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Environmental Implications of Intensive Marine Aquaculture in Earthen Ponds

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In recent decades, the importance of marine aquaculture has grown substantially in most countries. Following a period of uncontrolled activities, the concern for the environmental implications of intensive mariculture has increased notably, and environmental impact is often taken into account when aquaculture activities are established. Among the most important pollutant effects of aquaculture are the outputs of dissolved nutrients, suspended solids and organic matter. In the present study, we have determined the loadings of dissolved nutrients (ammonium, nitrite, nitrate and phosphate), total suspended solids (TSS) and organic matter (particulate organic matter (POM) and biochemical oxygen demand (BOD_5)) in the effluent of a marine fish farm devoted to the intensive culture of gilthead seabream (*Sparus aurata*) in earthen ponds. Samples of seawater were taken monthly during a two-year period (April 1997–March 1999) in the two inflows and the outflow of the fish farm. The environmental impact of marine aquaculture was established by estimating the total amount of each compound discharged into the receiving waters as a direct consequence of the culture activities. Thus, 9104.57 kg TSS, 843.20 kg POM, 235.40 kg BOD, 36.41 kg $N{-}NH_4^+$, 4.95 kg $N{-}NO_2^-$, 6.73 kg $N{-}NO_3^-$ and 2.57 kg $P{-}PO_4^{3-}$, dissolved in the seawater, were estimated to be discharged to the environment for each tonne of fish cultured. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: pollution; seawater; nutrients; suspended solids; organic matter; environmental impact; marine aquaculture; *Sparus aurata*.

Gilthead seabream (*Sparus aurata*) is widely considered as an extremely suitable species to be used in aquaculture and is successfully cultured in many parts of the world, due mainly to the high yields and the species' considerable commercial value (Girin and Harache, 1976). Spain is one of the most important producing countries, the Bay of Cádiz (SW of Spain) being a focus for the intensive mariculture of *S. aurata* in earthen ponds. The total area devoted to aquaculture in 1994 in the Bay of Cádiz was 2919 ha including extensive, semi-intensive and intensive farming systems (Márquez *et al.*, 1996). The farms largely consist of old salt-pans modified for fish farming purposes.

This development generates profit and income, but it also bears risks of negative environmental impact, such as pollution, landscape modification or biodiversity change. In general, it has been accepted that mariculture has a comparatively low impact on the environment. Nevertheless, wastewater discharged from intensive mariculture into coastal water may lead to deterioration in water quality resulting from depletion of dissolved oxygen, hypernutrification and discharge of organic matter. The environmental impact of marine fish-farming depends strongly on species, culture method, stocking density, food composition, feeding techniques and hydrography of the site. To date, there have been only a limited number of studies on the environmental impacts of culture of gilthead seabream (Barnabé, 1990; Barbato *et al.*, 1996; Reggiani, 1996; Papoutsoglou *et al.*, 1996).

Attention has previously been focused on nutrient loadings, which can boost primary production and lead to eutrophication as, for example, shrimp farming practices in the inner Gulf of Thailand (Suvapepun, 1995). Depending on the species and culture techniques, up to 85% of phosphorus and 52–95% of nitrogen input into a marine fish culture system as feed may be lost into the environment through feed wastage, fish excretion, faeces production and respiration (Wu, 1995). Although concentrations of total nitrogen and phosphorus are usually low, their impact on the environment cannot be ignored because of the high volumes of water utilized during fish farming.

Several studies have estimated the total nitrogen and phosphorous discharges into receiving waters for different species (Mäkinen, 1991; Beveridge *et al.*, 1991; Ackefors and Enell, 1994). Due to the improvements experimented in the quality of foods and feeding techniques, lower values have been obtained on the load estimations performed in recent years. Thus, an average of 9.2 kg N and 0.57 kg P, for each ton of channel catfish (*Ictalurus punctatus*) was estimated to be discharged (Schwartz and Boyd, 1994), while for juvenile atlantic salmon (*Salmo salar* L.) cultured in freshwater, loadings

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of 71 kg N and 10.9–11.1 kg P per tonne have been reported (Kelly *et al.*, 1996). In a semi-intensive shrimp (*P. vannamei*) farm in earthen ponds, the estimated losses of N and P were 28.6 and 4.6 kg, respectively, per tonne of product (Páez-Osuna *et al.*, 1997). In a preliminary study performed on gilthead seabream (*S. aurata*) cultured in cages, around 190 kg N and 28 kg P were estimated to be introduced in the environment for each tonne of fish produced (Barbato *et al.*, 1996).

The discharges of suspended solids and organic matter as a consequence of aquaculture activities have also been studied. Average values of 110–520 kg TSS and 145–720 kg BOD$_7$ were reported as loadings from Finish farms, per tonne of fish cultured (Mäkinen, 1991). Beveridge *et al.* reviewed several studies where the loadings from freshwater salmonid culture were reported. Thus, values of TSS and BOD discharges were in the ranges of 474–4015 and 285–990 kg, respectively, per tonne of fish cultured (Beveridge *et al.*, 1991). Similar values were obtained by Kelly *et al.*, for the same species, reporting a discharge of 327–337 kg TSS and 422–485 kg BOD$_5$ (Kelly *et al.*, 1996).

Páez-Osuna *et al.*, reported that 1302 kg TSS and 469 kg POM were discharged during the culture of 1822 kg of shrimp in earthen ponds (715 kg TSS and 257 kg POM per tonne) (Páez-Osuna *et al.*, 1997). In a study performed on a farm devoted to the culture of rainbow trout (*Oncorphyncus mykiss*), net mass flow variations were calculated. Thus, the daily increase of BOD$_5$ was 353–1510 g t^{-1}, while daily net variations of TSS were below 1753 g t^{-1} (129–551 kg BOD$_5$ and 640 kg TSS per ton) (Boaventura *et al.*, 1997).

Only one work was found on the study of the discharges of TSS and POM matter from the culture of seabream in earthen ponds. As a consequence of the production of 3205 kg of fish, very large amounts of TSS (25 557 kg) and POM (3236 kg) were reported to be obtained (7974 kg TSS and 1010 kg POM per tonne) (Jambrina *et al.*, 1995).

Lack of data relating to waste outputs produced by some species, as *S. aurata*, and culture systems, specially in earthen ponds, makes the planning and design of wastewater treatments systems difficult (SMAFF, 1999). The present paper focuses on the study of the environmental impact of a farm devoted to the intensive culture of *S. aurata* in earthen ponds, on the quality of the adjacent water. Total suspended solids, BOD$_5$, particulate organic matter and the dissolved concentrations of ammonium, nitrite, nitrate and phosphate in the inflows and outflow of the fish farm were quantified during a two-year period, corresponding to a complete culture cycle of the species.

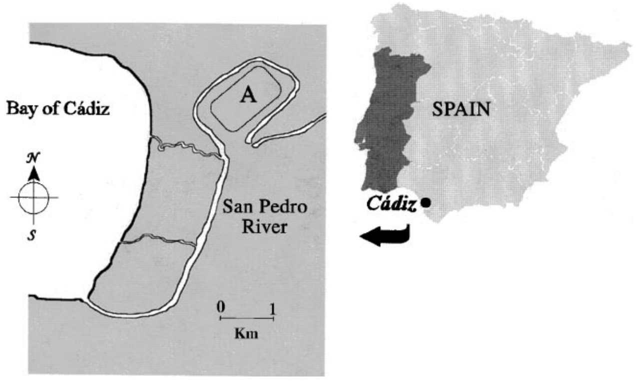

Fig. 1 Geographical situation of the San Pedro river. A: Fish farm under study.

Study Site

The study was carried out at a fish farm belonging to the company CUPIMAR, S.A., located in the margins of the San Pedro river (SW Spain) (see Fig. 1). This river was a tributary of Guadalete river, but was artificially blocked 12 km from the mouth. The San Pedro river is now an arm of the sea with a length of 12 km and a width ranging between 15 and 30 m. Water renovation from the Bay of Cádiz is controlled by tidal cycles; hence the water of this so-called river is seawater in character. It is located within a protected area (The Natural Park of the Bay of Cádiz), which promotes especially strict requirements in the water quality of the river (BOJA, 1997). In a previous work, the environmental conditions of San Pedro river were studied and the existence of two different zones, with different water quality, was described (Tovar *et al.*, 2000). The fish farm under study was located in the upper section of the river, which extends from 8 km from the mouth to the end of the river where it is artificially blocked, and is characterized by poorer water quality. Thus, low levels of dissolved oxygen and high contents of suspended solids and nutrients (especially ammonium) were found in this part of the river. The anomalies were suggested to be a consequence of, among others, aquaculture activities and poorer renovation of water by the tides, due to the hydrography of this arm of the sea.

Although three fish farms are using the water of the San Pedro river for their activities, the study farm (A in Fig. 1) is sufficiently large to be used to establish the relationships between aquaculture activities and the water quality of the river. The fish farm extends to an area of about 5 700 000 m^2 and, as can be observed in Fig. 2, consists of a series of batteries of earthen ponds where fish culture is carried out. The farm is divided in two different areas. In the first (I in Fig. 2) fishes are cultured in extensive or semi-intensive regime. The second area (II in Fig. 2) consisted of four batteries of earthen ponds where gilthead seabream is cultured under an intensive regime. In this zone, the majority of the fishes cultured in the farm are found, representing the greatest source of pollutants.

The seawater used in the culture process is introduced into the farm by two pumping stations. The water introduced by station number 1 (P1 in Fig. 2) passes through the zone I prior to feeding the lower half of the

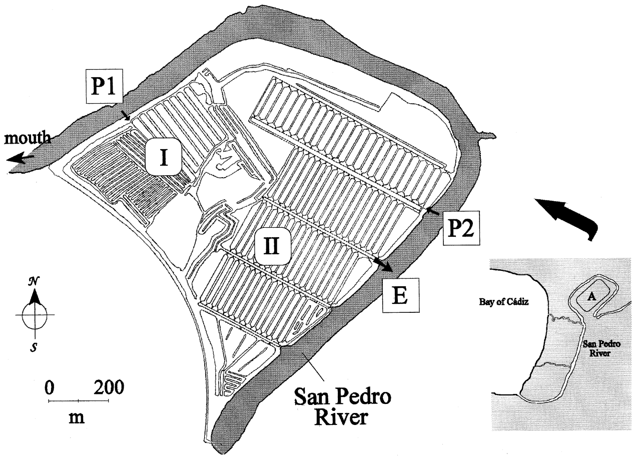

Fig. 2 Representation of the fish farm under study. I: Extensive or Semi-intensive culture. II: Intensive Culture. P1: Pumping station 1. P2: Pumping station 2. E: Effluent.

zone of intensive culture (zone II). The water pumped by station 2 (P2 in Fig. 2) goes directly to the upper half of zone II. Both sources of effluent are discharged via a single channel into the river.

The daily total volume of water introduced into the fish farm from the San Pedro river ranged from 181 151 m^3 to 287 795 m^3. Flow rate data were provided by the site manager, and occasionally checked using a Portable Velocity Meter, Model 3872, Sigma (USA). At the exit channel, the flow rate of the effluent was controlled by manipulating the opening of the sluice-gate to renovate the total volume of water in the farm once a day. The total effluent volume was estimated as the sum of the volume of influent plus, when needed, contribution of the rainwater.

Materials and Methods

Reagents and solutions

All the chemical reagents used in this work were of analytical grade and purchased from Merck (Daarmstadt, Germany). To evaluate the concentration of potential pollutants in seawater, corresponding calibration plots were constructed of six points each. Except for phosphate, all the calibration solutions were prepared with synthetic seawater, which was made by dissolving the needed amounts of salts to a final composition, in g l^{-1}, of: 23.926 ($NaCl$); 4.008 (Na_2SO_4); 0.677 (KCl); 0.196 ($NaHCO_3$); 0.098 (KBr); 0.026 (H_3BO_3); 0.003 (NaF); 10.826 ($MgCl_2.6H_2O$); 1.518 ($CaCl_2.2H_2O$); 0.024 ($SrCl_2.6H_2O$).

Water sampling

The measurements were carried out from April 1997 to March 1999. During this period, up to 30 sampling expeditions were performed. On each occasion, three samples were collected; two from the two pumping stations, P1 and P2, and the third from the effluent of the farm E (see Fig. 2), to characterize the inflows and outflow of the fish farm, respectively. Two different bottles were used for taking each sample: a 1-l polyethylene bottle was used for the sample for quantifying ammonium, BOD_5, POM and TSS; and a 1-l glass bottle was chosen for the sample used to determine nitrites, nitrates and phosphates. As a biocidal agent, 40 mg/l $HgCl_2$ were added to preserve the latter sample.

Determination of properties of the water

Once taken, samples were transported to the laboratory, where they were first filtered using a 0.45 m filter (N04SP04700, Micron Separations, USA) prior to ammonium, nitrite, nitrate and phosphate contents being analysed by standard methods (Grasshoff *et al.*, 1983, Rodier, 1990) (see Table 1).

To determine TSS and POM, a 500-ml sample was passed through a cellulose acetate filter (1110647N, Sartorius AG, Goettingen, Germany). Then TSS and POM were gravimetrically quantified, after heating the filter at 105°C (Heater Model 2000209, Selecta, Spain) and 525°C (Oven RHF 1400, Carbolite Furnaces, UK), respectively.

BOD_5 was determined by using a Model FOC 225 D manometric apparatus (Velp Scientifica, Usmate, Italy).

Results and Discussion

Nutrients

On the one hand, the environmental impact of marine aquaculture was evaluated by estimating the dissolved nutrients discharged into the San Pedro river as a consequence of the fish culture. As mentioned before, three samples were taken during each sampling expedition, corresponding to the two inflows and the outflow of the fish farm. In these three samples the concentrations of ammonium, nitrite, nitrate and phosphate were measured.

TABLE 1

Methodology applied to the quantification of each nutrient.

Nutrient	Method
$N\text{–}NH_4^+$	Spectrophotometry (Indophenol blue)
$N\text{–}NO_2^-$	Spectrophotometry (Sulphanilamide/N-(1-Naphthyl)-ethylenediamine dihydrochloride)
$N\text{–}NO_3^-$	Spectrophotometry (reduction in a Cd column and nitrite method)
$P\text{–}PO_4^{3-}$	Spectrophotometry (Ammonium molybdate/ascorbic acid)

The variations observed for each nutrient were analysed. Thus, on the one hand, the temporal variation of the concentration of the nutrients studied in the inflows and the outflow was represented during a two-year period, which is a whole culture cycle. On the other hand, the direct effect of the fish culture on the river was evaluated by performing the mass balances between the two inflows and the outflow. Thus, the total discharge of each nutrient was estimated. All the results mentioned above are discussed as follows:

Figs. 3–6 show the temporal variation of dissolved phosphate, ammonium, nitrite and nitrate, respectively, in the inflows and the outflow of the fish farm during the two-year period. The shape of the curves is an indication of seasonal variation, which was common to all the nutrients studied. However, the observed seasonal pattern is different from the known seasonal pattern for coastal seawater that is dependent on a series of factors such as the presence of phytoplankton, temperature, light intensity or flux of nutrients from sediments (Millero, 1996; Valiela, 1995). Thus, in coastal zones, a rapid removal of nutrients occurs in the spring, due to phytoplankton growth, the lowest values being measured in summer. Then, nutrient concentration increases in fall, and is usually highest in winter when they are not taken up by producers. This behaviour was not observed in the present work. From Figs. 3–6 the existence of a displacement of the periods of highest and lowest concentration was established. So, in the area under study, the increase in nutrient concentrations generally took place in summer, and highest concentrations are reached in fall. The amount of nutrients dissolved in seawater then decreased during winter, the concentration being minimum in spring. This displacement can be explained in terms of fish culture activities. Among the factors mentioned above as responsible for the seasonal variation of nutrients in seawater, the amount released from fish is generally not taken into account because of its relatively small contribution. However, the large amount of fishes contained in a fish farm devoted to intensive aquaculture determines that this becomes the main causative agent of the concentration of nutrients dissolved in the seawater used in the culture. In Fig. 7, the growth in mean weight of fish in a representative earthen pond during the period of time studied is shown. The curve follows a seasonal pattern with maximum growth rate (and, as a consequence, the maximum excretion and so, the release of nutrients from fishes) being obtained during the seasons of summer and fall, coinciding with the highest nutrient concentrations recorded in the seawater of the zone. By contrast, the minimum levels of nutrients dissolved in seawater are obtained during spring and winter, when the growth of fishes decreases and the release of nutrients decreases as well.

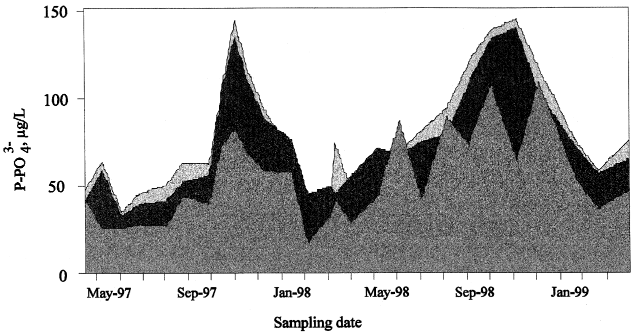

Fig. 3 Temporal variation of P–PO$_4^{3-}$ in the inflows and outflow of the fish farm. ▨: P1, ░: P2, ■: E.

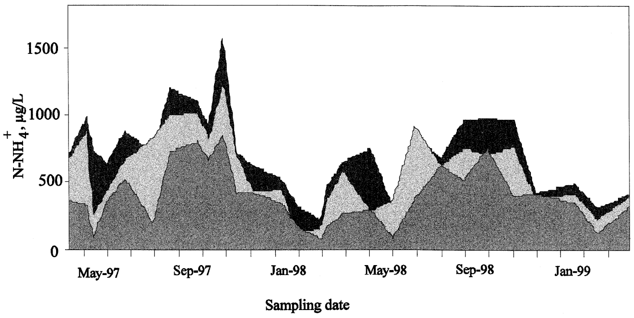

Fig. 4 Temporal variation of N–NH$_4^+$ in the inflows and outflow of the fish farm. ▨: P1, ░: P2, ■: E.

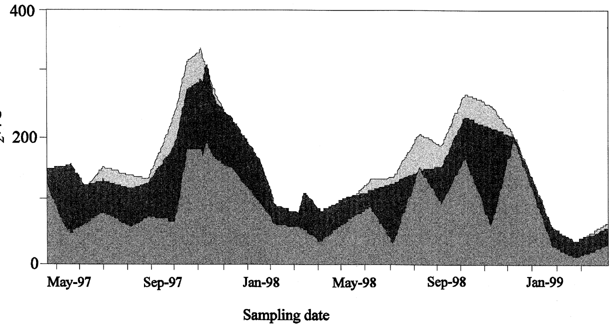

Fig. 5 Temporal variation of N–NO$_2^-$ in the inflows and outflow of the fish farm. ▨: P1, ░: P2, ■: E.

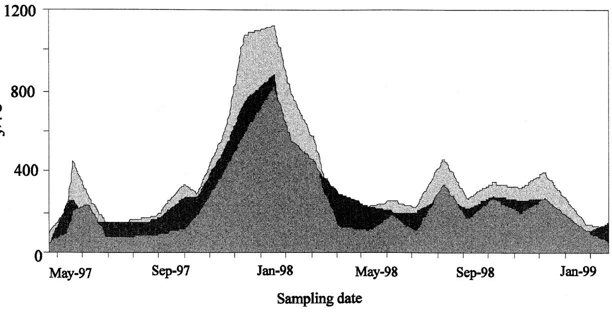

Fig. 6 Temporal variation of N–NO$_3^-$ in the inflows and outflow of the fish farm. ▨: P1, ░: P2, ■: E.

The levels of nutrients in the water samples taken in pumping station number 1 (P1) were always lower than those in samples taken from pumping station number 2 (P2) (Figs. 3–6). This was attributed to the proximity of P2 to the effluent of the fish farm. This, together with the poor renovation of water of the San Pedro river due to

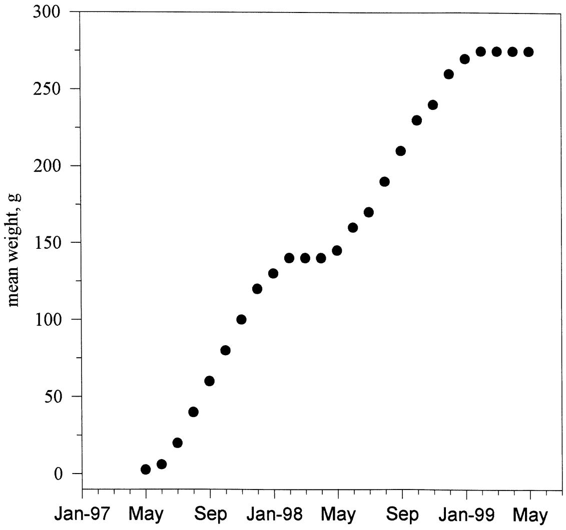

Fig. 7 Temporal variation of the mean weight of a fish.

its hydrography (Tovar *et al.*, 2000) results in the water being introduced into the fish farm by P2 being of worse quality than that introduced by P1, which is located closer to the mouth of the river and experiences a better renovation of the water by tides.

The only exception observed during the study was for nitrate concentrations (see Fig. 6). In this case, very high concentration values were recorded in winter, and only in the first year of the study. These samples were taken after a strong period of rains, which caused an increment in the concentration of nitrates, due to run-off from agricultural land adjacent to the river. Thus, some of the very high values measured during the study must be considered as caused by the effect of rains and cannot be attributed to aquaculture activities. In fact, nitrate levels always increased after a rainfall, the magnitude of this increase being directly related to the magnitude of the rains.

The next objective of this work was to carry out the mass balance estimates for each of the four dissolved nutrients in the fish farm to quantify the direct effect of aquaculture on the environment. These balances were made taking into account the volume of seawater introduced by each pumping station (V_1 and V_2) and the volume of effluent (V_E), together with the corresponding nutrient concentrations ($[N]_1$, $[N]_2$ and $[N]_E$, where N represents each nutrient) measured in the samples. As mentioned above, the data for V_1 and V_2 were given by the site manager and occasionally tested, while the volume of effluent, V_E, was estimated as the sum of two factors: total volume of seawater introduced in the system by both pumping stations, V_1 and V_2, plus volume of water introduced by rain, V_R (estimated from pluviometry and culture surface). Thus, the mass of each nutrient, n, was estimated as follows:

$$n = ([N]_E \cdot V_E) - ([N]_1 \cdot V_1 + [N]_2 \cdot V_2), \tag{1}$$

where $V_E = V_1 + V_2 + V_R$.

Because of the disturbance produced in the system due to the large amount of nitrates introduced from adjacent agricultural lands after a period of rain, the nitrate values measured during the rain periods were not considered when performing the mass balances.

Thus, the individual nutrient loads were calculated daily, the results being shown in Fig. 8. From the plotted data, the total amount of nutrients discharged during a period of time can be estimated for this particular case. The total nutrient loadings were calculated in relation to biomass production. Thus we have determined that 36.41 kg N–NH_4^+, 4.95 kg N–NO_2^-, 6.73 kg N–NO_3^- and 2.57 kg P–PO_4^{3-} were discharged for each ton of fish cultured. As was expected, there is an important difference between the amount of ammonium discharged into the environment and the amounts corresponding to the other three nutrients. This can be explained by the fact that ammonium is the principal nutrient released by fishes (Porter *et al.*, 1987; Echevarría *et al.*, 1993).

Suspended solids

The methodology applied to estimate the importance of the loadings of total suspended solids was similar to that used for nutrients. Thus, first, the temporal variations of TSS were quantified in the inflows and outflow of the farm and are presented in Fig. 9, from which a seasonal dependence can be established, with maximum values being obtained during summers while the lowest were obtained in winter.

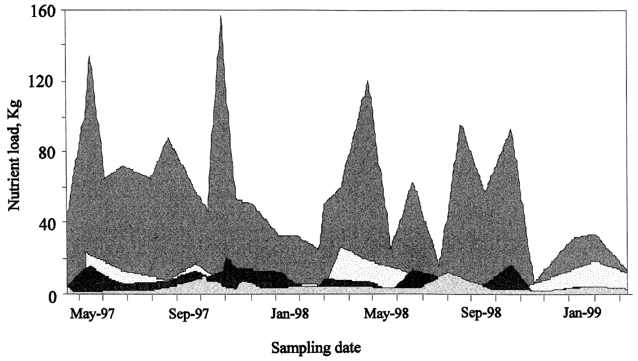

Fig. 8 Temporal variation of nutrients discharged into the river. ▨: N–NH_4^+, ■: N–NO_2^-, □: N–NO_3^-, ░: P–PO_4^{3-}.

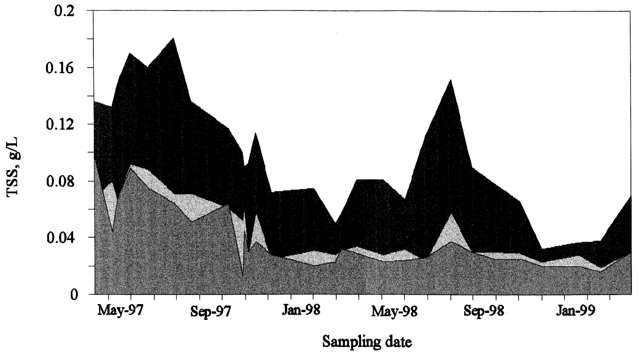

Fig. 9 Temporal variation of TSS in the inflows and outflow of the fish farm. ▨: P1, ░: P2, ■: E.

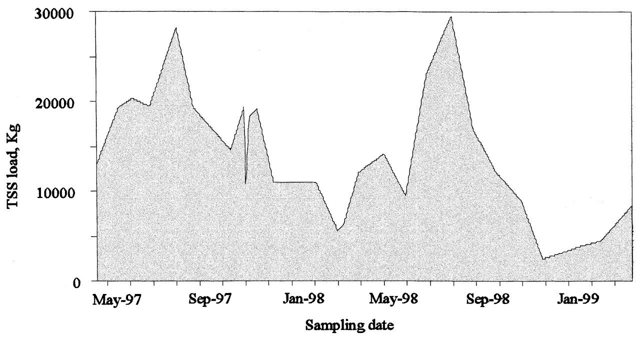

Fig. 10 Temporal variation of TSS discharged into the river.

The proximity of P2 to the effluent of the farm originates that higher values of suspended solids are measured in this pumping station, in relation to those measured in P1. However, the difference between the values obtained in both pumping stations was not so high as expected. This was attributed to the rapid sedimentation of solids once they are poured to the river, due to the relatively slow movements of the water in this part of the river (Tovar *et al.*, 2000).

The very high values recorded in the curve corresponding to the effluent in Fig. 9 show that, as expected, the discharge of suspended solids represents one of the main effects of the aquaculture activities.

Mass balances for TSS were estimated by using Eq. (1), adapted to the new parameter to be quantified. Thus, the daily net discharge of TSS was calculated and represented in Fig. 10. From these data, the total solid discharge was estimated in relation to fish production, and then a value of 9104.57 kg of suspended solids was calculated to be introduced into the river per tonne of seabream cultured.

Organic matter

To quantify the release of organic matter from aquaculture, two different parameters were studied: BOD_5 and particulate organic matter (estimated as volatile solids). The temporal variations of these two parameters are shown in Figs. 11 and 12, which show the expected pattern, with maximum values in summer and minimum in winter. Some BOD values were almost negligible, like those recorded from December 98 to March 99. The behaviour observed is in coincidence, once more, with the growth rate of the fishes.

Daily, mass balances of BOD and POM were calculated following the same procedure explained above, and based on the use of Eq. (1). The results obtained are shown in Figs. 13 and 14, respectively. These results cover a 20-month period for BOD, while POM loads were quantified during 15 months. The total loads were divided by the biomass increment of the corresponding period, and so, mean values of 235.40 kg BOD and 843.20 kg POM were estimated to be discharged into the receiving water for each tonne of fish cultured.

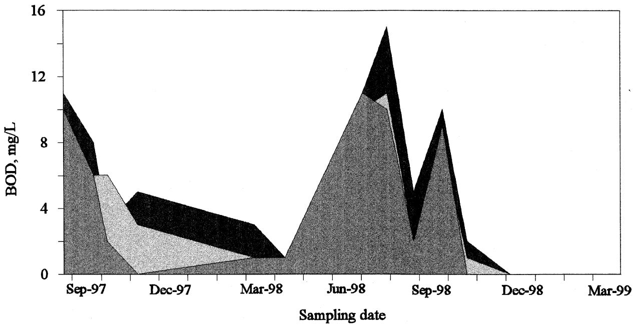

Fig. 11 Temporal variation of BOD in the inflows and outflow of the fish farm. ▒: P1, ░: P2, ■: E.

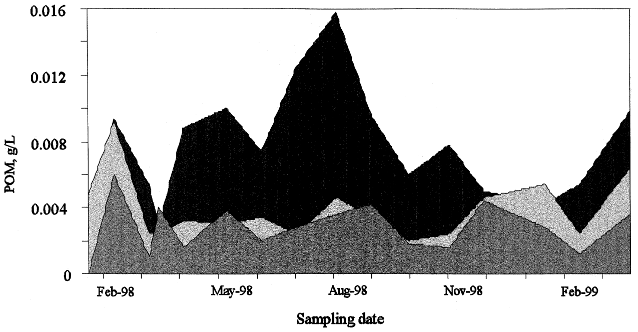

Fig. 12 Temporal variation of POM in the inflows and outflow of the fish farm. ▒: P1, ░: P2, ■: E.

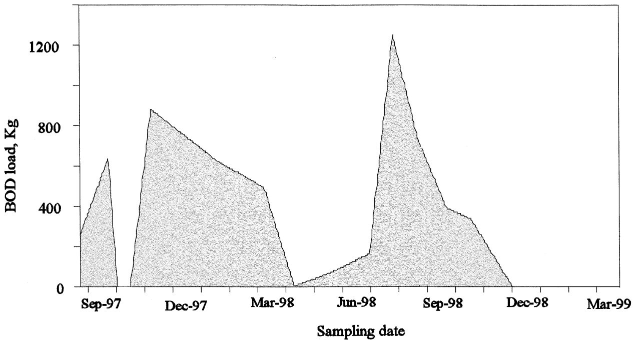

Fig. 13 Temporal variation of BOD discharged into the river.

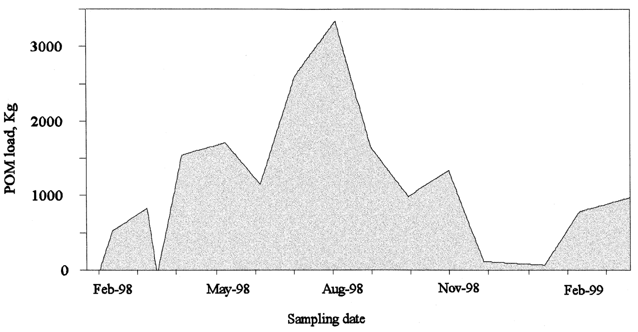

Fig. 14 Temporal variation of POM discharged into the river.

Conclusions

Because of the use of different species and culture systems, it is difficult to evaluate the results from the present work with those from other studies. Besides, some of these studies are based on theoretical calculations. Thus, Ackefors and Enell (1990) reviewed the discharge of nutrients from Swedish marine net-cage fish farms, and, with a feed coefficient of 1.5, estimated values of 2.2 kg of P and 61 kg of N as the total amounts of nutrients discharged in dissolved form into the environment per ton of fish produced. These figures are considered by the authors as average values for fish farms in general and therefore, applicable to further calculations in different farms. On the other hand, Kelly *et al.* (1996) reported values of 1.2–2.1 kg $P–PO_4^{3-}$ and 30–35 kg $N–NH_4^+$ from experimental measurements from a freshwater atlantic salmon farm in Scotland. As can be observed, even for different species and culture systems, the values of dissolved nutrients obtained in this work are very similar to those reported by other authors. This fact indicates that the role that species and culture system play in determining total waste loading is especially important for the particulate fraction, while it has lower influence on dissolved fraction. This can be confirmed by analysing the results obtained for both TSS and POM. In the present work, a very high value of TSS load was obtained (9104.57 kg/tonne), being in concordance with the value reported for the same species and culture system: 7974 kg/tonne (Jambrina *et al.*, 1995). These values are much higher (up to 80 times) than the TSS load reported for other species, which were previously discussed, even for shrimp in earthen ponds. Besides, the values of POM obtained (843.20 kg/tonne) were also higher than those reported by other authors, but, in this case, the difference was not so high (up to 3–4 times). This fact may indicate that the suspended solids contained in the water effluents of the fish farm were mainly of inorganic nature and probably coming from the bottom of the ponds, as a consequence of fish activity. Thus, less than 10% of the suspended solids poured into the river were of organic nature their origin being in uneaten food and fish excretions.

On the other hand, the values obtained in this work for BOD load (235.40 kg/ton) were in the same order of magnitude that the discharges produced for other species and cultured systems as can be observed in the values showed in the introduction of this paper. This indicates again that the amounts of products originated as a direct consequence of aquaculture activities (fish growing) are very similar for different species and culture systems, the main difference being in the inorganic solids re-suspended by fishes from the bottom of the earthen ponds, when used.

Finally, the results of the present study also indicate that, in general, the water quality of the effluents from the intensive culture of *S. aurata* shows very large seasonal variations, due mainly to the fish biology and related management practices. For this reason, optimal characterization of fish farm effluents must be based on continuous monitoring, information being limited if based on single samplings.

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