.2), in contrast with the non-significant change of the nitrate. Soluble reactive phosphorus (SRP) had the second highest rate of change ($r=0.26$). The behaviour of both compounds indicates how fast primary producers take up these nutrients. The epilimnion indeed exhibited nutrient limiting conditions. Nevertheless, ammonium disappeared faster than SRP, which is considered as evidence that nitrification was taking place. Silicate rates of change were quite low ($r=0.07$) because diatoms were not important components of the phytoplankton community during the study period.

Total nitrogen (Total N) and total phosphorus (Total P) had intermediate rates of change. Total phosphorus disappeared faster ($r=0.12$) than total nitrogen ($r=0.09$), which is interpreted as a higher capacity of mineralization of P than of N. The reservoir indeed has given evidence of phosphorus limitation.

In May 2000 (Fig. 2.4), the reservoir was stratified and temperatures and percentage of oxygen saturation decreased with depth. The river had a similar temperature to that of the epilimnion and overflowed through the reservoir. SRP showed decreasing concentrations from bottom to surface and from river to dam, revealing it was limiting to bacterioplankton and phytoplankton growth in the epilimnion from the middle of the reservoir to the dam. These populations were efficiently taking up the phosphorus inputs from the river.

Large changes in nutrient loadings, hydrology (mainly flows), and biological activity and biomass between samplings made it impossible to compare statistically obtained rates of change. During some samplings, nutrient loads were relatively low. On other occasions, variable concentrations were measured in inflows, describing irregular longitudinal gradients in the reservoir. In flash flood periods, we observed maximum silicate concentrations in the inflow, but, under mixing conditions in the reservoir, the maximum was located nearer to the dam area.

Figure 2.4
Longitudinal profiles of temperature, dissolved oxygen, conductivity and SRP concentration in the Sau Reservoir (May 2000).



Important autochthonous biological activity during some samplings disrupted the total N and total P gradients.

Constant reduction capacities of dissolved nutrients were observed in the reservoir. High loads of dissolved nutrients were reduced by primary producers, mainly ammonium and soluble reactive phosphorus, while dissolved organic carbon (DOC) did not show significant variations (cf. Fig. 2.5). DOC standing stocks throughout the reservoir were dependent not only on the river inputs, but also on phytoplankton excretion and release from the sediment. Phytoplankton biomass was larger at intermediate stations of the reservoir (cf. following chapters). The spatial heterogeneity in phytoplankton biomass together with the variable influence of the sediment on different sampling occasions (as deduced from turbidity) explain the lack of gradients in DOC through the epilimnion of the Sau Reservoir.

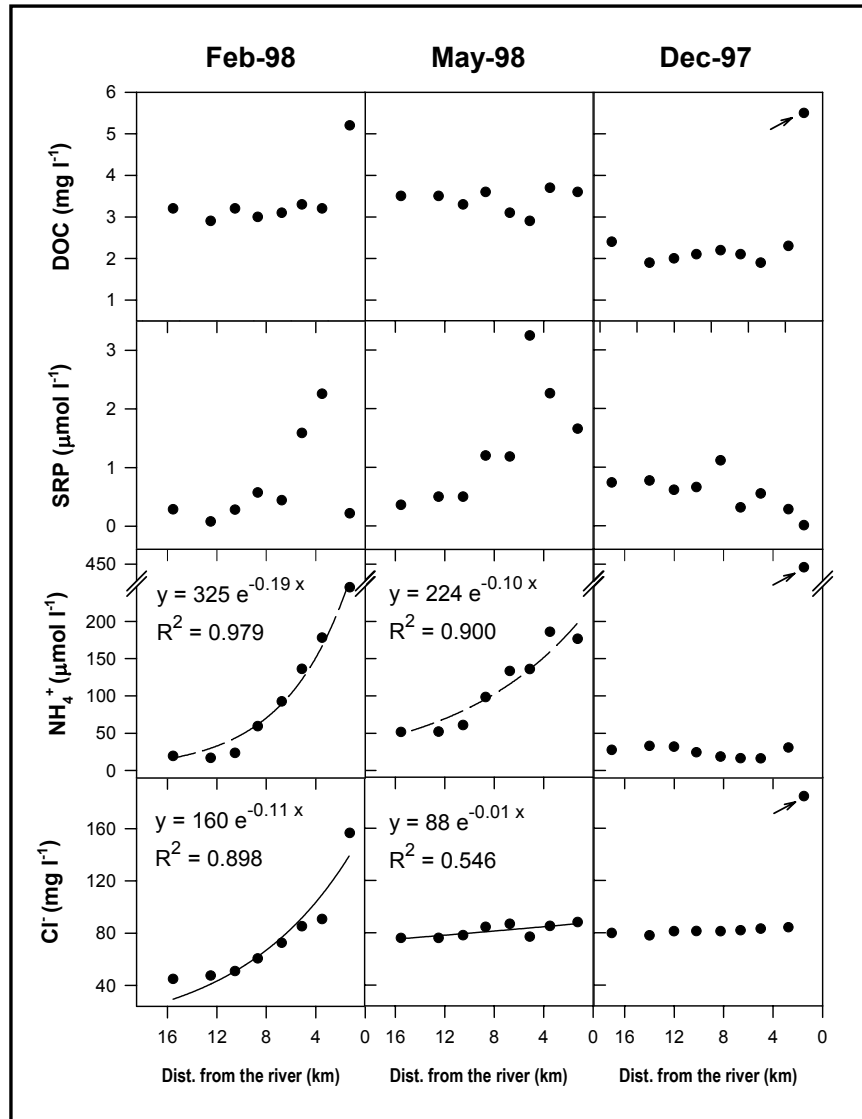
Horizontal chemical gradients controlled by river circulation patterns

The different types of river circulation established for Sau in Chapter 1 (i. e. over, inter and underflow) can contribute in a different way to the input of nutrients into the epilimnion. Focusing our discussion on dissolved nutrients (dissolved organic carbon, soluble reactive phosphorus and ammonium), we will see the effects of river circulation on this mixing.

The case of interflow has been described above (Figs. 2.1, 2.2 and 2.3). The mixing of river and epilimnion waters was highly variable and depended on changes in the river inflow and on the intensity of the vertical temperature gradient. During stratified periods, even small nutrient inputs from the river to the epilimnion produced strong gradients in nutrient concentrations due to nutrient-limiting conditions in this layer.

The overflow is the clearest situation because there is no plunge point and the epilimnion is basically formed by water from the river. Floods in fall produce the overturn of the water column, having the same effect. In this case, however, all the water profile is involved.

Figure 2.5
 Concentration of solutes (DOC, SRP, NH_4^+ and Cl^-) through the epilimnion of the reservoir in February 1998, May 1998 and December 1997. A first order decay model was applied ($p \leq 0.001$). Only significant regression lines have been plotted. Conservative variables are in continuous line and non-conservative variables in broken line. Arrows indicate the sampling point closest to the river inflow, where there is a large step in solute (DOC , NH_4^+ and Cl^-) concentrations.



Samplings from February 1998 and May 1998 show examples of overflow (Fig. 2.5), where 51% and 88% of the river water mixed with the epilimnion, respectively. February 1998 showed a high gradient in chloride concentrations, resting importance in the gradients of dissolved nutrients. In contrast, in May 1998, a clearly decreasing gradient in SRP and ammonium concentrations from the river to the dam existed which was not attributable to a dilution gradient (i. e. the chloride concentration

gradient).

During the underflow circulation, the river plunged very fast to the bottom of the reservoir with little mixing with the surface water layer (i. e. effectively, there was no epilimnion). The mixing was estimated in only a 15% of total epilimnion water volume in December 97 (Fig. 2.5). There was a clear step in nutrient concentrations between the sampling station closest to the river inflow (marked by an arrow, in Fig. 2.5) and downstream sampling stations. The exception was SRP during this sampling, which showed low values at the inflow. During underflow, falling chemical gradients at the surface were mainly due to hydrology, differing from the other two types of river circulation, in which biological activity in the epilimnion was the main factor controlling water quality improvement from river to dam.

CONCLUDING REMARKS

As KENNEDY and WALKER (1990) have described, an advective flow regime mainly caused by river inflows in combination with a long, narrow basin morphology, as in the Sau Reservoir, results in the spatial ordering of nutrient-related processes and the establishment of gradients from headwater to dam.

The manner in which the river flows through the reservoir influences the distribution of nutrients in the reservoir. During periods of river underflow, interflow, and overflow, less to more nutrients reach the surface layers. However, longitudinal gradients are also influenced by nutrient loading, nutrient availability to plankton in the reservoir, biological activity, and sedimentation.

A decrease in nutrient concentrations along the epilimnion of the reservoir, describable by a first order decay model, has been observed under stable conditions in the Sau Reservoir. Nevertheless, water quality of the Sau reservoir generally improved from the river to the dam. Overall, SRP and ammonium concentrations were effectively reduced along the longitudinal axis of the reservoir.