Aysén Sound, Chile

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Study area description

Chile has a large estuarine system in its southern extreme, which spreads between Puerto Montt (42.5ºS) and Cape Horn (55.5ºS), a distance of about 1,400 km, and includes a great quantity of islands surrounded by innumerable channels. The basins of this estuarine system were formed as a result of erosive glacier action and by the tectonic sinking of the longitudinal valley south from Puerto Montt (Borgel 1970-1971). After the last glacial age, the sea level rose and those basins were flooded by the sea, forming a mixed system of drowned river valleys, fjords and inner seas.

Due to the heavy rains in the area (e.g., 1,040 mm in Guafo; 3,170 mm in Melinka; 3,870 mm in Puyuhuapi: Pickard 1971), an estuarine system was generated. This system has a high economic value, due to the great quantity and diversity of natural resources and also because of its convenience for the culture of marine species. These characteristics have brought about a quick growth of urban areas, an increase of the riverine population and the establishment of more than 360 businesses using marine culture. Among these businesses, 125 are salmon and trout growth and nursery centers (Fundación Chile 1996).

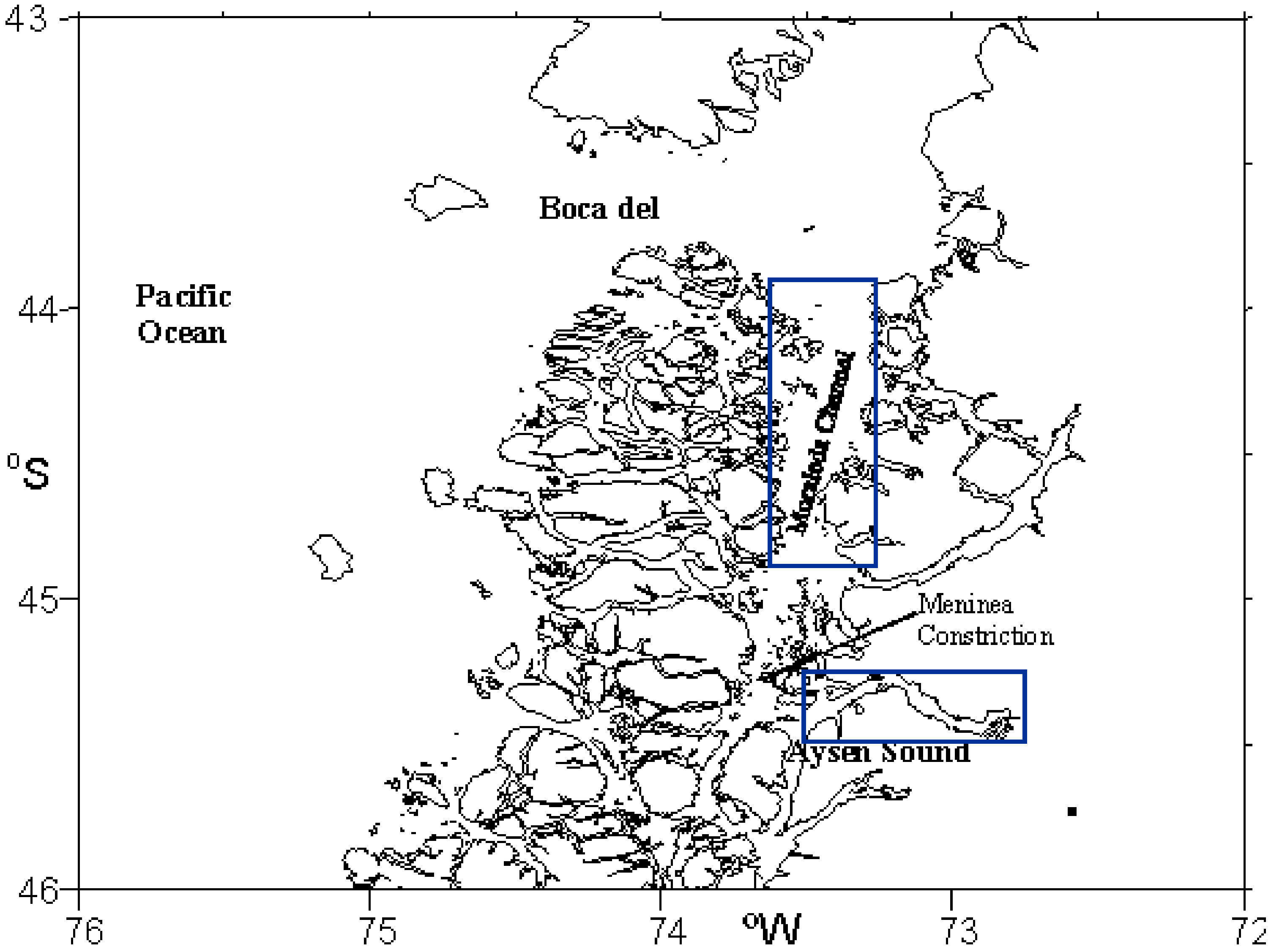

Figure 1 Location of Aysen Sound, Chile.

Hydrographic Aspects

Aysén Sound is a fjord which is located between 45.3°-45.5°S, 72.8º-73.8ºW, with a length of about 73 km, an average depth of 142 m and an area of about 470 km^2. Its mouth is connected to the southern extreme of the Moraleda Channel which is in turn connected to the sea at its northern extreme through the “Boca del Guafo” (Figure 1).

The Aysén River flows into the head of this fjord, and it has as principal discharges the Mañiguales (15 million m^3 day^{-1}), the Simpson (9 million m^3 day^{-1}) and the Claro (500 thousand m^3 day^{-1}) rivers. In addition, the Cuervo (9 million m^3 day^{-1}) and Lagunillas (4 million m^3 day^{-1}) rivers flow directly into the fjord (Ministerio de Obras Públicas 1997). There are other rivers for which there are no flow records; but which seem to be relatively unimportant.

Due to the large freshwater contribution from rivers and rain, Aysén Sound is characterized by a two-layer structure, separated by a strong halocline. The upper layer, which is about 25 m thick, has salinities between 0 psu at the head and 29 psu at the mouth. The lower layer is more homogeneous, with salinities between 30 and 31 psu (Figure 2) (Sievers and Prado 1994; Silva *et al.* 1995, 1997). The upper layers are well-oxygenated throughout the sound and have concentrations from 5 to 7 ml l^{-1}. However, the lower layers have concentrations about 5 ml l^{-1} in the first third of the sound, but then it rapidly decreases towards the head to values lower than 2.5 ml l^{-1} near the bottom (Silva *et al.* 1995, 1997). This situation is also seen in the pH measurements in the area, which are 7.75 at the mouth and 7.35 at the head (Silva *et al.* 1997).

Nitrate (DIN) and phosphate (DIP) also show a two-layer structure, with lower values at the surface, due to the contribution of low-nutrient rivers (Silva *et al.* 1990a, 1990b) and biological uptake. The upper layer has concentrations of 0-1.2 µM of phosphate and 0-12 µM of nitrate. The lower layer is more homogeneous, with concentrations of 1.4-1.8 µM of phosphate and 1.2-12 µM nitrate, increasing from the mouth to the head (Silva *et al.* 1997). The average N:P Redfield ratios for the sound waters, obtained by linear regression, were 10.6:1 with a correlation coefficient of 0.971 (Calvete 1997).

The decrease of dissolved oxygen and pH and the increase of dissolved nutrients towards the head of the fjord indicate a strong remineralization of organic material at the head of the fjord. The above would be due principally to the nutrient regeneration from marine organic matter produced in the sound and terrestrial organic matter brought by the rivers. A probable sluggish circulation in this upper part of the sound will contribute to the permanence of high values of DIN and DIP. Chemical measurements in sound sediments show high concentrations of organic matter (8-10%), organic carbon (1.5-4%) and Kjeldahl nitrogen (0.1-0.3%) (Silva *et al.* 1998), which are characteristic of the highly productive areas.

General circulation

Near the southern extreme of the Moraleda channel, off Meninea island (45.27º S; 73.63º W), there is a shallow sill (60 m deep), which makes the southern part of the Moraleda channel and Aysén Sound form a deep basin partially isolated from the open ocean. This “Meninea constriction” constrains the circulation in the levels below the sill (60-300 m) and results in different oceanographic characteristics in the two basins. The southern basin is warmer, less saline and more oxygenated than the northern one, which is connected to the open ocean through the Guafo mouth.

The former situation, where the isolated basin is more oxygenated than the basin with free exchange to the open ocean, could be explained on the basis of an estuarine circulation mechanism and the presence in the channels of low oxygen deep water from Equatorial Subsurface origin (Silva *et al.* 1995). The water from the 25 to 60 m depths has a small net flow towards the south that allows the northern basin water to pass into the southern basin, where it sinks into deeper levels because of its higher density than the interior water. Thus 25 to 60 m water fills most of the deep part of the southern basin, carrying its characteristics and producing the situation described above. In order to maintain the volume balance, the less saline upper layer water of the southern basin has a net flow to the north, flowing out towards the adjacent oceanic area.

A net current of 16 cm sec^{-1} towards the ocean for the surface layer, and a net current of 2 cm sec^{-1} for the subsurface layer, have been shown as a result of two-month current meter measurements in the Meninea area (Salinas and Hormazábal 1996).

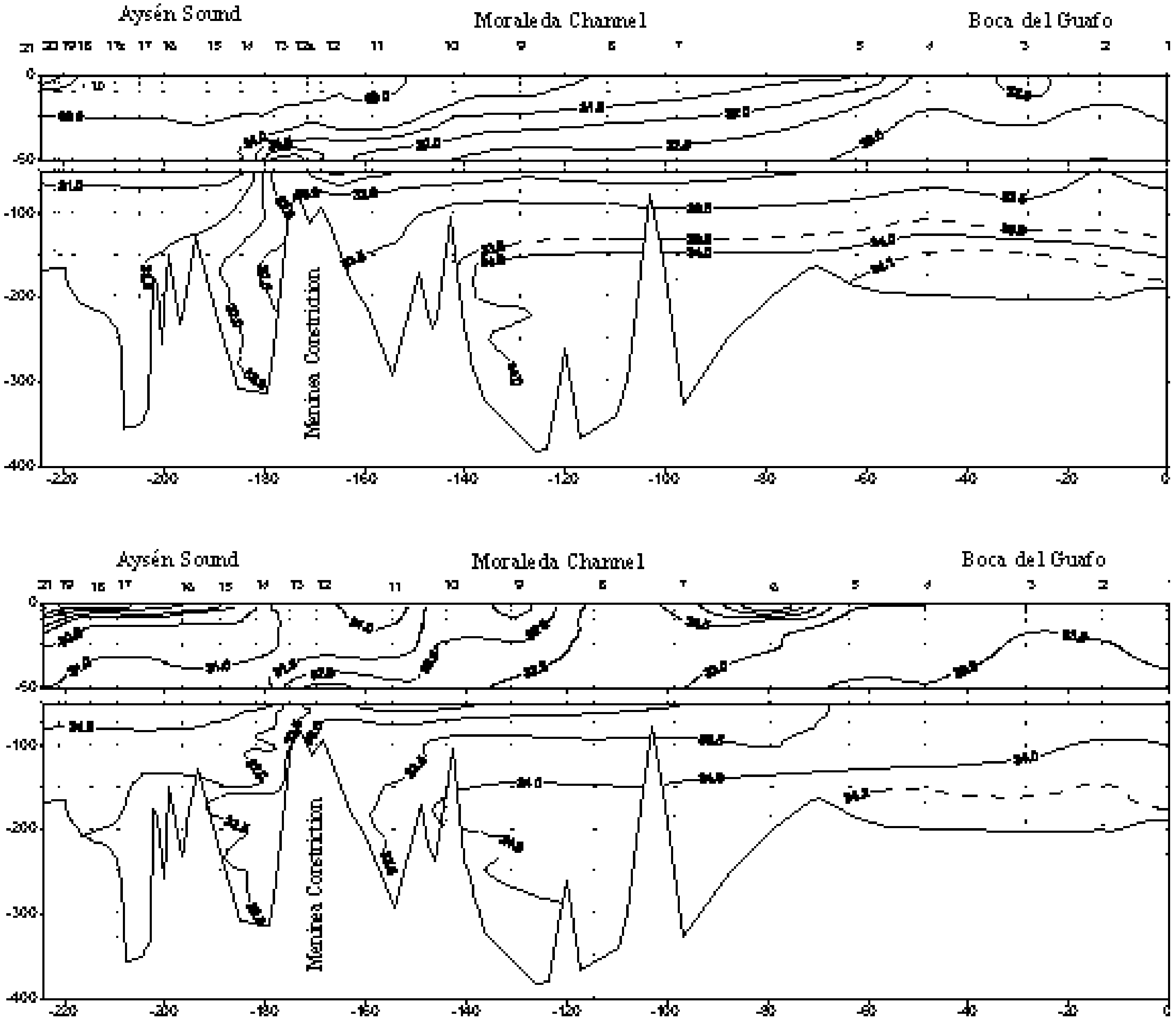

Figure 2 Vertical distribution of salinity for Cimar Fiordo 4-1 (upper) and Cimar Fiordo 4-2 (lower) cruises.

Water and salt budgets

By means of the employment of a two-layer box model and based on the methodology proposed by LOICZ, a water and salt budget for Aysén Sound was prepared. To do that, the following assumptions were made:

- $V_G = 0$ and $S_G = 0$ (groundwater), since it was not possible to estimate them. In any case, the terms seem likely to be small compared with river flow and rainfall.

- $V_0 = 0$ and $S_0 = 0$ (riverine fresh water). These terms were considered irrelevant, since the greater sources of freshwater are the rivers and the rain.

- $V_E = 0$ (evaporation), since it was considered as minor term in the estuarine system compared with high precipitation volumes (≈2 m year^{-1}) and relatively low mean annual air temperature (≈10ºC) of the area.

- V_Q (River flow) was obtained based on historical records of the Mañiguales, Simpson, Claro, Lagunillas and Cuervo rivers, which provide the estuarine system with fresh water. Since monthly records were available, the records were divided into two seasonal periods (summer and winter). These values were increased by 30%, to correct them for freshwater input provided by rivers and coastal runoff for which there are no records.

- S_Q (river salinity) was assumed to be 0.1 psu, as has been reported in other studies.

- V_P (precipitation) was obtained based on historical records from Puerto Aysén (Dirección Meteorológica de Chile 1983-1996). Monthly records were compiled into two seasonal periods (summer and winter).

- Due to the presence of a halocline centered around 25 m depth, the box model was considered as a two-layer one, with the first layer in the upper 25 m and the second below 25 m.

- Due to the presence of the Meninea constriction (which behaves as a physical barrier to water movement), the 25-80 m stratum was considered as the deep layer of the oceanic box. Meanwhile in the estuarine system, the deep layer was considered to cover the strata from 25 m to the bottom.

- The Meninea constriction was considered as the limit of the estuarine system, since it represents a physical barrier between the oceanic and the estuarine system.

Based on the previously stated considerations, and data taken by Cimar Fiordo 1 (winter 1995), Cimar Fiordo 4-1, (winter 1998) and Cimar Fiordo 4-2, (summer 1999) cruises, a water and salt budget for Aysén Sound was prepared (Tables 1 and 2; Figures 3, 6, 9).

Table 1. Summary of the estimated and measured variables in the Aysén Sound system.

Estimated Parameter	**Values**
System Area (10^6 m^2)	470
Average depth (m)	142
System volume (10^9 m^3)	66.8
Average winter rain (mm day^{-1})	8
Average summer rain (mm day^{-1})	6
Average winter river flow (10^6 m^3 day^{-1})	10
Average summer river flow (10^6 m^3 day^{-1})	8

Table 2. Summary of estimated and measured values for the Cimar Fiordo cruises.

	OCEANOGRAPHIC CRUISES		
Estimated and measured variables	Cimar Fiordo 1 (winter) - Oct 95	Cimar Fiordo 4 - 1 (winter) - Oct 98	Cimar Fiordo 4 - 2 (summer) - Mar 99
Flows (10^6 m^3 day^{-1})			
V_Q	10	10	8
V_P	4	4	3
V_{deep}	81	66	34
V_Z	37	30	8
V_{surf}	95	80	45
V_{deep}	81	66	34
Salinities (psu)			
S_{Syst-s}	27.9	27.3	25.1
S_{Syst-d}	31.2	31.3	31.7
S_{Ocn-s}	31.8	31.3	32.3
S_{Ocn-d}	32.7	33.1	33.3
S_Q	0.1	0.1	0.1
S_{Syst_tot}	29.3	29.3	28.4
S_{Ocn_tot}	32.2	32.2	32.8
Nutrients (mmol m^{-3})			
DIN_{Syst-s}	15.0	8.4	Data in process
DIN_{Syst-d}	17.6	17.5	Data in process
DIN_{Ocn-s}	10.5	6.9	Data in process

$\text{DIN}_{\text{Ocn-d}}$	15.9	16.7	Data in process
DIN_{P}	2	2	Data in process
DIN_{Q}	1	1	Data in process
$\text{DIP}_{\text{Syst-s}}$	1.5	0.9	Data in process
$\text{DIP}_{\text{Syst-d}}$	1.7	1.7	Data in process
$\text{DIP}_{\text{Ocn-s}}$	1.1	1.0	Data in process
$\text{DIP}_{\text{Ocn-d}}$	1.4	1.7	Data in process
DIP_{Q}	0.1	0.1	Data in process
Exchange time			
τ (days)	703	835	1,482
τ (years)	1.9	2.3	4.1

Even though the area is very rainy (precipitation ≈2 m yr^{-1}), it shows some degree of seasonality in precipitation and river discharge (Table 1). Therefore, the available data were analyzed in two parts: a southern fall-winter (April to October) period and southern spring-summer (November to March) period. Figures 3 and 6 summarize the water and salt budgets for two cruises performed in late winter (October 1995 and 1998), and Figure 9 summarizes the water and salt budgets for a cruise performed in late summer (March 1999). The river flow and precipitation used in the budgets (Table 2) correspond to seasonal averages based on monthly historical data taken during several years (Dirección Meteorológica de Chile 1983-1996).

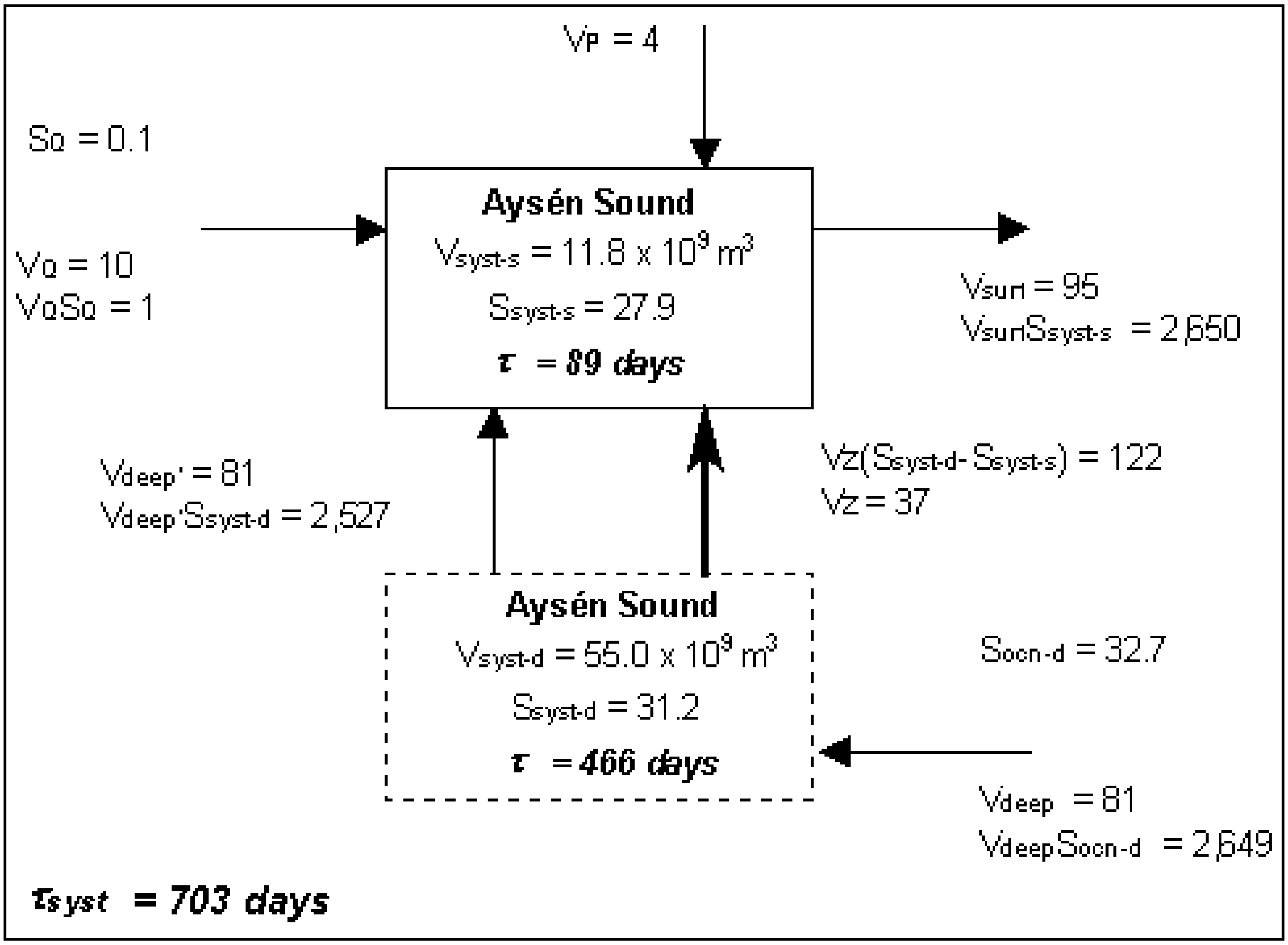

Figure 3 Box diagram for water and salt budget in a 1-box 2-layer model, for Aysén Sound (October 1995, southern winter, Cimar Fiordo 1 cruise)**.** Input and output fluxes (10^6 m^3 d^{-1}; 10^6 psu m^3 d^{-1}) and exchange time are indicated.

The average residence time of water in the Aysén basin was estimated to be around 3 years. However, due to the larger freshwater contribution in winter, the renewal is twice as fast as in the summer season (Table 2). Our estimated average exchange time results are somehow longer than the 12 months reported by Salinas and Hormazábal (1996). There is a strong need to get a better estimate of runoff not taken into account by the river discharge, and it would be preferable to use precipitation and runoff data for the period preceding the study rather than the long-term average data that are available. Evaporation and groundwater inflow are two variables that need a careful review to find out if the previously-stated assumptions on this matter can be kept or there is a need to get better estimates of them, to be substituted into the budgets.

Dissolved nonconservative materials budgets

Based only in nutrient data taken in the winter cruises (Cimar Fiordo 1 and 4-1), the nonconservative materials budgets were determined. The DIN budgets are shown in Figures 4 and 7, and the DIP budgets are shown in Figures 5 and 8.

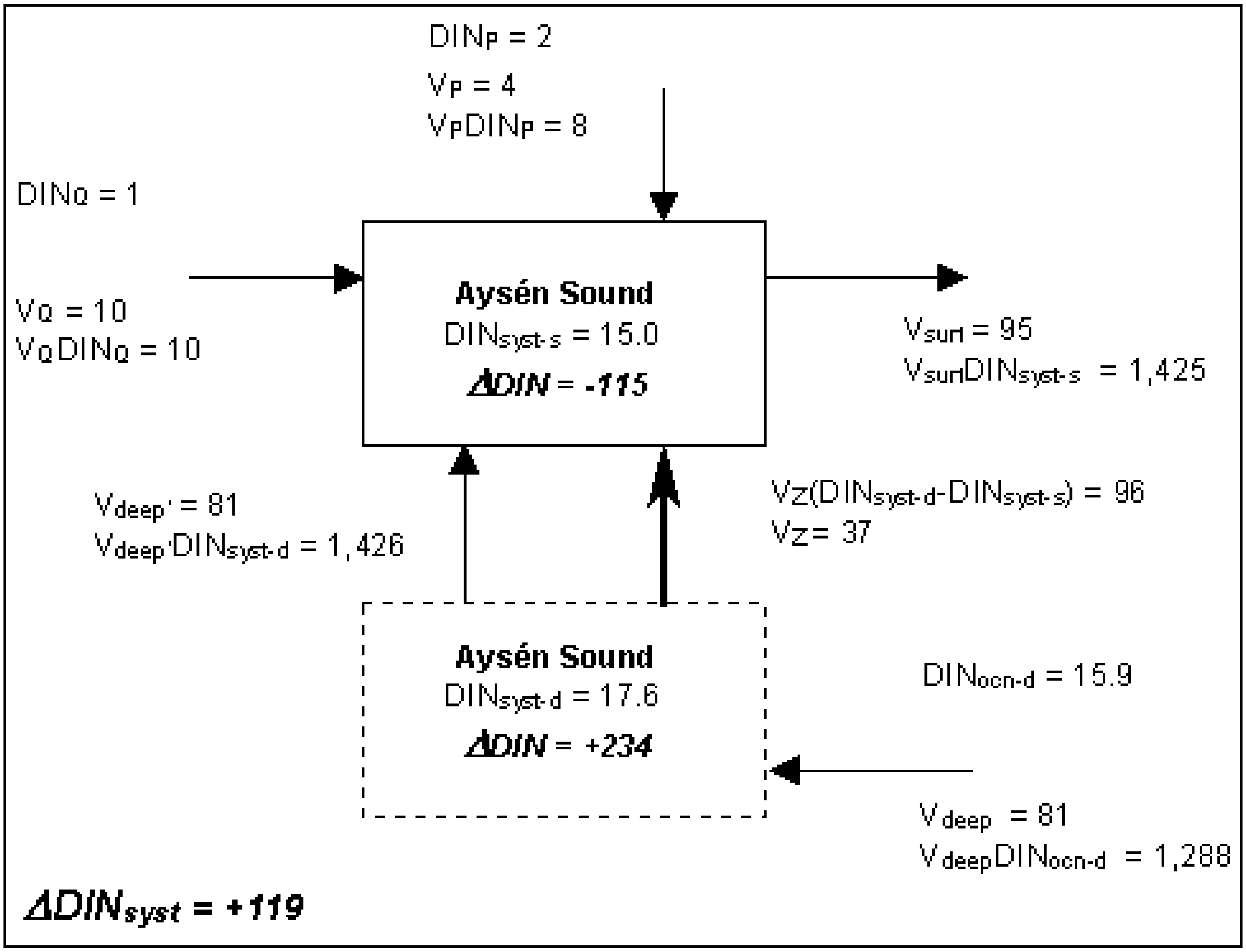

Figure 4. Box diagram for dissolved nitrate-nitrite budget in 1-box 2-layer model, for Aysén Sound (October 1995, southern winter, Cimar Fiordo 1 cruise). Fluxes in 10^3 mol d^{-1}.

For the DIN budget, only dissolved nitrate+nitrite were used, because the ammonium data, measured only in Cimar Fiordo 1, showed very low concentrations (< 1 mmol m^{-3}). In a general sense, DIN and DIP are provided to the fjord area from the ocean, since the rivers have very low nutrient concentrations (Silva *et al.* 1997).

The surface layer of Aysén Sound apparently behaves as a nitrogen fixation system, and the deep layer as a denitrifying system, for both winter cruises (Table 3). Nevertheless, the system as a whole did not show a constant behavior. During Cimar Fiordo 1, the whole system appeared to be denitrifying while in Cimar Fiordo 4-1 it showed to be fixing nitrogen. Both rates were low, and the average is near 0. It seems possible that slight differences in the timing of the spring bloom may at least partially account for the differences.

It is important to keep in mind that the budgets presented here are based on isolated measurements (cruises); therefore they have to be taken with caution and their results cannot be extrapolated to a full year conclusion for Aysén Sound.

Table 3. N:P stoichiometry for the CIMAR Fiordo winter cruises.			
N:P = 16	**(nfix-denit)**	**(nfix-denit)**	**net nitrogen status**
Cruises / layers	10^3 mol N day^{-1}	mmol N m^{-2} day^{-1}	
Cimar Fiordo 1			
Surface layer	-67	-0.1	Denitrification
Deep layer	-278	-0.6	Denitrification
System	-345	-0.7	Denitrification
Cimar Fiordo 4-1			
Surface layer	+276	+0.6	N-fixation
Deep layer	-58	-0.1	Denitrification
System	+218	+0.5	N-fixation

The net ecosystem metabolism *(p-r)* was estimated based on the behavior of Δ*DIP*, relative to the Redfield C:P ratio. It has been inferred that if Δ*DIP* shows a negative value, the system is autotrophic, producing organic matter and consuming dissolved inorganic carbon (DIC). This seems to be the situation for Aysén Sound surface layer in both cruises. As expected, the deep layer behaves as an heterotrophic system since Δ*DIP* is positive and *(p-r)* is negative (Table 4, Figures 5 and 8). In this case DIC is released due to the organic matter remineralization in the deep layer.

Table 4. C:P stoichiometry for the winter cruises.			
C:P = 106	***(p-r)***	***(p-r)***	**net trophic status**
Cruises / layers	10^3 mol C day^{-1}	mmol C m^{-2} day^{-1}	
Cimar Fiordo 1			
Surface layer	+318	+0.7	autotrophic
Deep layer	-3,392	-7.2	heterotrophic
System	-3,074	-6.5	heterotrophic
Cimar Fiordo 4-1			
Surface layer	+6,890	+14.7	autotrophic
Deep layer	-2,544	-5.4	heterotrophic
System	+4,346	+9.2	autotrophic

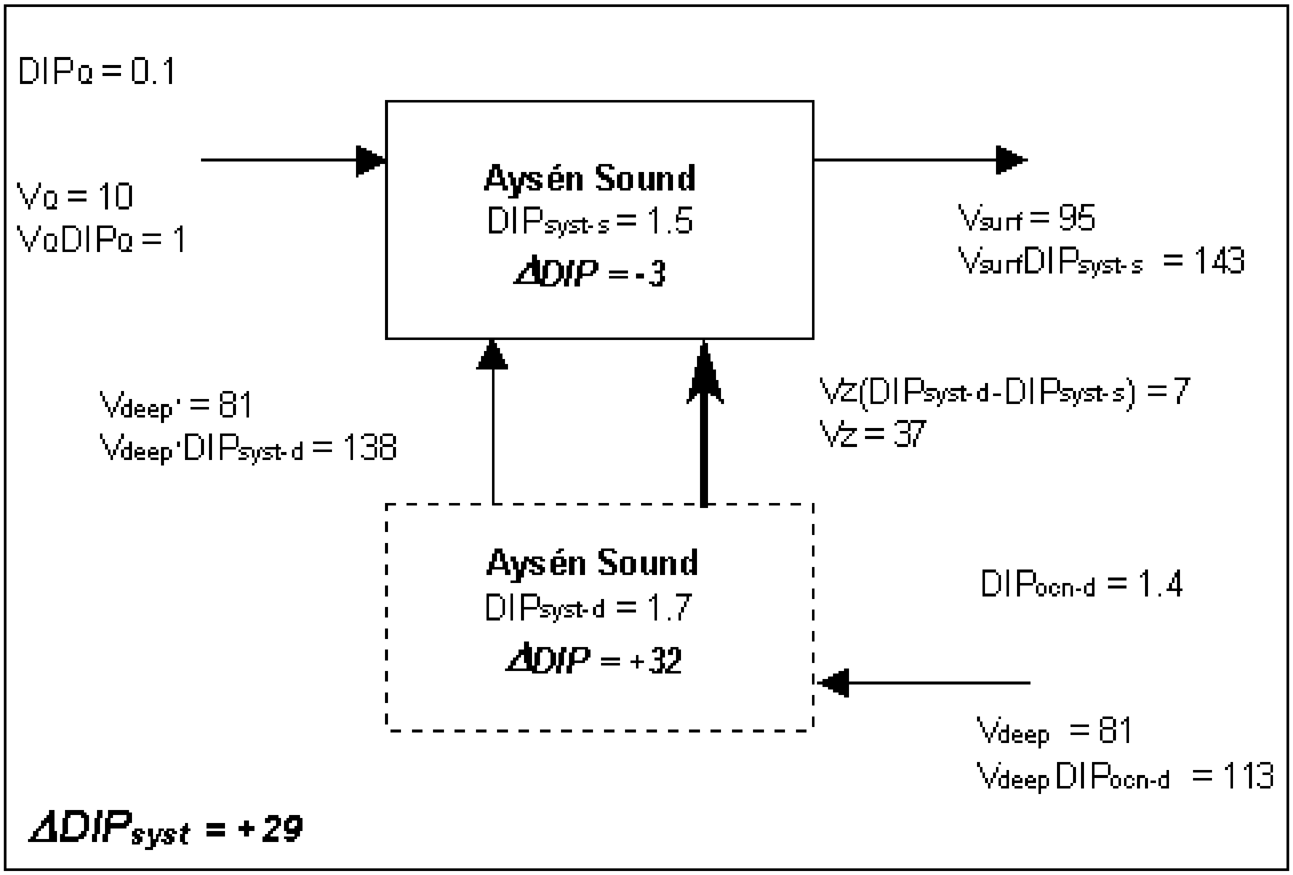

Figure 5. Box diagram for dissolved phosphate budget in 1-box 2-layer model, for Aysén Sound (October 1995, southern winter, Cimar Fiordo 1 cruise). Fluxes in 10^3 mol d^{-1}.

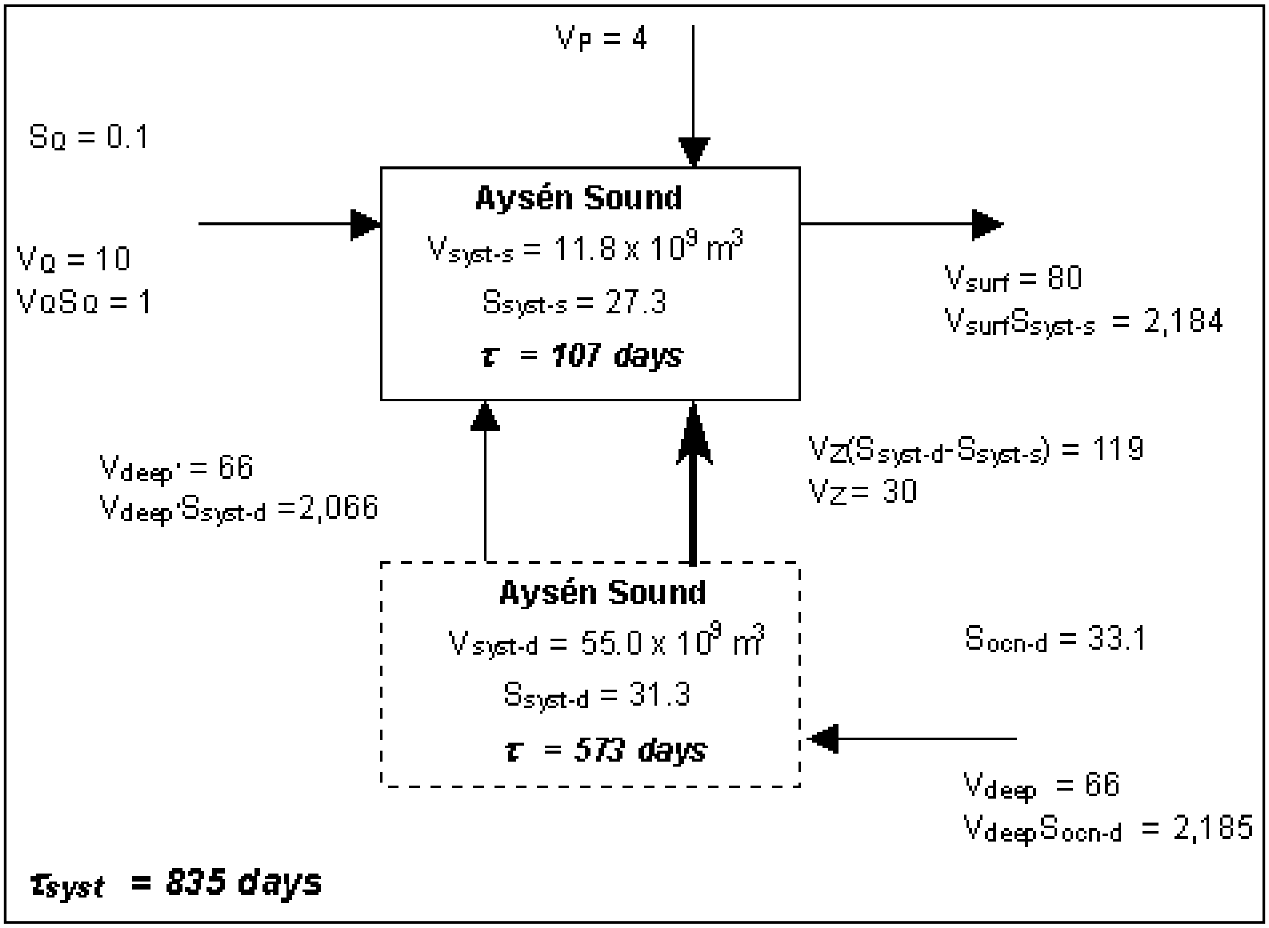

Figure 6. Box diagram for water and salt budget in 1-box 2-layer model, for Aysén Sound (October 1998, southern winter, Cimar Fiordo 4-1 cruise). Input and output fluxes (10^6 m^3 d^{-1}; 10^6 psu m^3 d^{-1}) and exchange time are indicated.

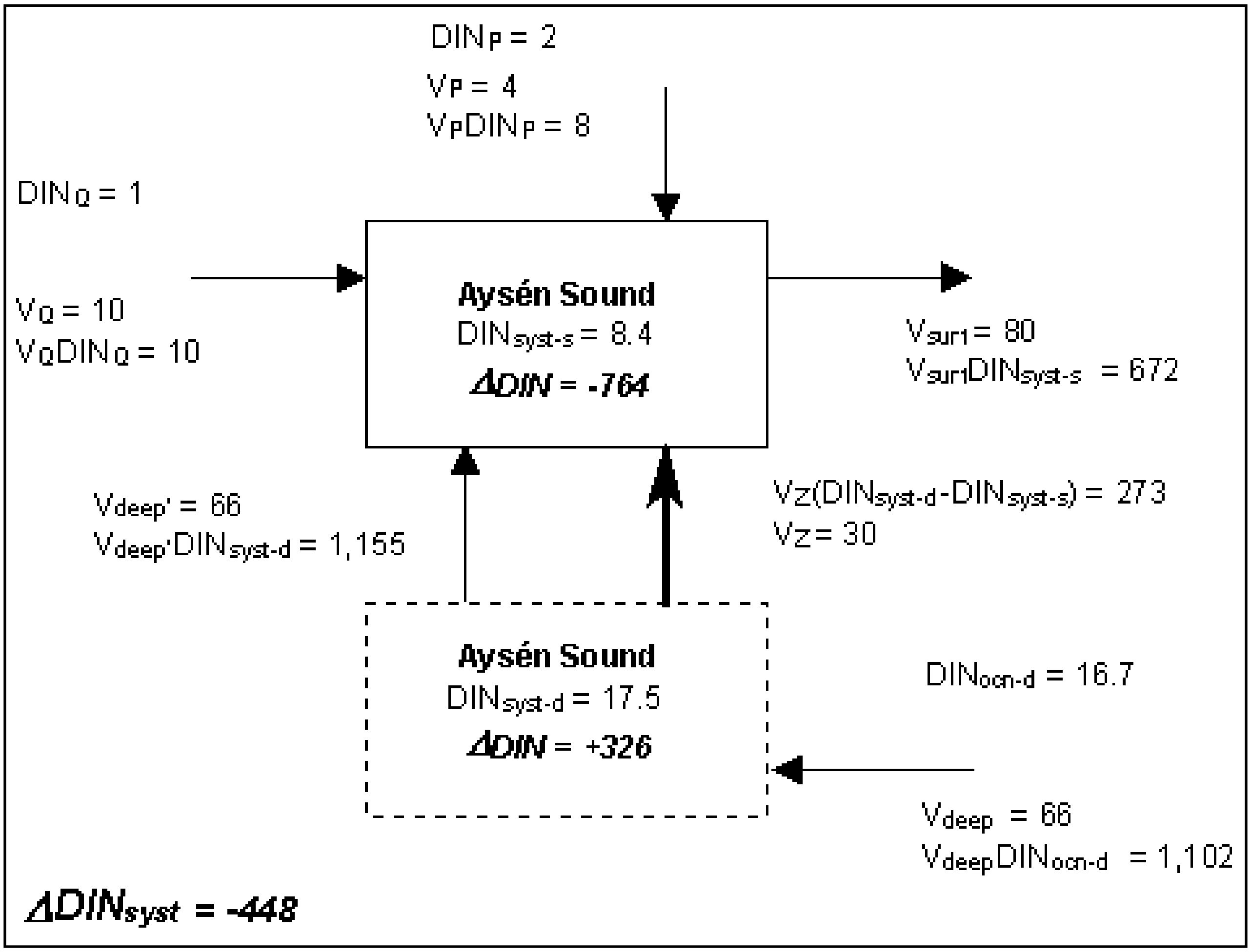

Figure 7. Box diagram for dissolved nitrate-nitrite budget in 1-box 2-layer model, for Aysén Sound (October 1998, southern winter, Cimar Fiordo 4-1 cruise)**.** Fluxes in 10^3 mol d^{-1}.

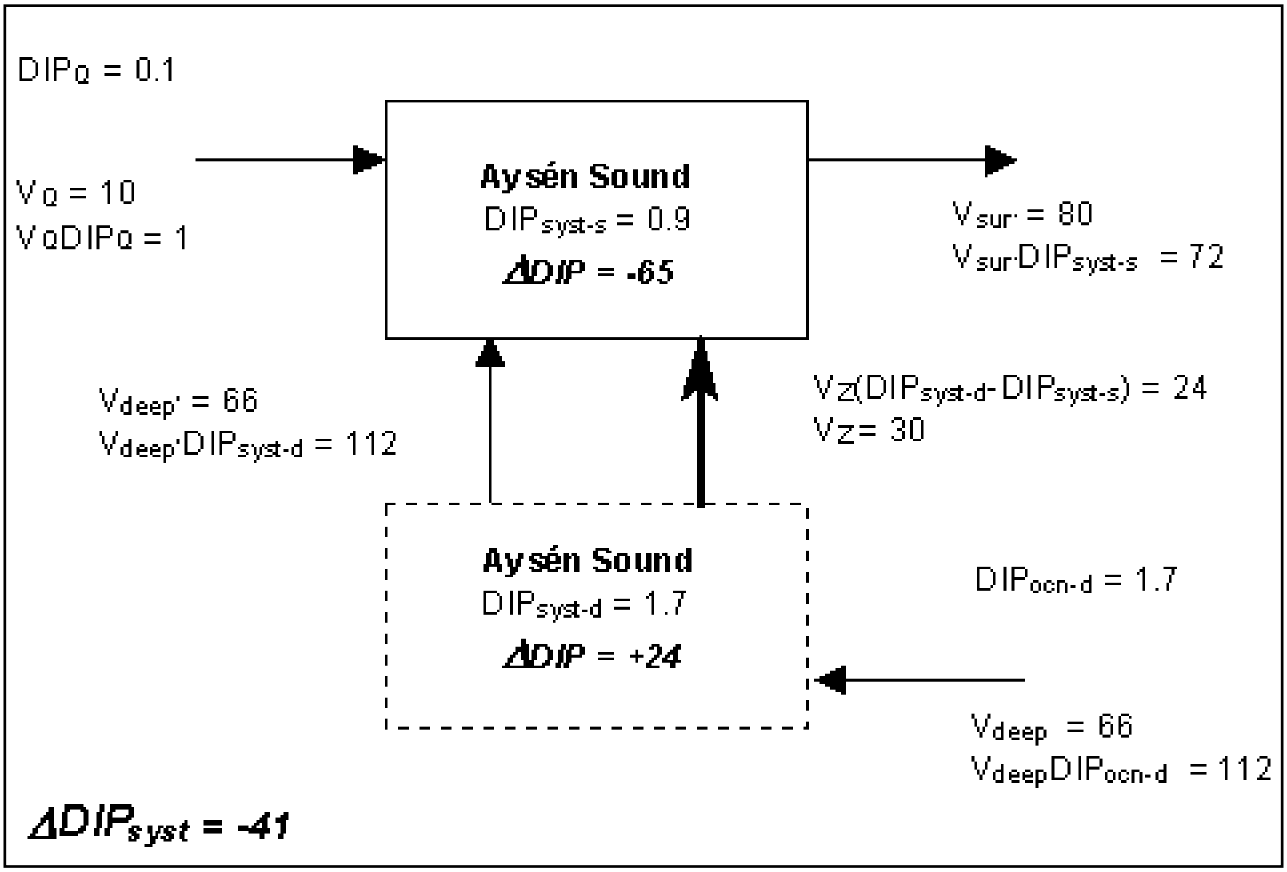

Figure 8. Box diagram for dissolved phosphate in 1-box 2-layer model, for Aysén Sound (October 1998, southern winter, Cimar Fiordo 4-1 cruise)**.** Fluxes in 10^3 mol d^{-1}.

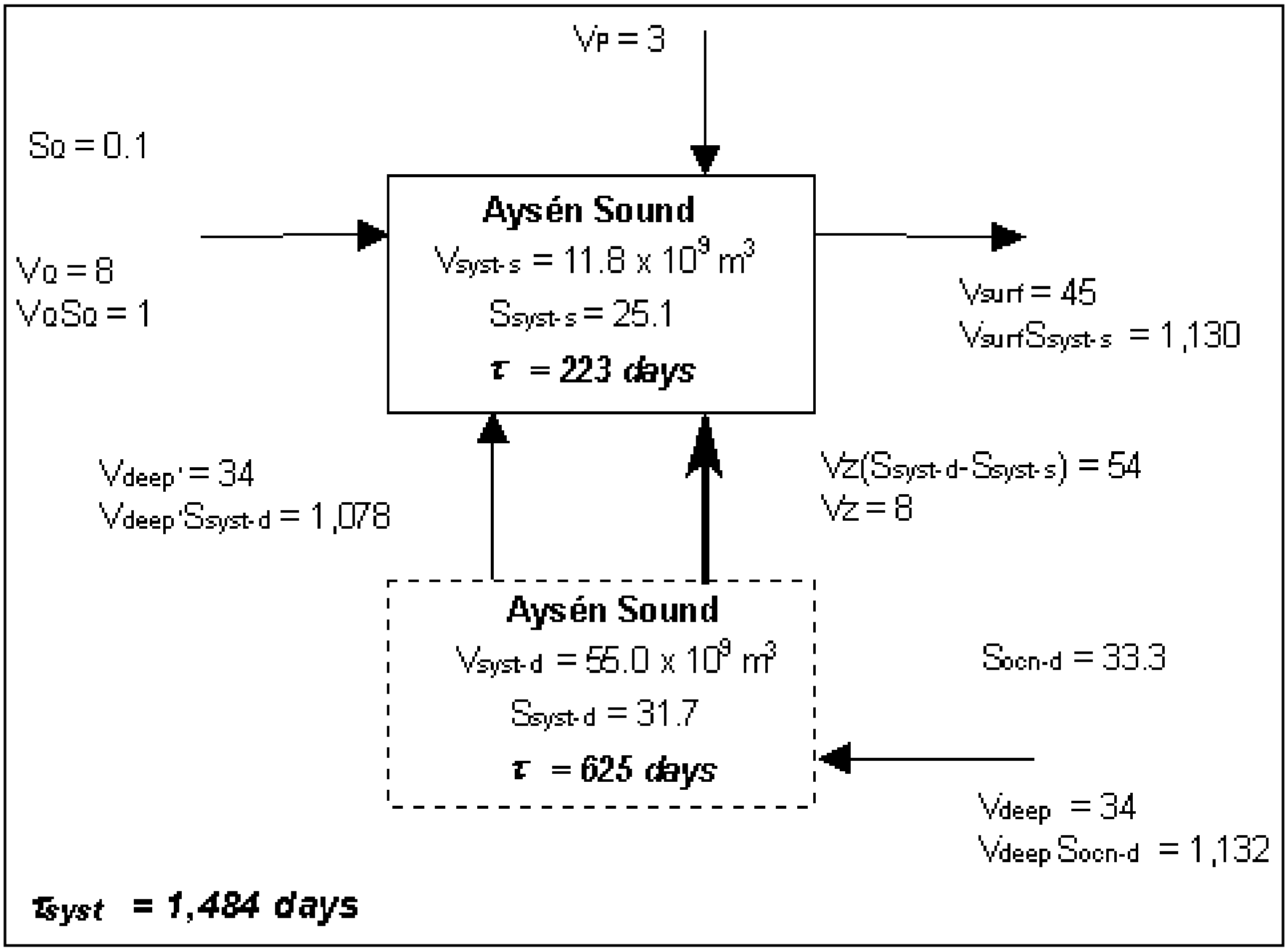

Figure 9. Box diagram for water and salt budget in 1-box 2-layer model, for Aysén Sound (March 1999, southern summer, Cimar Fiordo 4-2 cruise)**.** Input and output fluxes (10^6 m^3 d^{-1}; 10^6 psu m^3 d^{-1}) and exchange time are indicated.

Back to [Node Introduction] [Budgets][South America] [EXIT LOICZ]

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