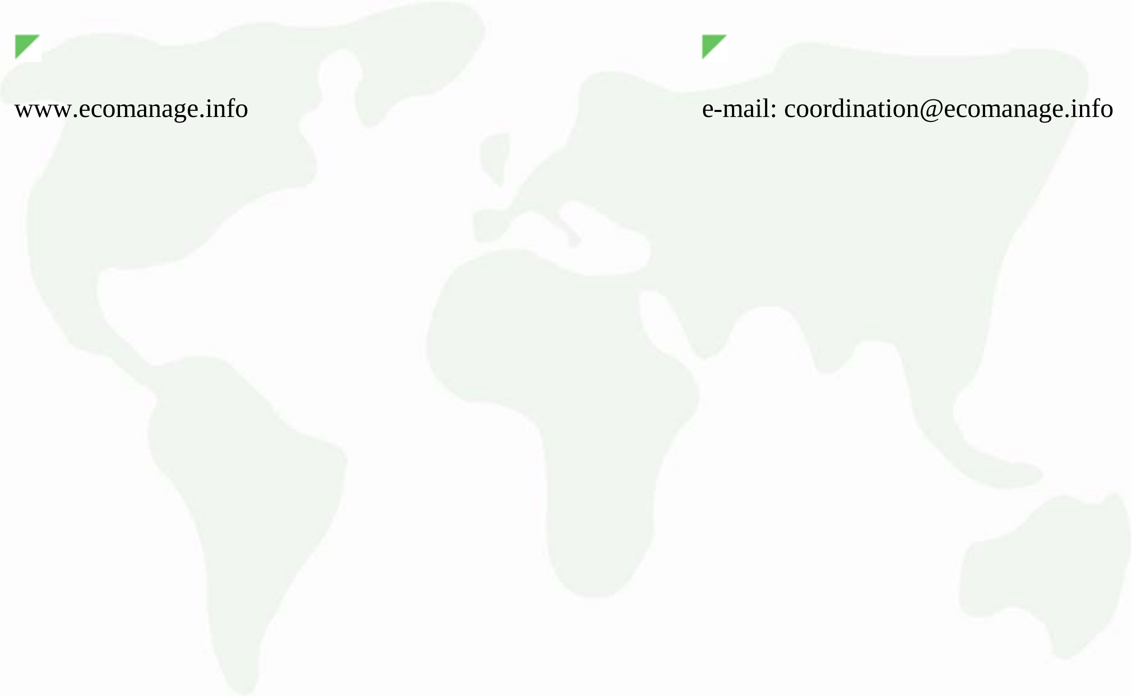

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Ecological Conceptual Modelling for the Bahía Blanca Estuary

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INTEGRATED ECOLOGICAL COASTAL
ZONE MANAGEMENT SYSTEM

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ABSTRACT

This report summarises the efforts to obtain a conceptual ecological model from historical data and bibliography review.

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Ecological Conceptual Model of the Bahía Blanca Estuary

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Abstract

An ecological conceptual model has been built for the Bahía Blanca estuary as a previous step to study, evaluate, calibrate and validate the results obtained through ecological numerical modelling. To achieve this objective, historical data from a set of stations along the Principal Channel and in the neighbouring coastal area of Bahía Blanca estuary has been re-analysed. In addition, a bibliographic review to establish the casual relationships between the abiotic components, nutrients and living compartments of the system has been completed.

The Bahía Blanca estuary after this analysis it would be divided in three different areas: head, mixed and ocean. In the head is the most active part of the estuary in regard to primary production, the mixed area would be the area where the products of this production are remineralised and thus serve as a buffer area of nutrient to the coastal area. And the oceanic area is where the processes and concentrations are very similar to the ones observed in the neighbour coast of Bahía Blanca estuary. Diatoms would be the main form of phytoplankton blooming during winter period and predated by copepods and ciliates. However, the limiting factor for diatoms growth seems to be a complex system of control that includes abiotic and biotic factors.

1 Introduction

Estuaries could be regarded as the coastal area where fresh water meets seawater, usually in the presence of tides, producing a salinity continuum from fresh water to seawater. In fact, estuarine limits would be related in a higher degree with salinity values than with geography. Bahía Blanca estuary is an especial case as could be regarded as an estuary connected to the sea by tidal channels. Fresh water inputs into the system are only significant in the most inner part of the estuary while a few kilometres seawards, salinity do not differ from an open ocean typical value.

Spatial evolution and climatological cycle of both the biotic and abiotic components of the system would be analysed in order to identify causal relationships that characterise the ecology of Bahía Blanca estuary. Through historical data revision a logical relationship would be constructed between the involved ecological processes and the components of the system. This exercise is performed to obtain an easy description to understand the involved ecological processes as an initial step previous to mathematical modelling.

2 Material and methods

This study focuses mainly on the Principal Channel of Bahía Blanca due to the scarce data available for the rest of the study area. A set of twelve stations (Figure 1 Left,Table 1) that runs along the Principal Channel in Bahía Blanca was selected and its temporal and spatial variations analysed. These twelve stations could be divided into three different sectors according to the properties described later on in the present paper. The head sector represents what could be considered as the *true* estuary, the ocean sector that presents conditions only slightly different from the coastal area and the mixed sector that is a transition between the other two sectors. Nevertheless, data for some of the chosen stations are scarce and some tendencies on their averages could be due to the availability of data only for specific periods. During a single campaign, Austral Campaign, carried out by IADO (Argentinean Institute of Oceanography, in its Spanish acronym) in November 1993 data was sampled on the vicinity of Bahía Blanca estuary (Figure 1 Right).

Table 1 Locations of stations with water properties data.

Sector	Name	Latitude	Longitude
Head	Villarino	38º45'41.18" S	62º25'22.12" W
	PC	38º45'09.68" S	62º22'41.30" W
	PGalvan	38º47'05.21" S	62º18'28.19" W
	IW	38º47'54.10" S	62º15'38.99" W
Mixed	Buoy 29	38º50'28.39" S	62º13'21.29" W
	Buoy 24	38º54'22.10" S	62º08'09.28" W
	Buoy 20	38º57'06.66" S	62º02'42.11" W
	Buoy 16	39º00'09.72" S	61º54'37.08" W
Ocean	Buoy 10	39º05'44.88" S	61º47'55.68" W
	Buoy 6	39º13'25.68" S	61º41'54.24" W
	Buoy 4	39º17'01.86" S	61º38'03.26" W
	Buoy 2	39º20'36.60" S	61º33'25.56" W

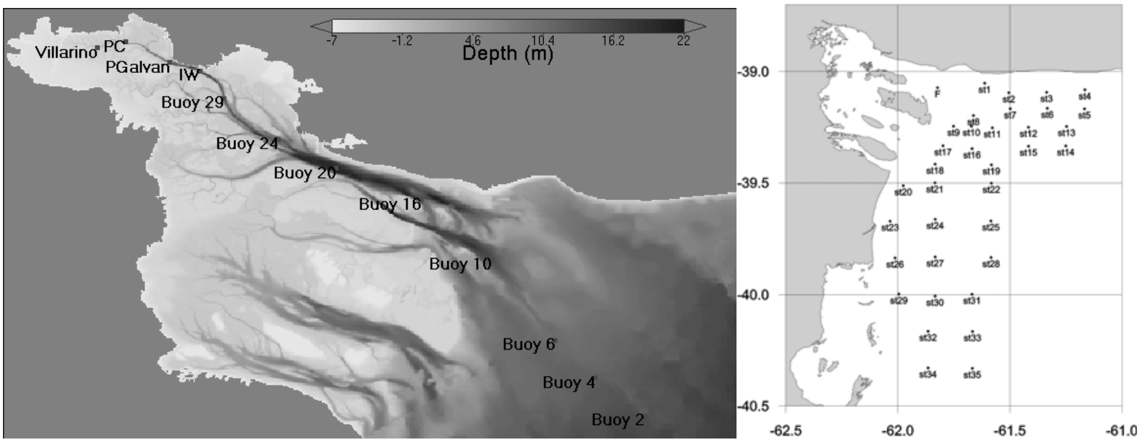

Figure 1 Location of the stations used for studying the water quality processes in the Bahía Blanca estuary (Left) and location of the Austral campaign stations (Right).

To study the spatial variations along the channel, all data available for the stations were processed, though not all stations have the same number of measurements. Additionally, semi-continuous surficial sampling performed by the IADO for the period April 2003-March 2004 from Puerto Cuatreros (hereafter PC station) to Buoy 24 during the campaign Petro III were analysed and employed to describe the properties variation on the inner area of the estuay. With the aid of this data it could be observed both the spatial and temporal variation for some of the studied variables. In order to characterise the temporal variations on water quality variables data from longest historical water quality data records: Ingeniero White harbour (hereafter IW) and Puerto Cuatreros harbour (hereafter PC) stations are also shown for the period 1994-2000.

3 Data analysis

3.1 Abiotic variables

Due to the freshwater inputs from rivers and the effect of precipitation and evaporation, it is only at its head were high variations take place, ranging values from nearly 20 to 40 PSU. On the open coast (Figure 2 Right) it can be observed a slow salinity increase from the coastal area; the Austral campaign was performed during spring conditions which could intensify the salinity signal. On the other hand biological and F-Q properties differ from the open ocean and concentrations present a continuum between the head and the ocean (Figure 2 Left).

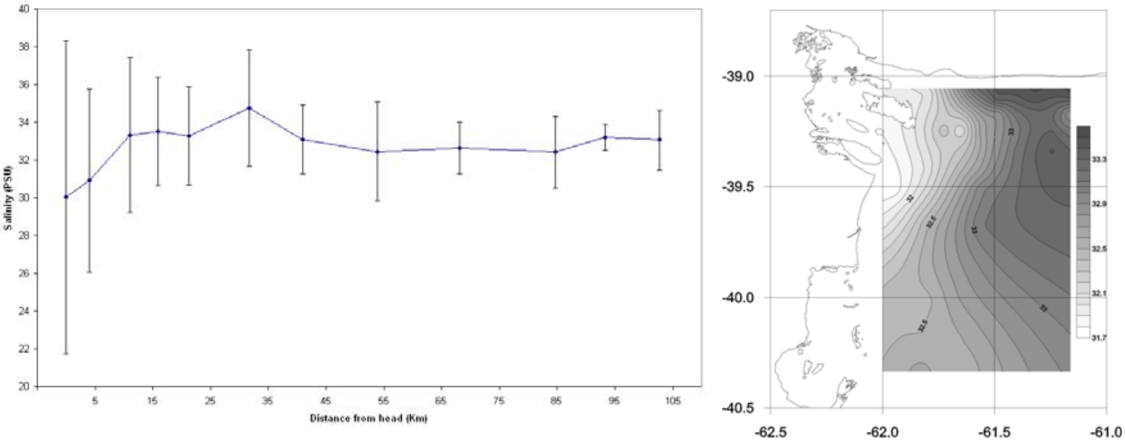

Figure 2 Station averaged salinity and standard deviation along the Bahía Blanca estuary Principal Channel (left) and values registered on the neighbouring coastal area (right).

Seasonally, it is observed that on the inner area salinities under the oceanic typical values are found during the rainy periods in Bahía Blanca especially during spring conditions, while for the rest of the year values found are similar to the open ocean values except for the innermost areas (Figure 3).

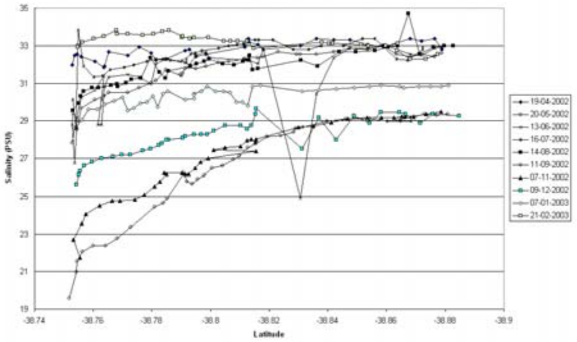

Figure 3 Salinity transects along the inner area of Bahía Blanca.

Focusing on PC and IW stations (Figure 4), it can be observed that on average salinity values are similar on both stations. However, maximum and minimum values observed for PC station shown a wider range for the same period with minimums smaller than 25 PSU and maximum values higher than 40 PSU. PC station salinities are affected in a higher degree by evaporation and precipitation processes than in IW station, because of its location in the shallow head of the estuary.

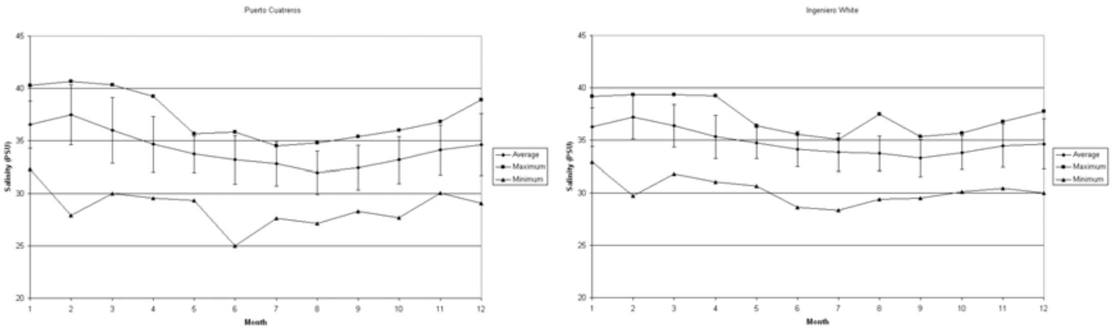

Figure 4 Monthly averaged salinity with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

Average and range of temperatures between stations along the Principal Channel show practically no differences between stations (Figure 5 Left). This implies the little influence that fresh water discharges impinges to the system as oceanic temperature and air temperature would be the main responsible for temperature variations on the system; as no differences on the inner area where fresh water discharges take place can be observed. In addition, on the inner part of the estuary the shallowness of the area intensifies the exchange with the atmosphere. Seasonally temperature values are comprised between 4-24 ºC, being found the maximum and minimum temperatures on the inner areas. The sharpest longitudinal gradient between stations occurs during winter with differences of 5 ºC between the most distant stations on winter periods where water is colder on the inner area of the estuary (Figure 6). Coldest month of the year is June and warmer is January (Figure 7). The Austral campaign, performed during spring conditions shows the vicinity area temperature decreases from the coast to the open ocean (Figure 5 Right).

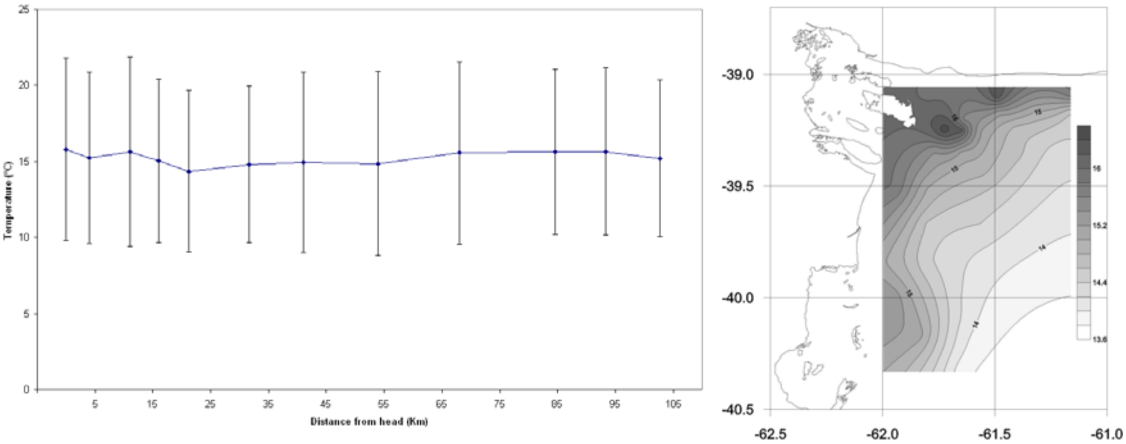

Figure 5 Station averaged temperature and standard deviation along the Bahía Blanca estuary Principal Channel.

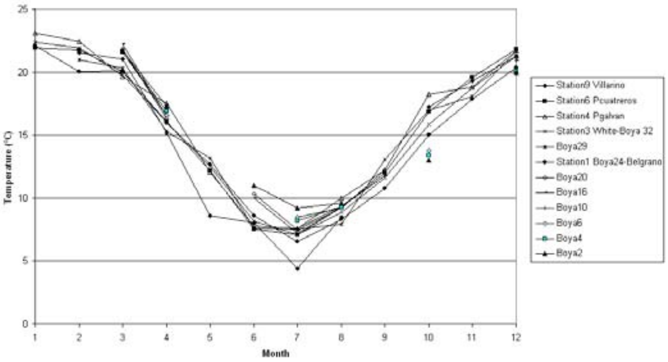

Figure 6 Monthly averaged temperatures for each sampled station along the year.

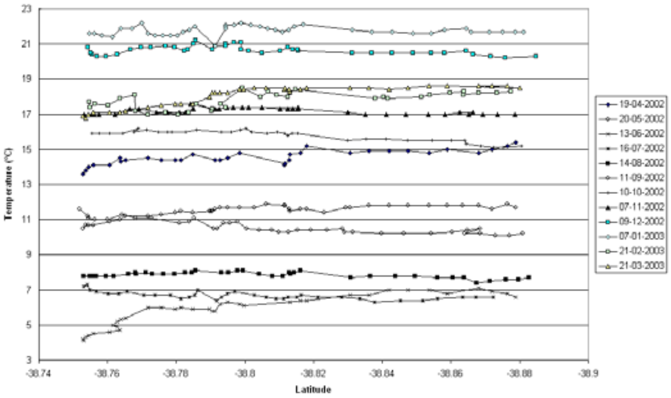

Figure 7 Temperature transects along the inner area of Bahía Blanca.

As was expected, temperature on PC and IW stations present a similar temperature pattern with no significant differences (Figure 8).

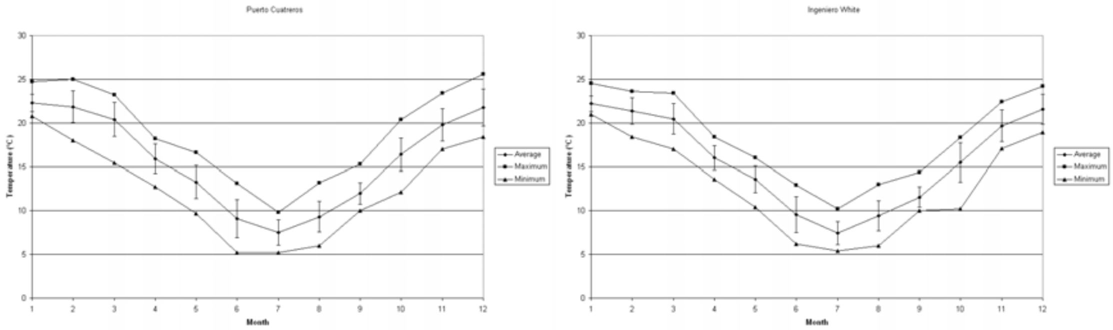

Figure 8 Monthly averaged temperatures with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

Turbidity on the inner area of the estuary seems to decrease seawards, as near the head its value ranges between 50 and 300 NTU (Figure 9) while seawards its maximum decrease to less than 200 NTU for this section of the estuary. The open ocean concentrations observed close to Bahía Blanca's mouth are lower than 30 NTU. The main source of variability of this variable could be the resuspension due to the different stages of the tide and the variables that affect the water level (mean sea level, winds, waves, atmospheric pressure…). Depending on the tidal and atmospheric conditions a different amount of suspended sediments could be found on the water column. The importance of the river discharges on this variable is not significant because water discharges exerts its influence near their discharge point.

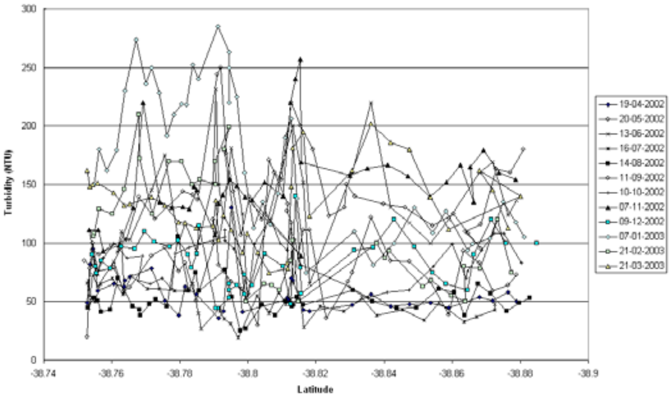

Figure 9 Turbidity transects along the inner area of Bahía Blanca estuary.

Looking closely to PC and IW stations (Figure 10), stands out those values for turbidity on the same stations can present at the same period of the year, i.e. values at IW station during July range from 16 to 260 NTU. Thus, could be stated that variations are not related with climatological variations. On average both stations show similar values between 50-100 NTU during the whole year. Though higher absolute values where registered in PC station for the period 1994-2000.

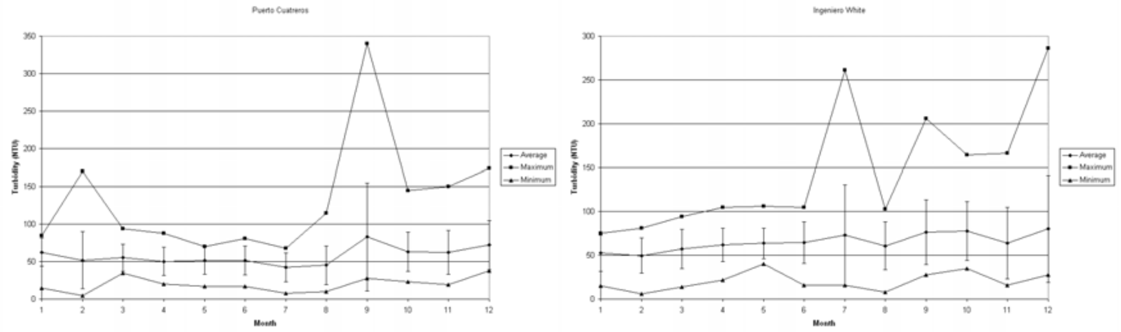

Figure 10 Monthly averaged turbidity value with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

From the middle estuary seawards, oxygen concentrations are steady while variations on its concentrations can be found near the head. In the Petro III campaign data can be observed a decrease on concentrations form the head till the latitude of -38.8, which is acuter in some periods of the year. Oxygen concentrations range from 4 to 11 mg l^{-1}. The same tendency is observed for oxygen saturation values, ranging from 50 to 110 % (Figure 11). Values for both variables are higher during winter period and lower during summer meaning that there is a source of oxygen in the water, most probably photosynthesis, which agrees with the fact that diatoms blooms are observed during winter, producing saturation levels over 100 % (Figure 12).

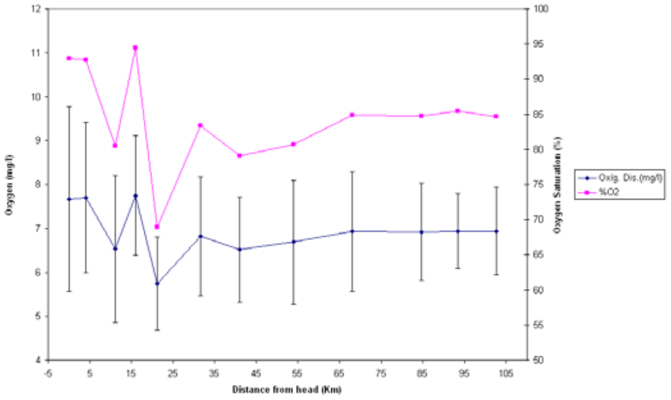

Figure 11 Station averaged oxygen concentration and oxygen saturation along the Bahía Blanca Principal Channel. The saturation levels in this figure suggest a dominance of respiration over production.

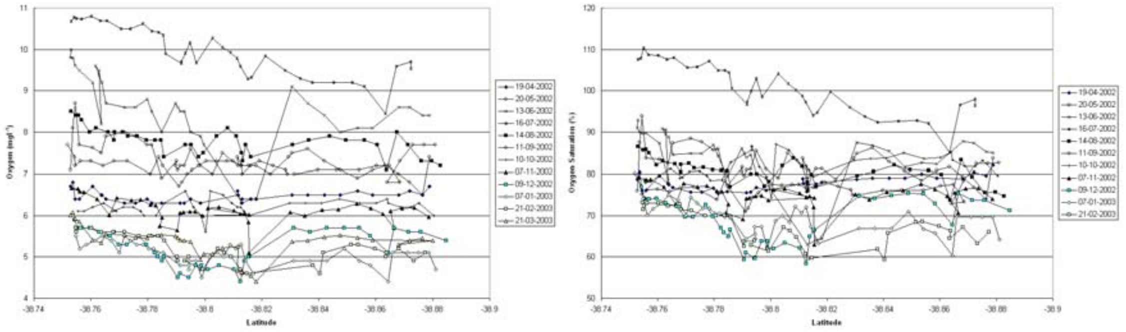

Figure 12 Oxygen concentration (Left) and oxygen saturation (Right) transects along the inner area of Bahía Blanca.

In PC and IW stations (Figure 13) the same seasonality was observed, higher values for both stations were measured during winter with concentrations on average between 8-10 mg l^{-1}. In comparison, PC station shows the highest and lowest values for this variable, being recorded values near 12 mg l^{-1} and lower than 4 mg l^{-1}. Also saturation levels over 120 % were recorded on both stations during the summertime that would indicate a secondary blooming period coinciding with windy period which promotes mechanical mix of the water with the consequent oxygen increase.

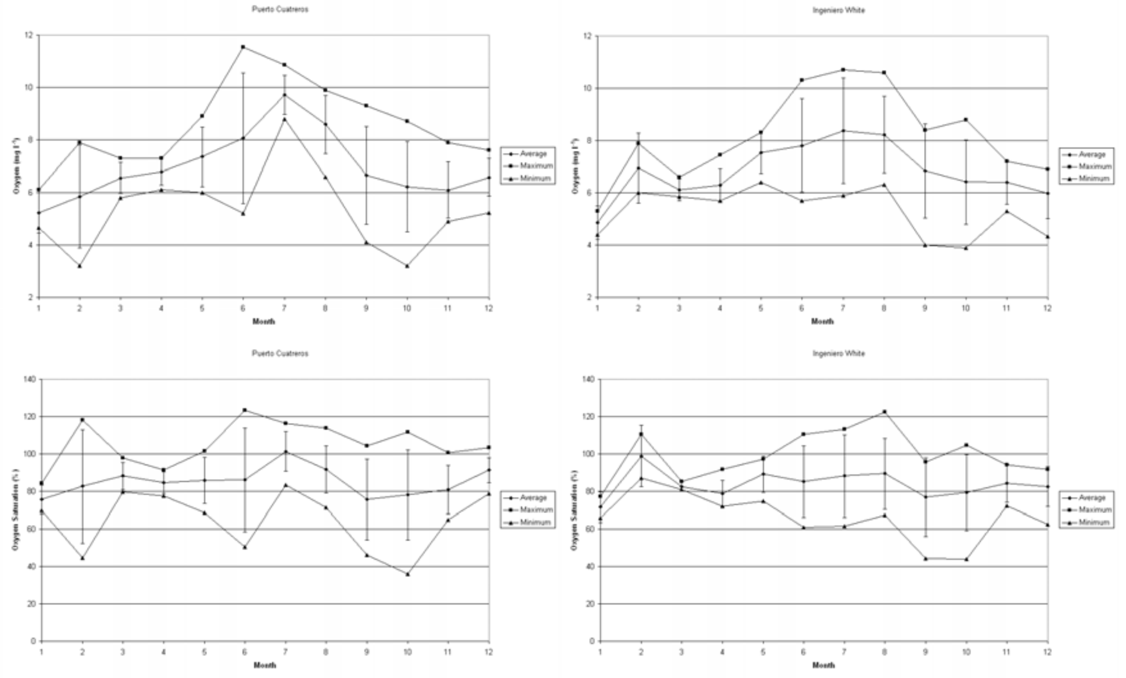

Figure 13 Monthly averaged oxygen concentration (top) and oxygen saturation (bottom) with their standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

According to Sverdrup et al (1942), pH concentrations on seawater typically range between 7.5 and 8.4 with their maximum values being found on the surface. When CO_2 values are in equilibrium with the atmosphere pH values would be around 8.1 to 8.3 though higher values can be observed when photosynthetic activity is very active. Below the euphotic zone, a relation between pH and oxygen concentrations is found. In areas where oxygen has been depleted values reach the minimum values of 7.5. In our study case, values for pH range from 7.5 to 9 (Figure 14) remaining practically constant along the sampled section. Lower values where found in April 2002 and highest in March 2003 what does not provide a clear seasonal explanation.

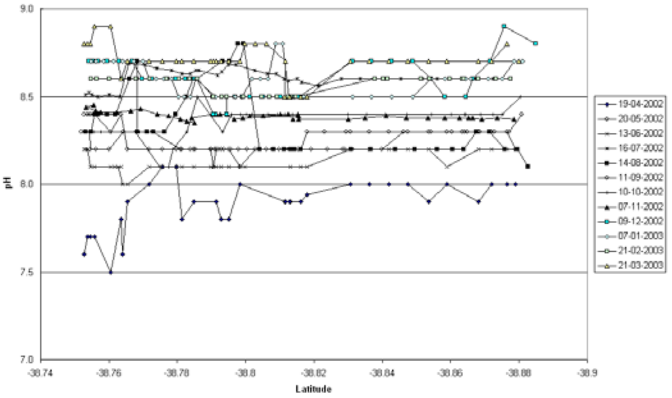

Figure 14 pH transects along the inner area of Bahía Blanca.

When observing the temporal evolution of pH at PC and IW stations (Figure 15), both stations presents a similar range of values. Seasonally, high values are observed on summer and winter coinciding in time with maximum oxygen saturation values, and the lowest observed values in spring with values of 7.5 that according to Sverdrup et al (1942) could be considered as oxygen depletion.

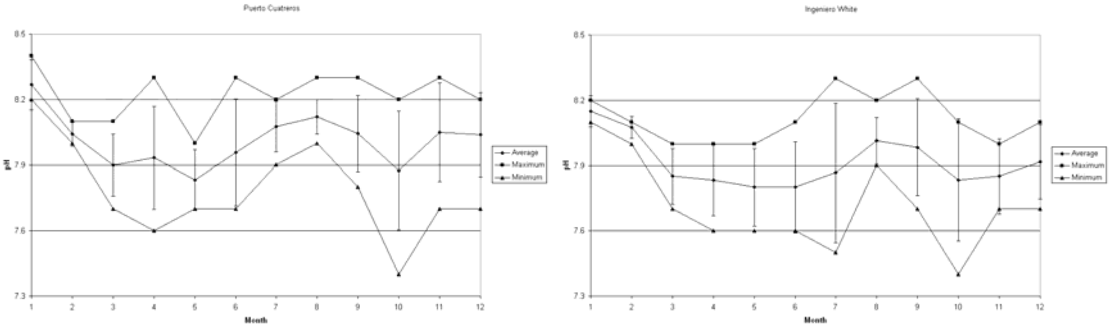

Figure 15 Monthly averaged pH values with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

3.2 Nutrient Concentrations

Nitrite is the nitrogen species nitrogen commonly found as an intermediate step in the process of nitrification (e.g. nitrate production). This process involves the participation of bacteria in the conversion from organic matter to nitrate going through ammonia and nitrite compounds. Nitrite is converted to nitrate very efficiently, generally is only measured when this process is taking place as no big pools of this compounds tend to occur. In Figure 16 it can be observed that this compound presents high concentrations on the inner part of the system and is in Puerto Galván station where maximum values are found, being also the station with the higher variability, probably induced by land inputs. Also the head should be regarded as a source of nutrients for the estuary and very active in remineralisation processes. Nitrite values decreases from the head to the ocean where its concentrations tend to be homogeneous with values around 0.2 µmol.

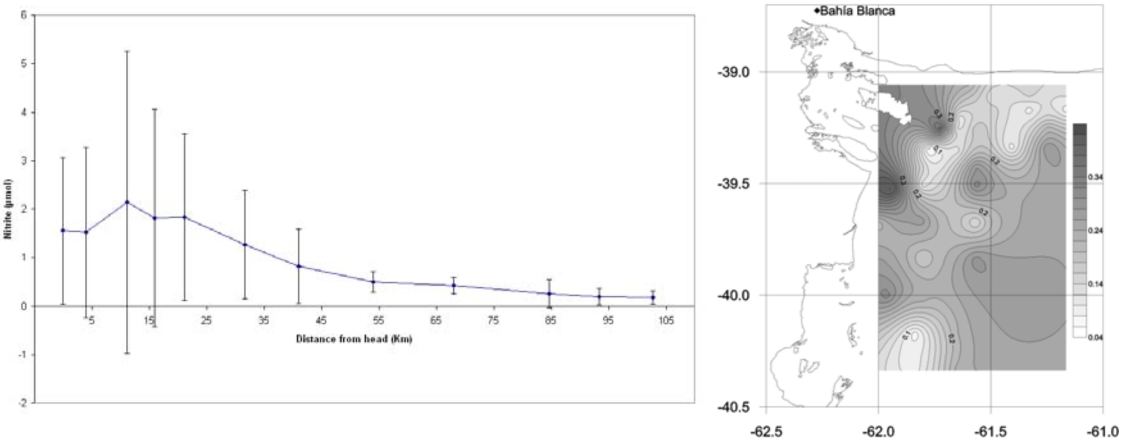

Figure 16 Station averaged nitrite concentration and standard deviation along the Bahía Blanca estuary Principal Channel.

Along the year is found a seasonal cycle, minimum nitrite concentrations are found by the end of the winter and early spring when this species is practically depleted. Meanwhile values recover during the summer and peak values are observed in autumn. Values are also slightly higher in IW station than in PC station (Figure 17). Maximum values found on the series are around 10 µm for both stations.

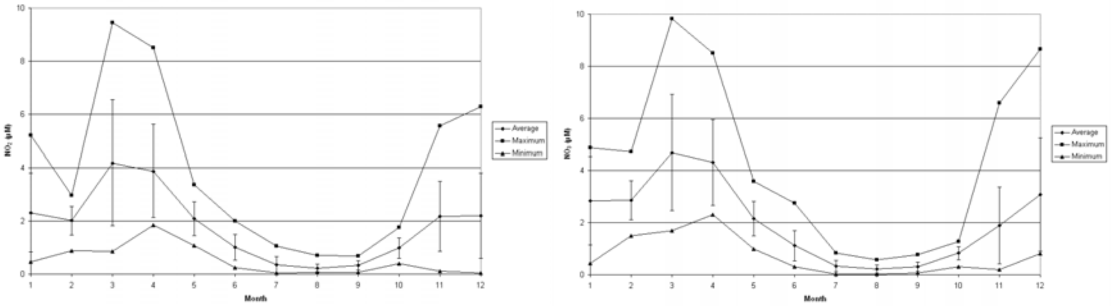

Figure 17 Monthly averaged nitrite concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

Nitrate concentrations decrease seawards (Figure 18), as occurred with nitrite concentrations. Both stations have a similar pattern of concentrations, also similar to the nitrite transects, with the exception of the maximum found on March of around 70 µm (Figure 19).

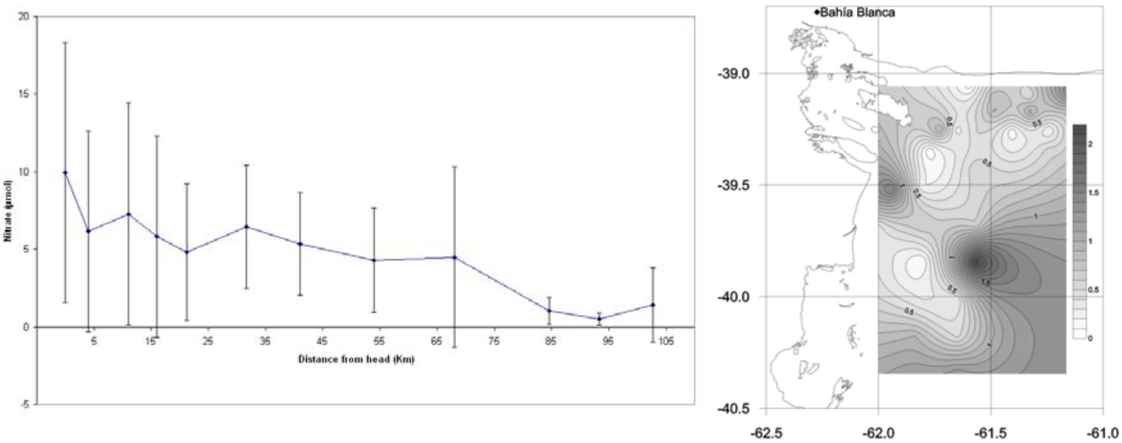

Figure 18 Station averaged nitrate concentration and standard deviation along the Bahía Blanca estuary Principal Channel.

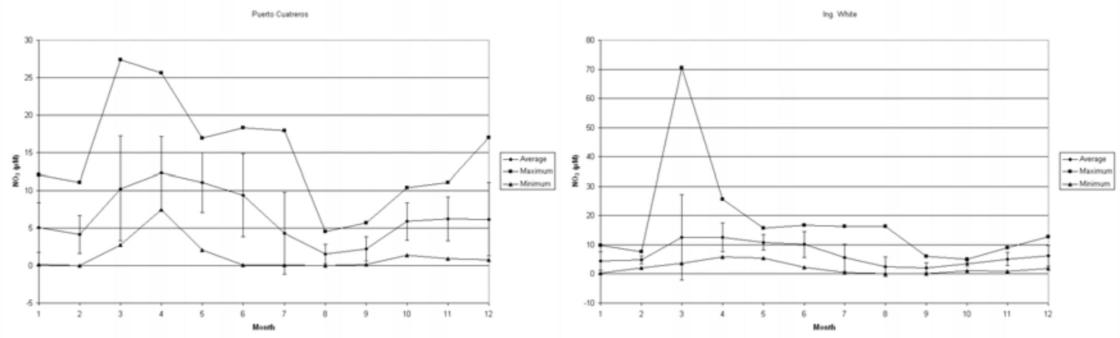

Figure 19 Monthly averaged nitrate concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

A particular case is the ammonia concentrations on Bahía Blanca estuary; it has been regarded traditionally to be the species more demanded by primary producers and thus the first to be depleted. Generally, once ammonia is minimal primary producers tend to consume any other nitrogen form as their source of nutrients. In Bahía Blanca estuary minimum concentrations during most of the time are higher than 15 µm and the seasonal pattern differs from the other two nitrogen species commented above. The maximum concentration in March (Figure 20) coincides with the other two nitrogen species maximum. However, while the other species have been depleted by the end of winter-beginning of spring, a second maximum of ammonia is reached. Concentrations, on average, seem to be higher on IW station than in PC station.

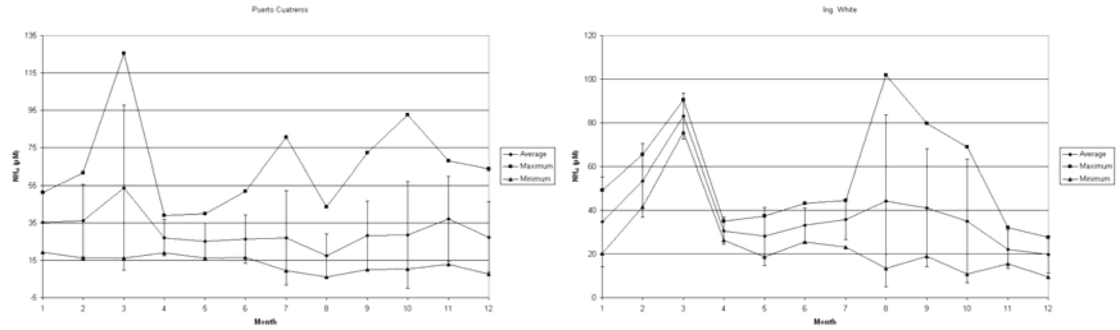

Figure 20 Monthly averaged ammonia concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

Phosphate main concentrations along the main channel seem to be very homogeneous, with slightly decreasing seawards. However the standard deviation is much higher in the inner area than on the seawards stations (Figure 21). It could be explained because on the inner area take place a high consumption of phosphorus due to primary production and also accumulation and remineralisation processes increase the quantity of this substance on this sector of the Bahía Blanca estuary. Along the entire estuary, concentrations on average are comprised between 1-2 µm, which in addition are typical concentrations for the surrounding coastal area.

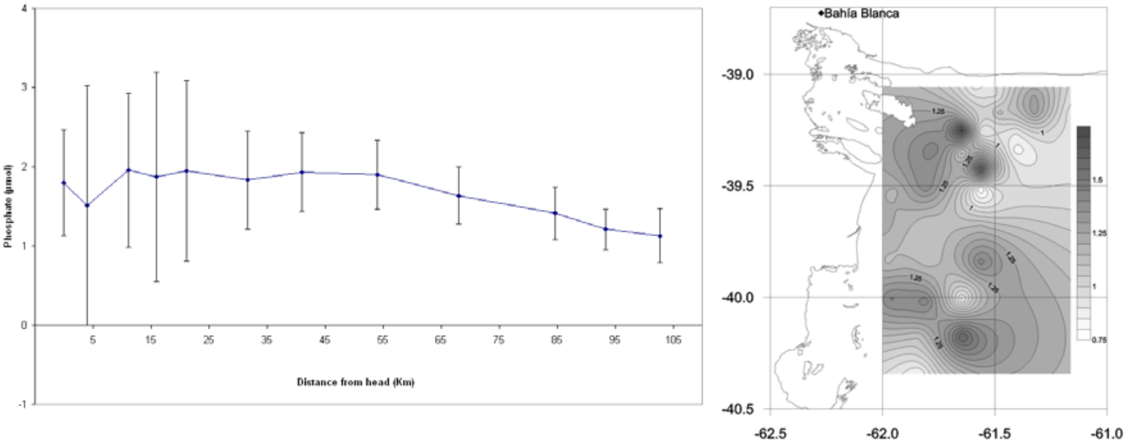

Figure 21 Station averaged phosphate concentration and standard deviation along the Bahía Blanca estuary Principal Channel.

Phosphate concentrations present a different annual cycle when compared with the other nutrients. Maximum concentrations are observed during autumn, mainly in May-June, while for the nitrogen species was in March (Figure 22). A secondary maximum appears in springtime. Maximum values observed are around 7 µm, being slightly higher the concentrations in IW than in PC station. As with the nitrogen species, phosphorus concentrations decrease strongly during winter.

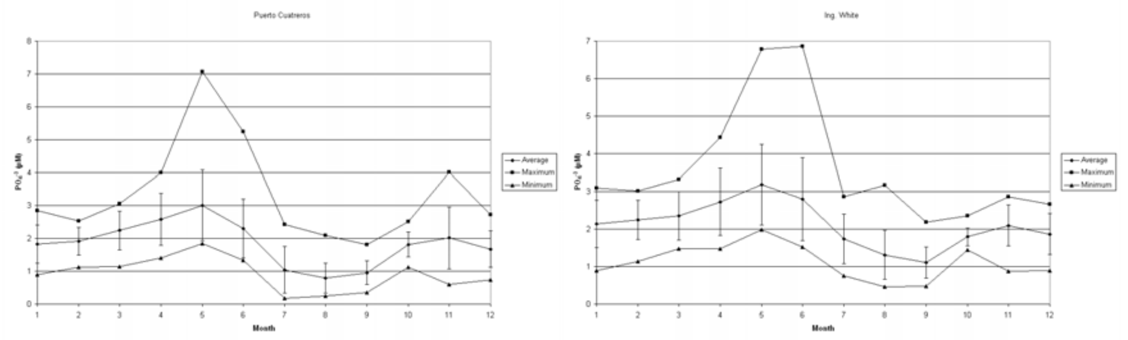

Figure 22 Monthly averaged phosphate concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

Silica decreases steadily from the inner stations to the ocean (Figure 23), showing a clear gradient for the whole Principal Channel. Silica is a nutrient which main source are land inputs, however freshwater inputs in the system are insignificant when compared with the estuary tidal prism. For this reason, the main source of this nutrient is uncertain. Probably the reasons behind the wide range of concentrations found on the innermost areas are due to accumulation, remineralisation, land runoff and consumption by diatoms, the largest blooming species in Bahía Blanca estuary. Silica concentrations range from 120 µm in the innermost station to 10 µm in Buoy 2 station where concentrations are of the same range as in the coastal area

. The southern channels of Bahía Blanca seem to influence concentrations near the coast and probably some of this silica would re-enter the system in the same way that with phosphorus.

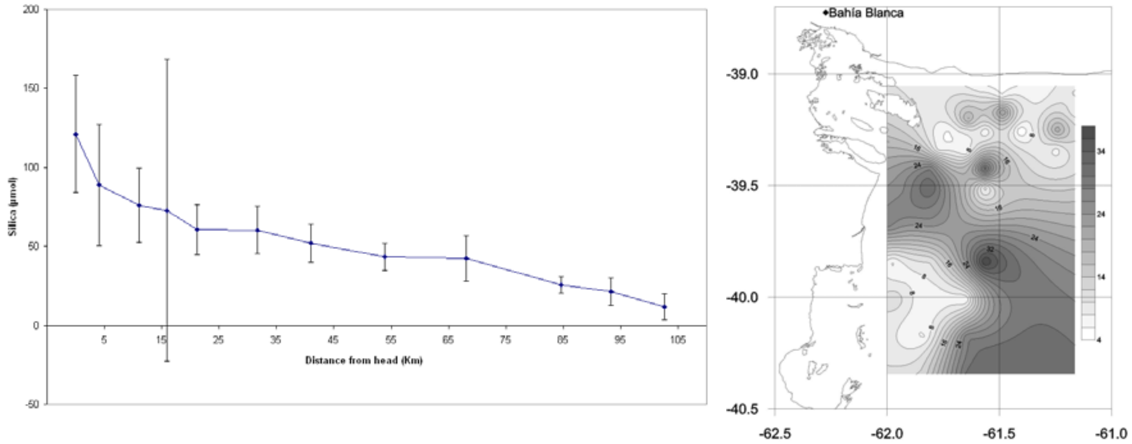

Figure 23 Station averaged silica concentration and standard deviation along the Bahía Blanca Principal Channel.

Silica concentrations, as shown on the previous figure, decrease seawards. This tendency is confirmed on PC and IW stations (Figure 24). Concentrations stay stable during most of the year with values around 100 µm being consumed strongly only during the winter period, when the concentrations halve. Minimum silica records are around 20 µm Si.

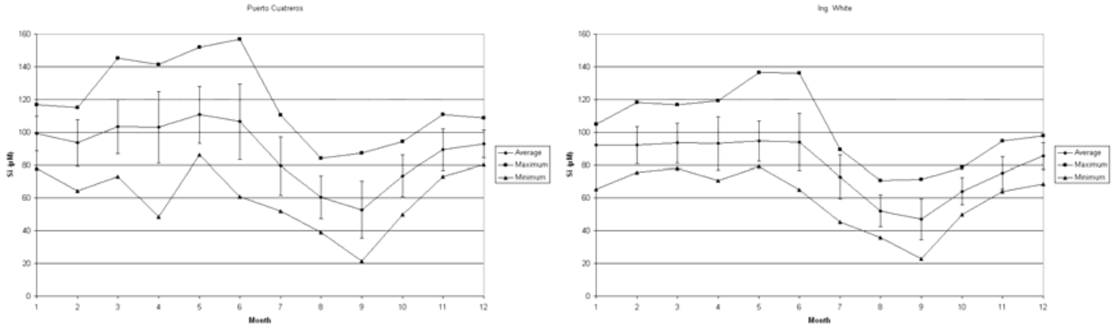

Figure 24 Monthly averaged silica concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

3.3 Biotic variables

Particulated organic matter (POM) concentrations are steady on average, not being found a seasonal pattern, though its values could double or halve as observations confirm (Figure 25). However, this variability is not seasonal as can be observed on Figure 26. For these two stations average values would be around 2000 mg C m^{-3}, being slightly higher at Ingeniero White. Values on the vicinity of the Bahía Blanca estuary are between 500 and 1000 mg C m^{-3} (Figure 27).

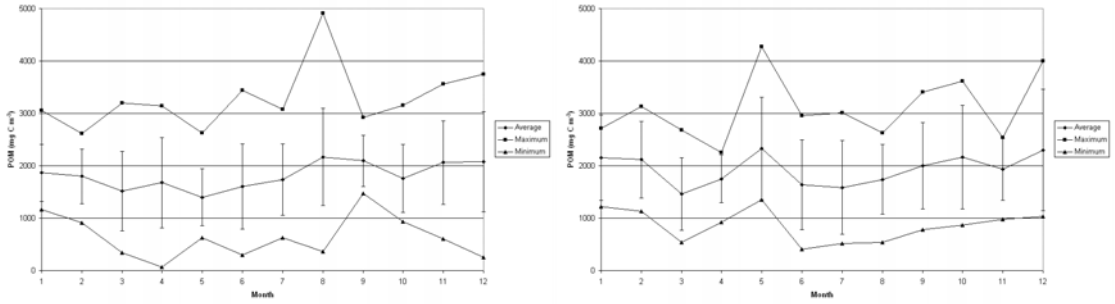

Figure 25 Monthly averaged POM concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

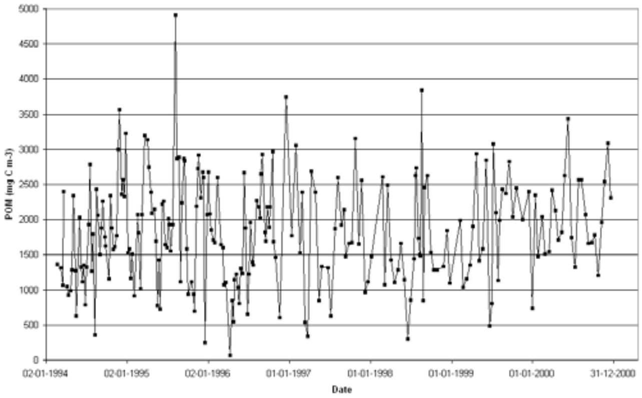

Figure 26 Sample of records for POM concentration in PC station.

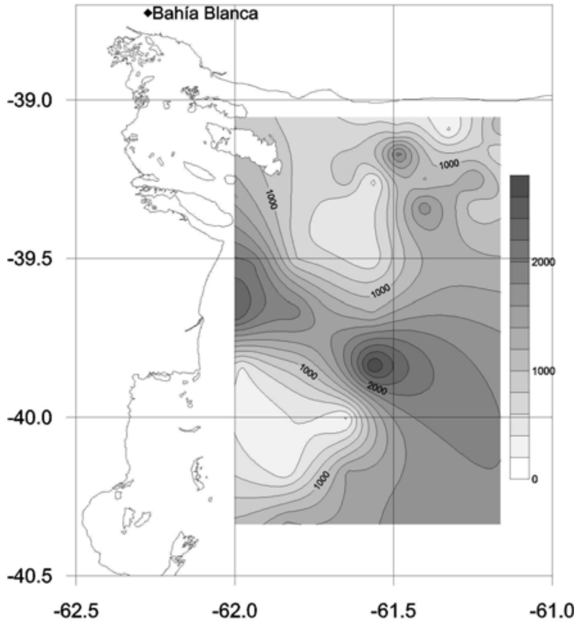

Figure 27 POM concentration in Bahía Blanca estuary coastal area.

As commented above, it is in the inner area of the estuary where the most intense ecological processes take place. This is pointed out by the quantity and variability of chlorophyll *a* and phaeopigments. In the vicinity of the estuary values of Chl *a* are comprised between 1 and 2 µg m^{-3} (Figure 28), while maximum values registered were located between PC and IW stations with nearly 18 µg m^{-3} (Figure 29), average values in the inner area would be around 8 µg Chl *a* m^{-3}.

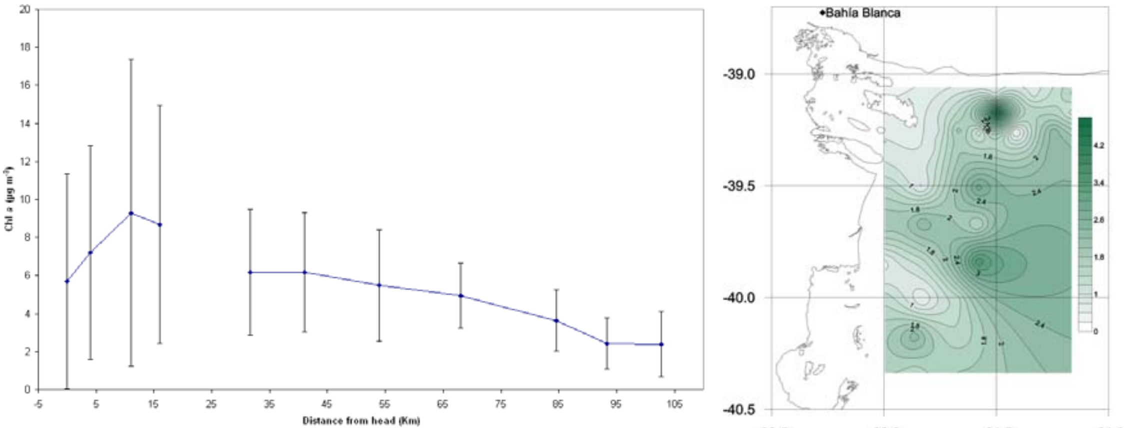

Figure 28 Station averaged Chl *a* concentration and its standard deviation along the Bahía Blanca estuary Principal Channel.

In PC and IW stations is observed a clear seasonal variation. Two blooms of different intensities are identified, a main bloom starting at late autumn, reaching its maximum intensities in winter and ending at early spring. Also a secondary bloom with a lesser intensity is centred in summertime. This Chl *a* bimodal curve was also reported by Hoffmeyer and Torres (2001), they found a maximum peak on August and a secondary peak in January. The main bloom reaches higher intensities in the innermost station.

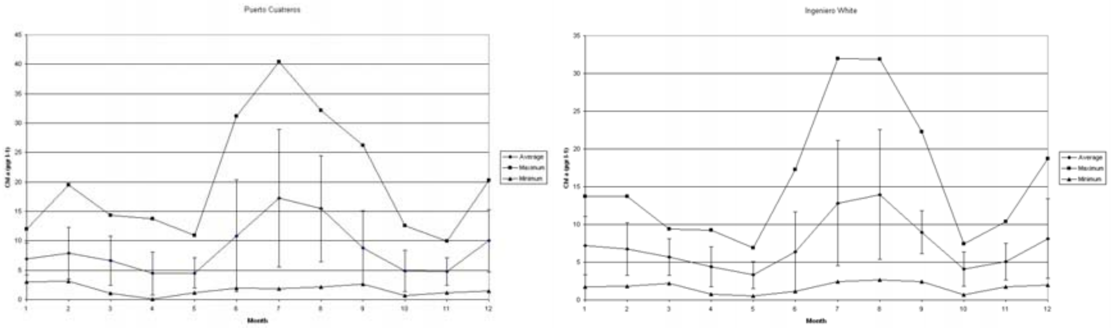

Figure 29 Monthly averaged Chl *a* concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

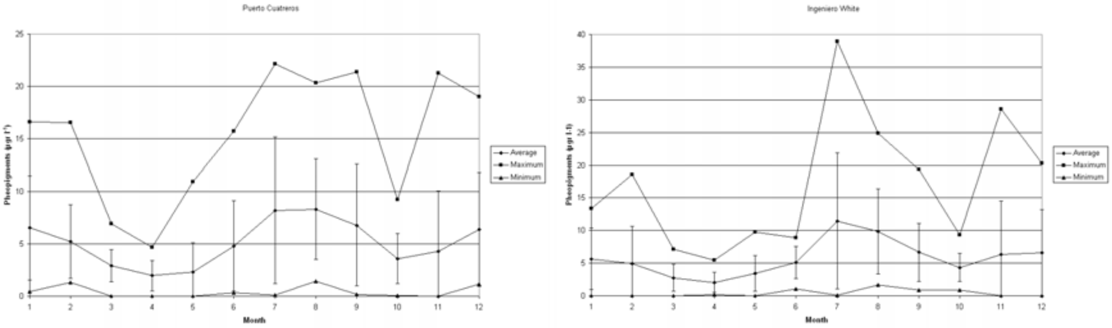

Figure 30 Monthly averaged phaeopigments concentration with its standard deviation and maximum and minimum values recorded for each month at PC (Left) and IW (Right) stations.

4 Plankton description

In Bahía Blanca estuary primary producers and consumers are related through complex relationships as the conditions differ along the study site. Conditioned by the sensibility to the climatological conditions that favour the growth of some components of the trophic system in addition to interspecies competition and predation from higher trophic levels would play a relevant role on the amount of any of the variables commented on the previous sections.

4.1 Phytoplankton

Gayoso (1999) summarised the composition and seasonal variation of phytoplankton in Bahía Blanca estuary. After performing a Principal Component Analysis (PCA), Gayoso (1999) concluded that the most important phytoplankton taxa in Bahía Blanca estuary exhibited one of three types of seasonal patterns: recurrent, winter-early spring blooming formed by diatoms; phytoflagellates species with peaks of abundance in late spring or summer and with great interannual variability, and diatom species present all the year round but not forming blooms.

Phytoplankton abundance in the external reaches of the estuary is lower, and maximal abundance occurs later than in the inner reaches.

4.1.1 Diatoms

The genus *Thalassiosira* is the most conspicuous component of the local phytoplankton. Chain-forming species dominate being the most abundant species *Thalassiosira curviserata* Takano. This species is observed during all year round presenting a strong peak in winter. Other species from the same genus only observed during the bloom are *Thalassiosira anguste-lineata* Fryxell *et* Hasle., *T. pacifica* Gran *et* Angst, *T. rotula* Meunier and *T. hibernalis* Gayoso (Gayoso, 1999). The highest observation of *Thalassiosira* spp. during 1980-1991 was 12.74×10^6 cells l^{-1} (Popovich and Gayoso, 1999)

Chaetoceros, is the second most important genus in the annual cycle. The small *Chaetoceros* sp. dominates the winter bloom with maximum peaks of 5.6×10^6 cells l^{-1}. Also present during the winter bloom was *C. diadema* (Enrenberg) Gran. Other species were present during different times of the year as *Chaetoceros ceratosporus* var. *Brachysetus* Rines *et* Hargraves observed during autumn and winter, *Chaetoceros subtilis* Cleve and *C. subtilies* var. *abnormis* Proschinka-Lavrenko observed during summer and autumn (Gayoso, 1999)

4.1.2 Phytoflagellates

Small forms (10-20 µm) of phytoflagellates occurred all year round with maximum numbers in summer, dominated by unidentified gymnodinians and Cryptophyceae. The maximum peak observed during this period was 1.5×10^6 cells l^{-1}. During spring *Scrippsiella trochoidea* (Stein) Loeblich III and the Xanthophyceae *Ophiocytium* sp were reported with densities of around 2.7×10^6 cells l^{-1} and 10^5 cells l^{-1} respectively (Gayoso, 1999).

4.2 Zooplankton

Hoffmeyer (2004b) reported that man-made changes during the 1980s and 1990s affected zooplankton assemblages (e.g. on composition structure and dynamics) especially on the innermost zone of the estuary due to an increase on dredging, industrial activities, maritime traffic and pollution (Lara et al, 1985 and Villa, 1988 in Hoffmeyer (2004b))

4.2.1 Ciliates

4.2.1.1 Aloricate Ciliates

Pettigrosso et al (1997) determined that the aloricate planktonic ciliates of the Bahía Blanca estuary are a diverse taxonomic group, being the most common genera *Strombidium*, *Strombidinopsis* and *Tontonia*. *A Strombidium* genus *was* the most numerous and *Strombidinopsis* the one with the larger specimens found. They were all considered herbivorous on that study.

During the study period of Pettigrosso et al (1997), June-October 1994, the maximum value found was 4.3×10^3 individuals l^{-1} at the beginning of the bloom due to the smaller size class of ciliates (<30 µm). Minimum values were found on July and August with densities of 0.2×10^3 and 0.5×10^3 individuals l^{-1} respectively. A second peak of ciliates corresponding to larger volumes is also found in September.

Two peaks of ciliate biovolume were registered on August 11 of 34×10^7 µm^3 l^{-1} (64.6 µg C l^{-1}) and a second on August 31 of 13.1×10^7 µm^3 l^{-1} (25 µg C l^{-1}). The latter was due to large species.

The most numerous ciliates corresponded to the category grouping values under 10^3 µm with 64.1 % of the total number of individuals. Maximum values were found at the middle of June and at the beginning of September and lowest in July and August.

In conclusion, microzooplankton, being ciliates the most abundant group, is considered as a major consumer of nanophytoplankton and thus controlling their populations. The total biomass of aloricate ciliates during the bloom period follows the total phytoplankton biomass trend. Though the small diatoms seems to be the source of food for the zooplankton of larger volume while the smaller size of zooplankton might feed on smaller ciliates picoplankton (bacteria and flagellates). Mean value of carbon biomass for ciliate during the study period was 14.7 µg C l^{-1} that corresponds to a 3.7% of the total phytoplankton biomass for the same period (396.3 µg C l^{-1}).

Pettigrosso et al (1997) also concluded that there is no direct relationship between Chl *a* concentrations and ciliate biomass peaks and might not have a direct impact on phytoplankton bloom. They also concluded that variations in ciliate abundance were due to variations in grazing pressure (top-down control), that should not be the case at high phytoplankton concentrations.

4.2.1.2 Tintinnids Ciliates

This is the main group of microplankton (Hoffmeyer and Barría de Cao, 2007). Barría de Cao et al (2005) identified four genera with 15 species in Bahía Blanca estuary being the genus *Tintinnopsis* the most abundant in terms of number of species comprising the 73% of the total number of species. Tintinnids ranged from 100 individuals l^{-1} in winter to 7800 individuals l^{-1} at the beginning of spring in Puerto Cuatreros and from 20 to 12400 individuals l^{-1} in the same periods in Puerto Rosales. Minimum diversity index (Shannon Index) was observed in winter, only one species, and maximum during summer. Biomass values also ranged from 0.64 to 127.78×10^6 µm^3 l^{-1}, equivalent to 0.3 and 39.4 µg C l^{-1}, at Puerto Cuatreros and from 0.03 to 101.52×10^6 µm^3 l^{-1}, equivalent to 0.02 and 34.9 µg C l^{-1}, at Puerto Rosales. Minimum values were observed in autumn for Puerto Cuatreros and in winter for Puerto Rosales while maximum values were observed in winter for Puerto Cuatreros and in summer-autumn in Puerto Rosales. Numerical correlation of numerical abundance was significant for both sites while it was not for biomass. At Puerto Cuatreros numerical abundance was significantly related to temperature, solar radiation and Secchi depth, while diversity was significantly related to temperature and solar radiation; on the other hand biomass was not significant to any parameters measured. At

Puerto Rosales, biomass was related to numerical abundance and temperature while diversity was related to salinity.

Barría de Cao et al (2005) concluded that during the phytoplankton bloom the lowest density of tintinnids was observed and also diversity was low. PCA analysis performed show that temperature and solar radiation explained those variations. Barría de Cao et al (2005) suggested that because the bloom is mainly composed of chain forming diatoms only a few tintinnids are able to feed on them and only at the end of the bloom is when maximum abundance and diversity of tintinnids occur. The latter might be explained by trophic coupling with other peaks of phytoplankton that take place during late spring-summer described on Gayoso (1998).

Temperature and salinity are the main environmental factors that regulate both species populations in the estuary. In addition, food availability and predation represent other control factors (Hoffmeyer and Torres, 2001).

4.2.2 Copepods

Hoffmeyer and Barría de Cao (2007) found that the abundance of mesozooplankton in a tidal channel of the Bahía Blanca estuary ranged from 449 in March 1997 and 1 individual m^{-3} in October 1997. Minimum values were observed during May-June with maxima at the end of the spring and at the end of the summer-early autumn. Mesozooplankton abundance in intertidal channels was higher than in the main channel.

Hoffmeyer (2004a) noted that holoplanktonic species are basically copepods from the orders Calanoida, Cyclopoida and Harpacticoida. *Acartia tonsa* is the only species that occurs through the whole year (Hoffmeyer, 2004b). *Eurytemora americana Williams 1906* is considered as an invading species introduced accidentally via ballast water from ships (Hoffmeyer et al, 2000). This species have increased it densities over the years, coexisting with *A. tonsa* sharing the planktonic pulse (June-July to October) (Hoffmeyer, 2004b). Both species compete for the same trophic niches being *E. americana* more efficient on capturing phytoplankton during the winter bloom than *A. tonsa* (Hoffmeyer and Figueroa, 1997 in Hoffmeyer, 2004b). Due to this competition, abundances of *A. tonsa* have decreased since the introduction of *E. americana*. Hoffmeyer and Barría de Cao (2007) also found a high correlation between the abundances of tintinnids and *A. tonsa* indicating trophic coupling.

5 Discussion

Of all the variables studied on this analysis, only temperature seems to be spatially homogeneous for the whole system. Temperature is mainly determined by air temperature as can be appreciated when comparing with water temperature for the decade 1981-1990 (Figrure 31, data source: http://www.smn.gov.ar/). Salinities are quite homogeneous except for the innermost area of the estuary where due to evaporation and fresh water inputs presents a wide range of values (20-40 PSU). Turbidity also shows a high variability along the inner area with not being found a clear seasonality, ranging for the same station values comprised between 50-250 NTU in the innermost area, with its maximum value decreasing seawards. Oxygen concentrations and saturation presents higher levels on the innermost area of the system, probably due to be the area with highest primary production and reaeration from the atmosphere. Oxygen saturation levels range from around 50 to 120 % indicating the effect of organic matter consumption and planktonic blooms respectively.

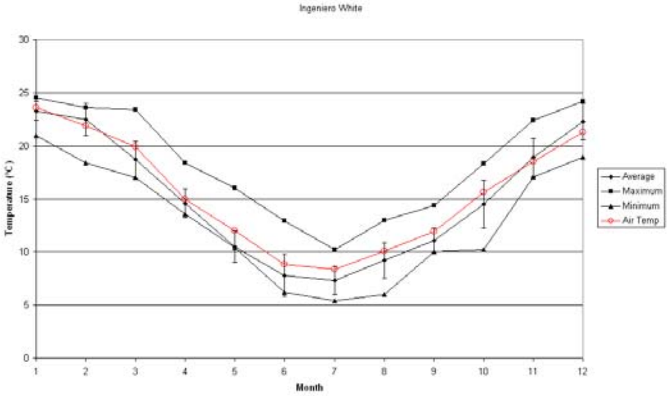

Figure 31 Monthly averaged temperature with its standard deviation and maximum and minimum values recorded for each month at IW station and air temperature (Red line).

Nutrients seasonal cycle does not coincide for all the species. In the case of nitrogen, nitrite and nitrate maximum values appears on March-April, also in March ammonia presents it first maximum, though in April values sharply decreases. In the case of nitrite and nitrate both seem to be consumed during the winter period in agreement with the phytoplankton bloom development, while ammonia concentrations keep steady with slightly increases during the end of winter. Phosphorus concentrations reach its maximums during autumn with peaks on May meanwhile nitrogen species are consumed during winter. Silica concentrations seem to be steady with high concentrations that halve during the winter bloom (Figure 32). Silica decreases at the same time of the winter bloom, some of it can be in equilibrium with remineralisation though part of it would be washed away.

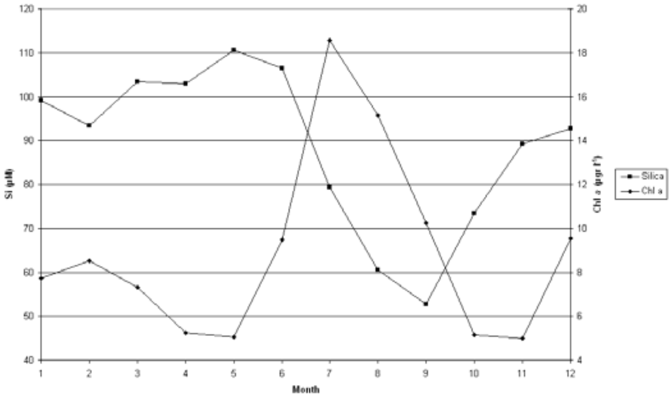

Figure 32 Monthly averaged Silica and Chl *a* concentrations at PC station.

To study the relationship of production-consumption of each property along the system a regression between the distance and the different variables has been performed. Typically to perform this kind of analysis in estuaries it has been used salinity as it is better indicator of the processes that take place on the estuary though in Bahía Blanca estuary salinity do not represent a variation along the whole system.

From these type of representations, it could be concluded that oxygen is produced and consumed in high quantities on the head of the estuary while is only consumed on the mixed zone. The inner area is neither the only source of phosphorus of the system, probably it is shared by the inputs from the ocean, and this distance only explains 50 % of the concentration. Phosphate is consumed at the head of the estuary and produced in the mixed area while in the oceanic area values are slightly lower. The suggestion made by Smayda (1983) in Gayoso (1998) agrees with this explanation for phosphorus, phosphate is introduced by tidal mixing from marine water and recycled. On the other hand for nitrate and especially for silicate, main source is the Bahía Blanca estuary itself and specially the inner areas. Nitrogen is consumed at the head of the Principal Channel and generated in the mixed area. Also Chl *a* contents decrease from the head to the open ocean, corroborating that most of the primary producers found are autochthonous from Bahía Blanca. Two points can be concluded from these regressions: a) Concentrations for all variables decreases with distance from the head, there is a negative regression between distance and concentrations and b) The mixed section of the estuary could serve as sink for organic matter and oxygen being produced remineralisation mainly on this sector (Figures 33-37).

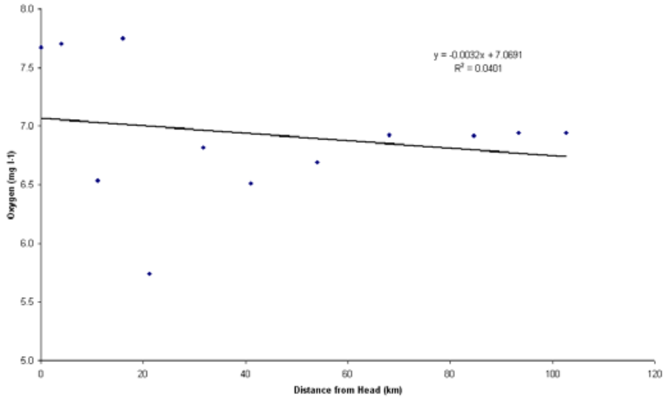

Figure 33 Regression of oxygen concentration vs distance from the head.

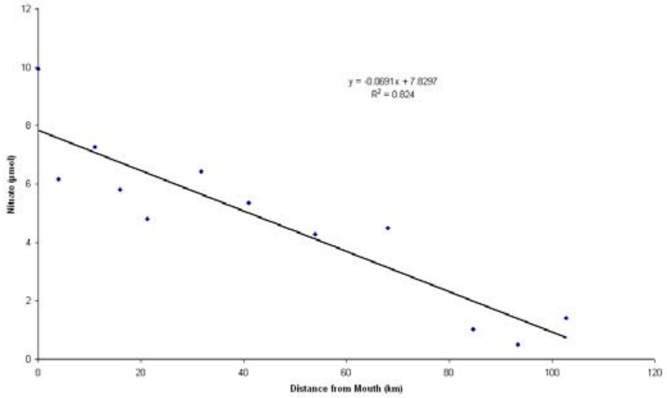

Figure 34 Regression of nitrate concentration vs distance from the head.

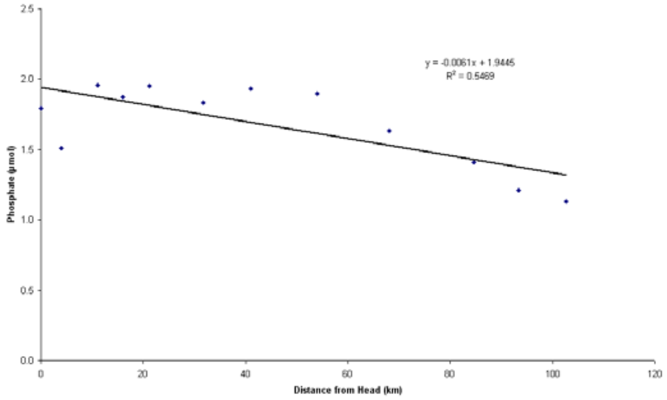

Figure 35 Regression of phosphate concentration vs distance from the head.

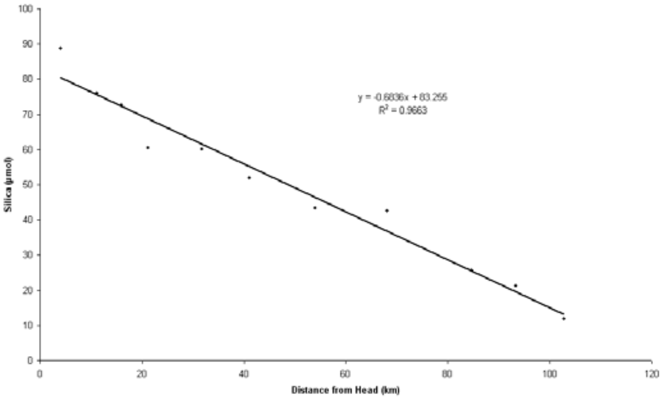

Figure 36 Regression of silica concentration vs distance from the head (innermost value removed).

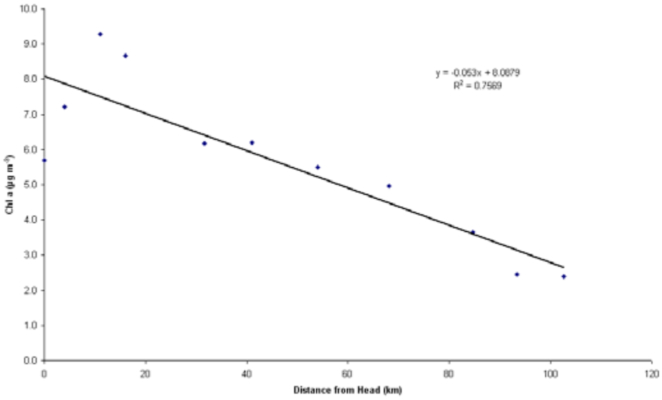

Figure 37 Regression of Chl a concentration vs distance from the head.

The phytoplankton of Bahía Blanca estuary is dominated by diatoms (Popovich and Gayoso, 1999) presenting a major bloom in winter-late spring in which *Thalassiosira* species are the main contributors representing the 60-90% of cells (Gayoso, 1998; Popovich and Gayoso, 1999).

The primary production in Bahía Blanca estuary takes place in their inner reaches, a highly turbid area that presents a wide range of temperatures and salinities. These conditions would have limited growth for many other species. However maxima abundances of *Thalassiosira curviseriata* coincided with minima temperatures while salinity did not seem to affect its seasonality (Popovich and Gayoso, 1999), also Chl *a* maxima coincide with minima temperatures (Figure 38).

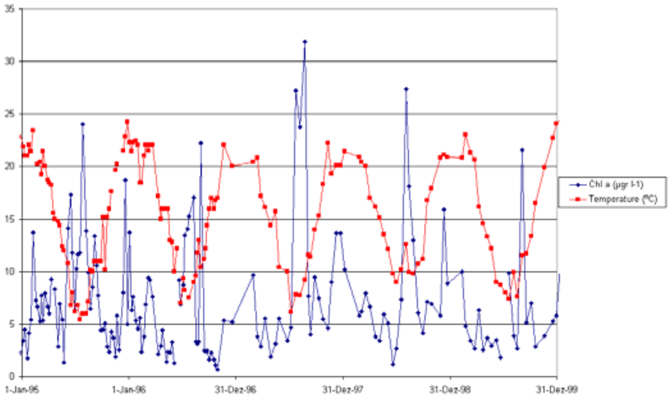

Figure 38 Seasonal variation of Chl *a* in IW station during 1995-2000 in relation with surface water temperature.

In order to understand how this species is able to bloom in such conditions, Popovich and Gayoso (1999) performed batch cultures to test the influence of these environmental factors on its growing. From those tests they concluded that: a) mean specific growth rate was not affected by salinity over the tested range (25-40 PSU); b) cellular chlorophyll *a* content increased with decreasing photon flux density and also was influenced by temperature, maximum concentrations were observed at 5 ºC and low densities, and highest concentration was observed always at 5 ºC independently of the intensity; c) Maximum daily growth rate occurred at 20 ºC.

This feature is not only related to *T. curviseriata*, other species from the genus *Thalassiosira* grow well at low temperatures and relatively low light intensities (Popovich and Gayoso, 1999).

Summarising, field data and experimental observations depict *T. curviseriata* as a eurythermal and euryhaline species, adapted to grow at relatively low light intensity. Those features explain its presence all year round and the ability to bloom when conditions appear to be adverse. In addition, other factors as the absence of herbivorous zooplankton, confirmed by field data, during the winter-early spring diatom bloom may play an important role for the bloom development on those conditions (Gayoso, 1998; Popovich and Gayoso, 1999).

The diatom bloom is also dominated by the nanophytoplankton (<25 µm) in opposition to the microphytoplankton (>25 µm). *Thalassiosira curviseriata* (valve diameter between 6.0-21.5 µm) and *Chaetoceros spp*. (valve diameter between 2.4-15.0 µm) were the most important diatom species during the 1994 bloom presented by Pettigrosso et al (1997). Microphytoplankton was responsible for a latter peak of Chl *a*. Carbon: Chl *a* conversion factor for phytoplankton during the winter bloom ranges between 25.34 and 27.97.

Gayoso (1998) suggest that phosphorus is the key nutrient for phytoplankton growth, though assuming that seasonality (temperature) (R^2=0.18) is not limiting the production, a regression between Chl *a* and phosphorus shows a R^2= 0.55 and with nitrate of 0.31 at IW station. With ammonia this relation does not exists R^2= 0.0027 and neither with turbidity R^2 = 0.0398.

6 Conclusion

The Bahía Blanca estuary after this analysis it would be divided in three different areas: head, mixed and ocean. In the head is the most active part of the estuary in regard to primary production, the mixed area would be the area where the products of this production are remineralised and thus serve as a buffer area of nutrient to the coastal area. And the oceanic area is where the processes and concentrations are very similar to the ones observed in the neighbour coast of Bahía Blanca estuary. Most nutrient species present higher values at the head of the estuary decreasing when moving to the mouth of the Principal Channel. Because there are not significant sources of nutrients in the inner area, values at the head could be due to accumulation. However, not all nutrients present the same degree of accumulation, as phosphate in the head show similar concentrations than the mid-reaches of the Principal Channel.

In general, most of the nutrients present a similar pattern with distance and seasons. During winter nitrite, nitrate, phosphate and silica decrease while ammonia increases. During summer-autumn most nutrients concentrations increase this time including ammonia. Phosphorus maximum values do not coincide with the other nutrients maximum as it takes in late autumn (May) while for the rest maximum occurs in March.

Phytoplankton growth in adverse conditions, as low light availability due to high turbidity and low temperatures, could be explained if it is considered that primary productivity could be mainly taking place in the intertidal areas where light penetration due to the shallowness of the system would not limit the production. Thus, it would be assumed that intertidal areas play a key role for the whole Bahía Blanca ecosystem, exporting with the tides the products of the processes that take place in these areas to the tidal channels.

Pettigrosso et al (1997) found a coupling between diatoms populations, especially on cells < 25 µm, and aloricate ciliates. In Popovich et al (in press) it was also mentioned the double role that ciliates could play on the bloom in Bahía Blanca, one as a source of ammonia and additionally favouring the growth of diatoms of larger size, as other species of Thalassiosira and Chaetoceros that are found on later phases of the bloom. It was also concluded that probably phosphorus could act as the main limiting nutrient as silica and nitrogen, in any of their forms is available. It was also noted the appearance of dinoflagellates that are more competitive capturing phosphorus sources. In addition the increase on the populations of the autochthonous copepod *A. tonsa* (omnivorous) and *E. americana* (herbivorous) in August and September could help explaining the diatom blooms collapse (Hoffmayer et al, 2000).

Popovich *et al.* (in press) concluded that during the early stages of the bloom, the dominance of *T. curviseriata* would be favoured by inputs from freshwater in combination with other environmental factors as low light intensities, shallow mixing, low predation and low temperatures. During the later stages, nutrient regeneration will sustain the production of other blooming species.

As Hoffmeyer and Torres (2001) described, *E. americana* lives only in the inner part of the estuary while *A. tonsa* lives on the whole system. They co-exist from June-July to October that is the period where the former can live a planktonic life, meanwhile *A. tonsa* lives all the year round being predominant during spring, summer and autumn, and is scant during June-July. During this period diatoms start to grow and the bloom starts.

The explanation proposed by Popovich et al (in press) agrees mainly in what have been reported on this conceptual model. In summary, nutrients do not limit production yet better environmental conditions produce an increase in competition due to an increase on the population of species, both competitors and predators that could not grow during the cold temperatures of August and probably are controlling the population during the whole year. A conceptual model summarising the trophic levels and their predation relationship is represented in Figure 39.

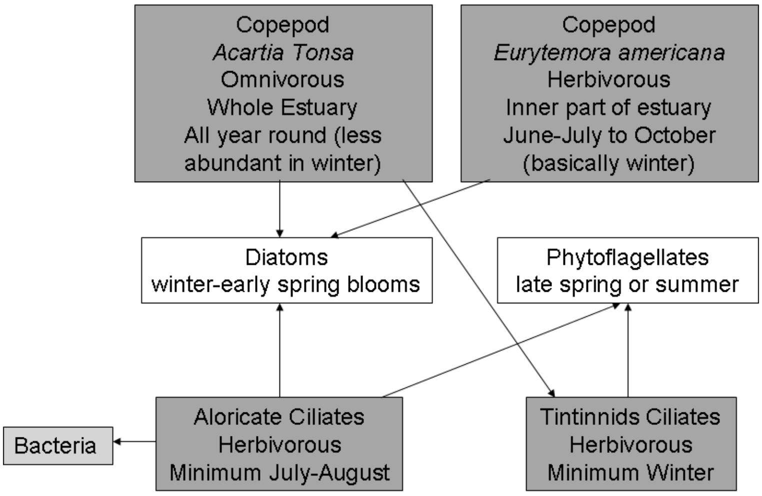

Figure 39 Trophic dynamics conceptual diagram for the Bahía Blanca estuary.

The conceptual model leaves open questions that would have to be solved through modelling exercises as the true limiting factor for primary production: light, nutrients or other factor; the source and the origin of inorganic nutrients, the place where remineralisation takes place in the estuary.

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