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Sources and Sinks of Nutrients and Pollutants in Cullera Bay

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ABSTRACT

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Water quality plays a very important role in the ecological balance and economic development of coastal and estuarine areas. However, these areas have been progressively degraded in recent decades due to different factors, including an increase in nutrient and pollutant loads introduced into the system, which may cause eutrophication problems. This paper analyzes the water quality of one such area, Cullera Bay, located on the Spanish Mediterranean coast. This study focuses on the main sources and sinks of pollutant substances and the relationship between the distribution of these substances within the bay and local meteorological and oceanographic conditions. Two main sources of nutrients and pollutants were identified: the discharges of the Júcar River and the marine outfall, although other secondary sources are also present. The river discharge varies greatly depending on the season. The freshwater it carries is very rich in nutrients due to the presence of fertilizers and pesticides from its agricultural use. The domestic wastewater discharged through the marine outfall is occasionally untreated, particularly in the summer, when the tourist population increases and the capacity of the water treatment plant is exceeded. This study is based on data recorded during nine field campaigns carried out in the area in 2002 and 2003 and numerical simulations of hydrodynamics and pollutant dispersion. By analyzing the field data and the numerical simulation results, wind is identified as the main driving factor in the bay because the other possible driving factors either have negligible effects (tide), affect only a very localized area (waves, usual river discharges) or are infrequent (storm surges, river floods).

ADDITIONAL INDEX WORDS: *Water quality, hydrodynamics, numerical simulation, dispersion, marine outfall.*

INTRODUCTION

Water quality plays an important role in both the ecological balance and economic development of coastal and estuarine areas. However, these areas have been progressively degraded in recent decades due to different factors, including an increase in nutrient and pollutant loads introduced into the system. Estuaries are important routes for nutrients from the land to the ocean. As the nutrients pass through the estuary, they undergo various biochemical transformations that affect their spatial distribution. To understand these processes we must characterize the sources of nutrients that enter the estuary, their spatial and temporal variations, and the degree to which they are affected by human activities (Hager and Schemel, 1992). Thus, some estuaries receive most nutrients from their watersheds (Peterson *et al.*, 1988) while others are dominated by anthropogenic waste inputs (Jaworski, 1981).

Therefore, human activities on land inevitably increase nutrient inputs to coastal waters from deforestation, wastewater, fertilizers and other sources (Peierls *et al.*, 1991; Turner and Rabalais, 1991; Lapointe and Clark, 1992). Increased nutrient loading from sewage inputs can depress dissolved oxygen levels and induce chemical stress and bacterial contamination in marine ecosystems (Pastorok and Bilyard, 1985; Lapointe and Clark, 1992).

In particular, land-derived nitrogen (N) loading in estuaries has increased recently as land use has intensified in watersheds (Jordan and Weller, 1996; Jaworski *et al.*, 1997; Bowen and Valiela, 2004). An increase in the supply of N to estuaries stimulates eutrophication and causes phytoplankton and macroalgae blooms (Lavery *et al.*, 1991; Duarte, 1995; Valiela *et al.*, 1997; Hauxwell *et al.*, 2001), which has an ecological impact. The increased N loads occurring throughout the world (Vitousek *et al.*, 1997) are largely driven by changes in land use in watersheds, such as increased urban and agricultural development (Constanzo *et al.*, 2003 and Bowen and Valiela, 2004). Global production of fertilizers has also increased markedly in recent decades (Smil, 1997; Galloway, 1998) and fertilizers are major sources of nutrients to some estuaries (Lee and Olsen, 1985; Boynton *et al.*, 1995; Jordan *et al.*, 1997; Sierra *et al.*, 2002).

The aforementioned problems have been observed throughout the world, especially in tropical and subtropical areas. However, algal blooms and eutrophication have even occurred in temperate and oligotrophic regions such as the Mediterranean Sea (González del Río, 1987; Soler *et al.*, 1988; Mestres *et al.*, 2004).

To manage these water-quality problems, nutrient sources must be identified and cost-effective controls must be implemented (CASTRO *et al.*, 2003). This is difficult, however, because nutrients originate from many different sources.

Scientists are challenged to predict and detect the resulting amount and the timing of water-quality improvement. Prediction often involves modeling, whereas detection requires appropriate monitoring (CHRISTIAN and THOMAS, 2003).

Numerical simulations of hydrodynamics and water quality are commonly based on advanced models whose local validation against observations has been limited (MESTRES *et al.*, 2006). Moreover, these numerical simulations use a "smooth" or simplified coastline and/or bathymetry and therefore many of the nearshore water and pollutant-flux features are lost (BROOKS *et al.*, 1999; INOUE and WISEMAN, 2000). One such feature, the accumulation of pollutants and sediments associated with stagnation areas, plays an important role in water quality and, in particular, its degradation (MESTRES *et al.*, 2006).

In summary, water quality in coastal areas is a growing problem. Water quality depends on nutrient and pollutant loads introduced into the system ("sources"), as well as local hydrodynamics, which contribute to the advection and diffusion of these substances and eventually to their accumulation in certain areas ("sinks"). Complex biochemical processes also affect water quality in coastal areas by increasing or decreasing the concentrations of these substances.

This study aims to analyze the general water quality in Cullera Bay (Spain), understood as the conservation or nonconservation of water properties due to the presence of various substances including sediments, nutrients and pollutants. This study of Cullera Bay's water quality involved the analysis of data recorded during several field campaigns and numerical simulations with models previously validated against field observations (MESTRES *et al.*, 2003). It assesses the sources and sinks of nutrients and pollutants by relating them to meteorological and oceanographic conditions. The results obtained should help make the management of coastal areas more efficient, by enabling managers to make decisions (DOODY, 2003; ELEVELD *et al.*, 2003; KING, 2003) based on the regulation of discharges as a function of the prevailing meteorological and oceanographic conditions and the development of indexes (FERREIRA, 2000).

STUDY AREA

Cullera Bay and estuary of the Júcar River are located on the Gulf of Valencia (Figure 1), on the Spanish Mediterranean coast (0°13′ → 0°15′ W and 39°08′ → 39°12′ N). Cullera Bay presents some environmental problems due to certain natural and man-made features.

First, the agricultural activities on the surrounding plains involve large amounts of nutrients, detritus and pesticides, which are drained directly into the Júcar River and flow into the bay near the southern boundary.

The tourism industry in the town of Cullera is an additional factor. The population of the town is usually about 20,000 people, but it grows to over 250,000 (SOLER *et al.*, 1988) in the summer. This increase in the population density leads to a dramatic increase in the volume of wastewater dumped directly into the bay through a marine outfall located close to the mouth of the Júcar River. The small size of this marine outfall, its proximity to the coast and the shallowness of the bay negatively affect the water quality in the area.

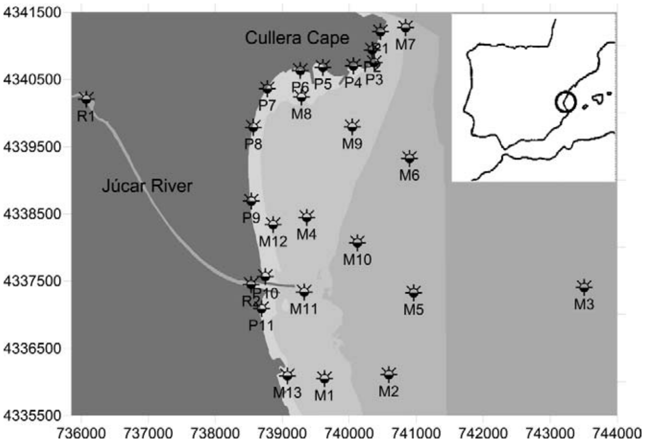

Figure 1. Study area location and sampling stations.

Finally, Cullera Bay is semi-enclosed. To the north, it is limited by Cullera Cape, a rocky mass that protrudes into the sea, but the southern end of the bay is open. This also influences the hydrodynamic pattern and therefore the water quality of the area. The most important driver of hydrodynamics and pollutant dispersion is the wind field (because this is a micro-tidal environment).

The freshwater discharge, the discharge from the marine outfall and the shallowness of the water body (which allows benthonic nutrients to be released into the water column) cause major environmental problems related to the quality of the bay's waters (MESTRES *et al.*, 2006). The frequent dense blooms of phytoplankton and red algae observed in Cullera in recent years are typical features of highly eutrophic coastal ecosystems (GONZÁLEZ DEL RÍO, 1987).

MATERIAL AND METHODS

Field Campaigns

To improve knowledge of the natural processes related to water quality, nutrient/pollutant dispersion and driving mechanisms in Cullera Bay, nine field campaigns were carried out from June 2002 to July 2003 on a seasonal basis (Table 1).

The field campaigns involved five different kinds of measurements under different climatic and wastewater-discharge scenarios:

- Profiles of water-quality parameters (CTD and a multi-parameter probe).
- Water sampling (for extended laboratory analyses of biochemical constituents).
- Sediment sampling (the same measurements as for water samples, plus granulometry analyses).
- Flow velocity along the last stretch of the Júcar River (Sta-

Table 1. *Field campaigns in the Júcar Estuary and Cullera Bay.*

Campaign	Dates
ECOSUD 1	June 20–25, 2002
ECOSUD 2	July 9, 2002
ECOSUD 3	July 24–27, 2002
ECOSUD 4	August 5–6, 2002
ECOSUD 5	September 4–5, 2002
ECOSUD 6	November 20–21, 2002
ECOSUD 7	February 8–9, 2003
ECOSUD 8	April 23–24, 2003
ECOSUD 9	July 22–23, 2003

tions R1 and R2) and the circulation field at the southern end of the bay at 7 m and 10 m depth (Stations M1 and M2). These last measurements were carried out at a relative depth of ($z/h \approx 1/3$), where h is the total depth and z the distance from the bottom.

– (v) Wind field (because it is the main circulation-driving term) close to the river-mouth station (R2).

For a detailed description of the field campaigns, see MÖSSO *et al.* (2002).

Numerical Models

In this study, two different numerical models were used to simulate the hydrodynamic field and transport induced by wind and river outflow in Cullera Bay. The first model is the COHERENS code (LUYTEN, 1999), to which LIMMIX, a Lagrangian particle random-walk transport model (MESTRES, 2002), was coupled.

COHERENS is a 3-D hydrodynamic model that solves momentum and continuity equations in a (x,y,σ) reference system, assuming vertical hydrostatic equilibrium. It also includes temperature and salinity equations. The complete set of equations can be found in LUYTEN (1999) and LUYTEN *et al.* (1999).

LIMMIX, the transport model used to simulate the behavior of the outfall plume, is based on a Lagrangian approach to the convection-diffusion equation. The numerical code solves a discretized version of the 3-D Fokker-Planck equation (TOMPSON and GELHAR, 1990). A detailed description of the complete transport model and the mapping algorithms used can be found in MESTRES (2002) and SANCHEZ-ARCILLA *et al.* (1998).

This suite of models was validated for Cullera Bay against observations from the field campaigns described above (MÖSSO *et al.*, 2002; MESTRES *et al.*, 2004).

RESULTS AND DISCUSSION

There are two main sources of nutrients and pollutants in Cullera Bay. The first is the flow of the Júcar River. The other is the marine outfall, which discharges part of the wastewater collected in the area near the river mouth (Station M11).

The Júcar waters have high nutrient concentrations due to the intensive agricultural exploitation of the river's drainage basin, with the subsequent return of waters "enriched" with fertilizers and pesticides, and to the discharge of partially treated domestic and industrial wastewater from upstream towns (MÖSSO *et al.*, 2007).

The Júcar River has a typical Mediterranean flow pattern, with relatively high flows from October to May and lower rates during the summer months. The statistical analysis of the low river flow from 1911 to 1997 shows that the mean daily flow rate was under 5 m^3/s 53% of the time and only exceeds 20 m^3/s 12% of the time (MÖSSO, 2003; MESTRES *et al.*, 2006). Nevertheless, as in many other Spanish Mediterranean rivers, extreme flood events are observed periodically, although the regulation of the river reduces the effects of these floods.

Figure 2 shows the average daily river flows recorded during the period studied (June 2002 to July 2003). The measuring station is located in the town of Cullera, several kilometers from the river mouth. The freshwater flow is zero or negligible throughout most of the year. The same figure shows the temporary location of the field campaigns. From the figure, we could conclude that freshwater flow was inexistent during all of the field campaigns (except the 7th and 8th) and therefore the nutrient flux from the river to the bay was negligible.

Nevertheless, the observations recorded during the field campaigns (especially the salinity and nutrient data recorded at Station R2) show the existence of a salt wedge and therefore freshwater flow and nutrient flux in the last stretch of the river, close to its mouth. This suggests freshwater inputs downstream from the gauging station, originated from water treatment plant discharges and small agricultural ditches. This is also supported by velocities recorded at Station R2, where a seaward flow exists in the surface layer in most of the campaigns and where velocities reach 20 cm/s.

To have an idea of the nutrient load supplied by the river, Figure 3 shows nutrient concentrations measured at different depths at the river mouth (Station R2). The figure clearly shows that the river acts as a nutrient source, since concentrations are higher for all nutrients (nitrate, ammonium, SRP and orthosilicic acid) in the upper depths (surface and -0.5 m), where the freshwater layer is. Moreover, higher concentrations were found during the ECOSUD 8 field campaign (April 2003), with major differences with respect to the other campaigns. This was due to the higher river flows recorded during this campaign, ranging from 4 to 21 m^3/s (measured at the gauge station), again showing the close relationship between freshwater flow and nutrient load.

This nutrient accumulation in the surface layer is apparent, for example, at Station R2 during ECOSUD 8. Thus, while nitrate concentrations range from 152.1 to 194.7 μmol/L in the surface layer (0 to 0.5 m depth), this concentration drops to 24.2 μmol/L at 1 m depth and to 4.5 μmol/L at 3.4 m depth. The same behavior was observed for the other nutrients analyzed. Ammonium levels drop from a range of 42.3 to 51.2 μmol/L in the surface layer to 7.2 μmol/L at 1 m depth and 4.8 μmol/L at 3.4 m depth. SRP follows the same pattern—it decreases from a range of 4.2 to 6.2 μmol/L in the freshwater layer to 0.4 μmol/L at 1 m depth and disappears near the bottom. Orthosilicic acid concentrations range from 66 to 78 μmol/L in the upper layer and drop to 12.5 μmol/L

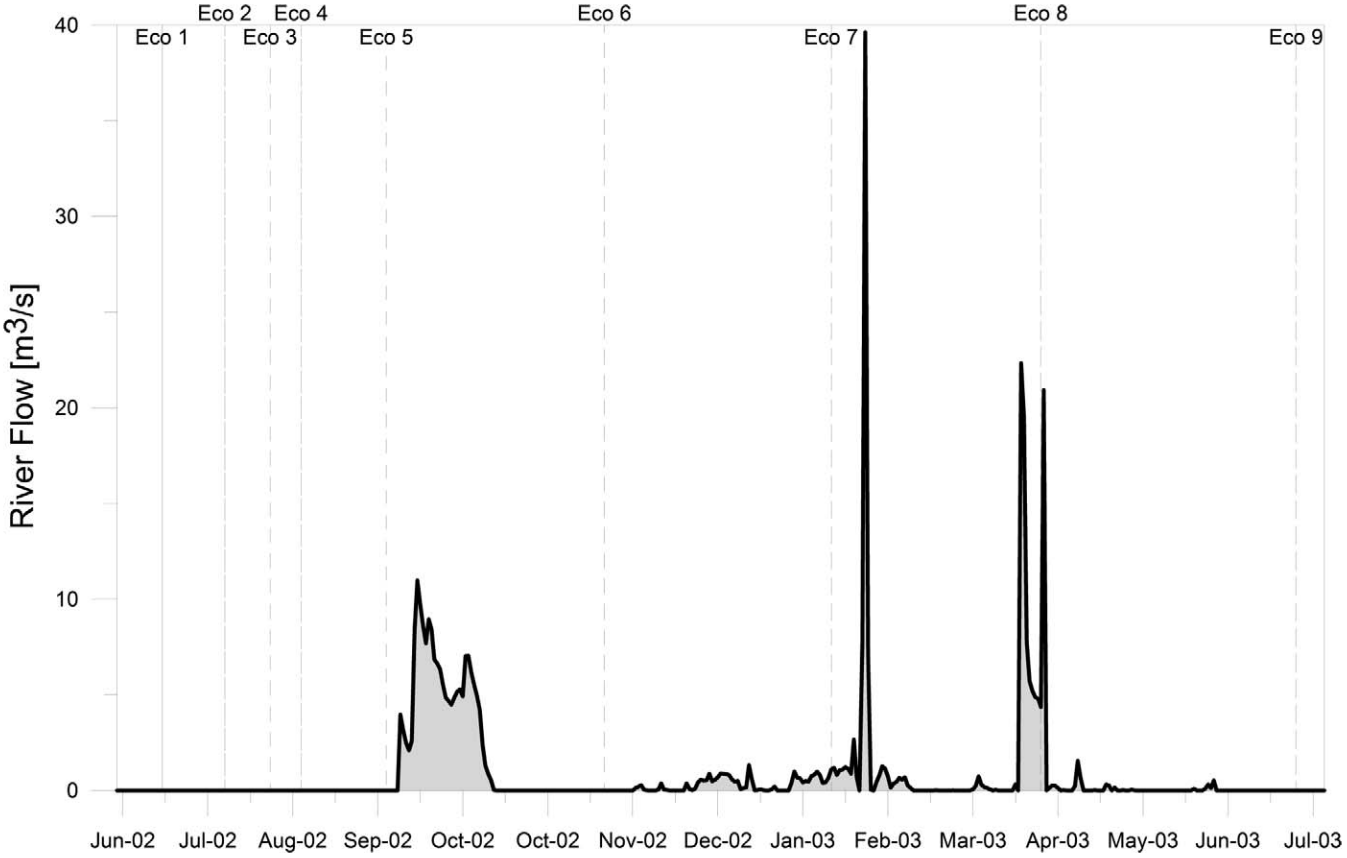

Figure 2. River flow during the period studied and field campaigns.

at 1 m depth and 3.5 μmol/L at 3.4 m depth. The river is therefore a major nutrient source for the bay.

The second major source of nutrients and especially pollutants in the bay is the marine outfall, which discharges close to the river mouth at Station M11. Since data from the outfall discharge were not available, measurements at point M11 were considered as a reference for the outfall discharges. Nevertheless, M11 does not only represent the output conditions of the marine outfall; it is also under the influence of river discharges, which are dispersed into the bay by advection and diffusion.

Despite this drawback, the pollutant and nutrient concentrations recorded at M11 allow us to understand the importance of this source. These concentrations are plotted in Figure 4. Although nutrient concentrations at this point are lower than those found at Station R2 in the river and present low values overall (except in the ECOSUD 7 campaign), they are clearly higher than the values recorded at nearby marine stations. Thus, at Station M11 during the ECOSUD 7 campaign, nutrient concentrations in the surface layer (up to 0.5 m depth) range from 5.1 to 8.5 μmol/L for ammonium, 17.5 to 35.6 μmol/L for nitrate, 0.42 to 0.84 μmol/L for SRP and 5.4 to 11.2 μmol/L for orthosilicic acid. At Station M10, these values are one order of magnitude lower than those measured at M11: 2.9 to 3.3 μmol/L for nitrate, 0.02 to 0.04 μmol/L for SRP, 1.1 to 1.5 μmol/L for orthosilicic acid and under the detection limit (0.1 μmol/L) for ammonium. Therefore, despite the influence of the river at Station M11, the contribution of the marine outfall to water quality in the bay cannot be disregarded.

In addition to the two major sources of nutrients and pollutants, there are also secondary sources. Their location is more significant than the amount of nutrients or pollutants they introduce into the bay. Both sources are located in the northern part of Cullera Bay (at some distance from the river mouth), so the substances discharged by the Júcar River and the marine outfall undergo a series of transformations (dilution, dispersion, decay, *etc.*) before arriving at this area. However, the loads carried by these secondary sources affect the northern part of the bay directly.

One of these secondary sources is located on Cullera Cape. This rocky protuberance consists of a karst that filters freshwater into the northern part of the bay. These filtrations carry runoff, which decreases salinity levels in the northern part of the bay. Occasionally, these filtrations also contain wastewater from leaks in the sewage system. Figure 5 shows bacteria concentration peaks detected during the ECOSUD 4 field campaign (August 2002) close to Cullera Cape.

Figure 5 shows high bacteria concentrations detected in several campaigns at Station P1, located at the northern part

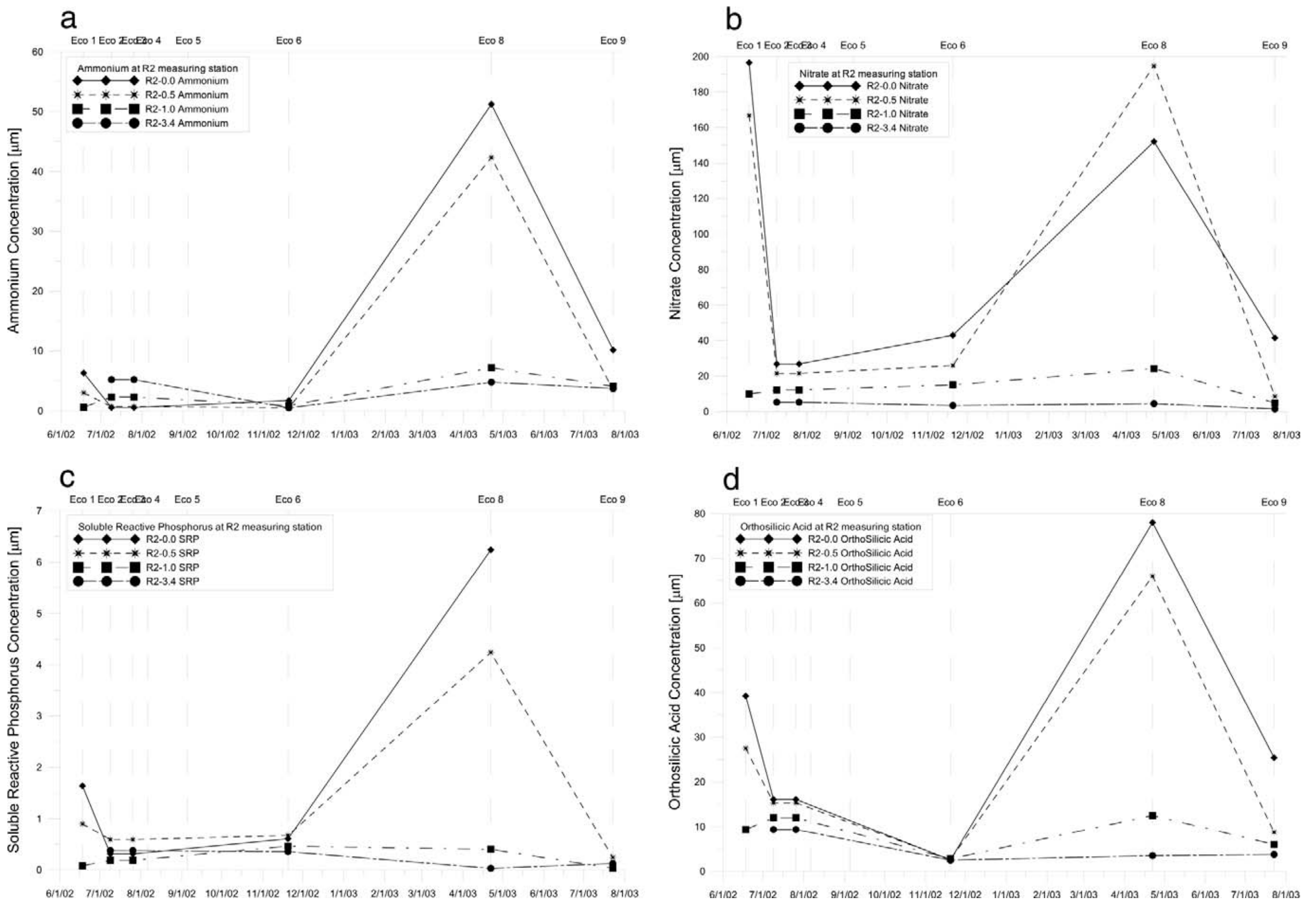

Figure 3. Nutrient (ammonium, nitrate, soluble reactive phosphorus and orthosilicic acid) concentration at 0, 0.5, 1 and 3.4 m depth measured at Station R2 (close to the river mouth) from June 2002 to July 2003.

of the cape. This is due to sporadic freshwater inputs from an irrigation ditch on the northern side of the cape that may significantly affect salinity values measured at M7, P1 and P3 (although not P2, since it is located in a confined cove). This effect is particularly enhanced when significant irrigation flows in the ditch concur with north-northeast winds, as occurs in the 9th campaign (FALCO *et al.*, 2007). Figure 6 illustrates this freshwater intrusion from the northern part of the bay, where two lower-salinity areas can be observed. The first, located at the river mouth, corresponds to the freshwater discharges from the river and the marine outfall. The second, stretching from Cullera Cape towards the north, indicates freshwater intrusion coming from this side.

Once the pollutant and nutrient sources have been described, the possible sinks of these substances must be identified in order to determine their effect on the water quality of Cullera Bay.

The whole bay behaves as a semi-enclosed system, retaining most of the substances that arrive there. This is due to two factors: the morphology of the bay and the prevailing wind regime.

To evaluate the effect of the bay's morphology on waterborne substance dispersion two approaches were used. First, the currents measured at Stations M1 and M2 were analyzed and their speeds and directions were computed. A strong correlation between current direction and bottom topography was detected because currents generally follow the direction of bottom contours. A detailed description of this dependence of current direction on depth-contour direction can be seen in MÖSSO *et al.* (2007).

The second approach involved using the aforementioned numerical models to simulate pollutant dispersion in the bay, taking into account the wind conditions recorded during the field campaigns. The wind regime shows strong seasonal behavior in the wind field, varying from daily breeze patterns to persistent winds coming from inland. Although the wind field is highly variable throughout the year, the overall pattern is mainly daily breeze (MÖSSO *et al.*, 2007). The summer conditions in particular were well characterized due to the persistent wind pattern observed during measurements, which has the following features.

In the evening, at night and in the early morning the wind is smooth with low velocities (0.5 to 3 m/s) and a NW direction (from land to sea).

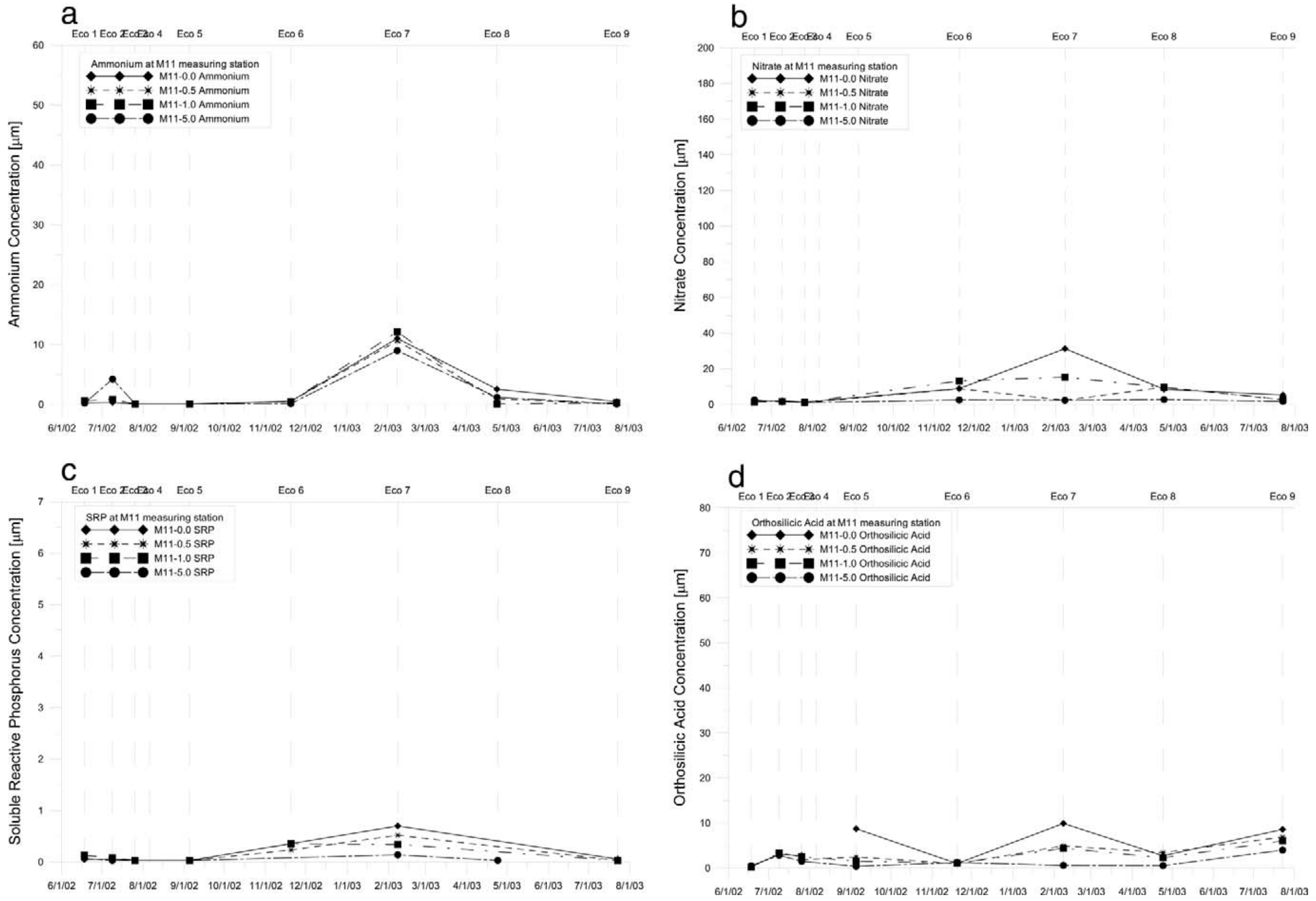

Figure 4. Nutrient (ammonium, nitrate, soluble reactive phosphorus and orthsilicic acid) concentration at 0, 0.5, 1 and 5 m depth measured at Station M11 (the marine outfall) from June 2002 to July 2003.

In the morning and afternoon the wind has higher velocities, with remarkable peaks (7 to 9 m/s) and a direction between E and SE (from sea to land).

This pattern has major implications for the water quality of the bay and especially for Cullera's beaches, as numerical simulations show. By introducing these wind conditions as forcing terms in the numerical models, a complex hydrodynamic pattern can be observed due to the particular morphological conditions of the bay. In this pattern, eddies and circulation cells are frequent, especially near Cullera Cape. The numerical simulations show that Cullera Cape determines the hydrodynamics of the whole bay by acting as a barrier. Therefore, particles discharged into this area are unlikely to leave it. This implies that the bay acts as a sink for particles (sediments, nutrients and pollutants), which affects the water quality of the area. For a complete analysis of the barrier effect caused by the cape, see MESTRES *et al.* (2006).

Figure 7 summarizes this phenomenon and shows the simulation of the dispersion of wastewater spilled by the marine outfall, which is driven to Cullera's beach under summer conditions and affects the coastal water quality. Since more bathers are present in the summer, this dispersion pattern can cause a public-health problem. In the summer, these negative effects are worsened by the prevailing local wind direction, which, as mentioned above, blows from the SE during the day and pushes the river and outfall plumes towards the coast.

The set of model simulations performed confirmed that the cape plays an important role in determining water circulation and the overall transport of waterborne substances in Cullera Bay. Moreover, both the river plume and the effluent from the marine outfall may become trapped in the bay under most wind and freshwater conditions (Figure 7).

Therefore, most of the substances transported inside the bay are deposited there and are dragged towards the beaches or settle on the bottom. In particular, pollutants and nutrients that settle on the bottom may become resuspended under mean energetic meteorological and oceanographic conditions, thus increasing their concentration, affecting water quality in the bay and eventually giving rise to algal blooms.

Analyses of field data and the results of numerical simulations show that wind is the main driving factor in the bay, due to the features of the other possible driving factors in the area. Some of these driving factors have negligible effects,

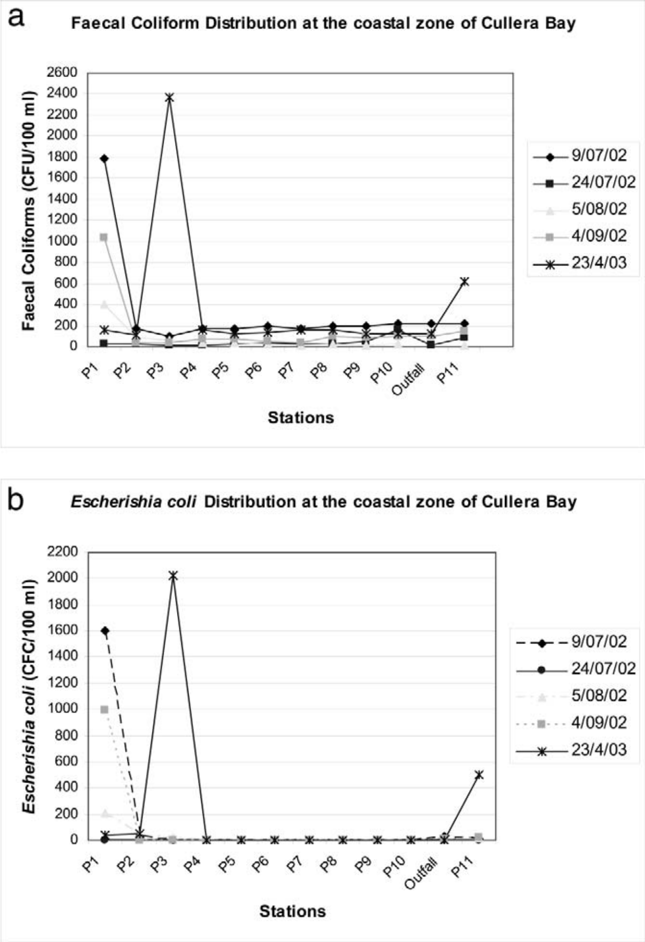

Figure 5. Faecal Coliforms and *Escherichia coli* distribution in the coastal area of Cullera Bay (Cullera Cape: P1, P2, P3; Beaches: P4, P5, P6, P7, P8 and P9; Marine Outfall zone of influence: P10 and P11)

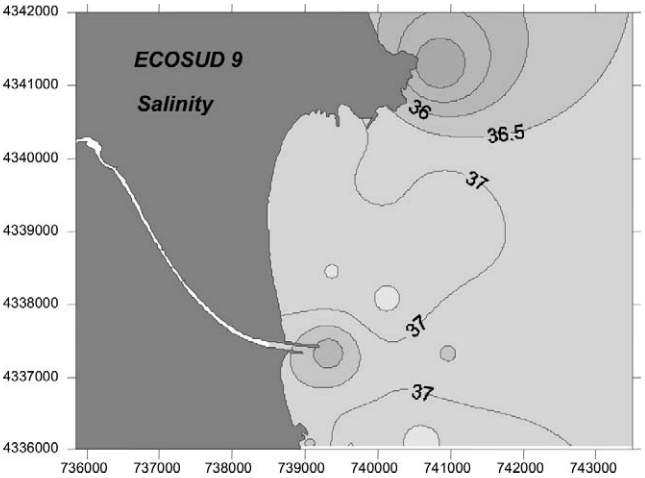

Figure 6. Salinity distribution at the surface of the bay.

such as the tide, whose range is about 20 cm. Other factors affect only a localized area, such as the usual river discharges, which are very limited (see Figure 2) and the waves, since the currents they generate are only significant inside the surf zone, which is a narrow area. Finally, other driving factors such as storm surges and river floods are infrequent due to the prevailing meteorological conditions.

CONCLUSIONS

This study analyzed the water quality in Cullera Bay using data recorded during several field campaigns and numerical simulation of hydrodynamics and pollutant transport.

Two main sources discharge nutrients and pollutants into Cullera Bay. One is the Júcar River, which carries a limited freshwater discharge due to its Mediterranean flow pattern, regulation and intensive use for irrigation. Its freshwater carries high concentrations of nutrients due to the intensive use of fertilizers and pesticides in agriculture, one of the main activities in the region. The other significant substance source for the bay is a marine outfall that discharges close to the river mouth. Due to its location (too close to the coast and too shallow), dilution of the discharged wastewater is limited and the pollutants can reach the beaches along the bay, as demonstrated by numerical simulation.

Besides the two main pollutant and nutrient sources, there are secondary sources that have only local effects in the northern area of the bay.

The hydrodynamic pattern of the bay is rather complex, since it is highly affected by the morphology (geometry and bathymetry) of the bay. The currents (in the subsurface layers) follow the isobaths and, when they arrive at Cullera Cape, eddies and circulation cells form. This implies that the bay shows semi-confined behavior, with Cullera Cape acting as a barrier. Circulation in the surface layers is driven by the wind, since other possible driving factors are of little importance. Although its features vary during the year, the wind follows a seasonal pattern.

In general—although with some exceptions due to biochemical processes—nutrients have a conservative relationship with salinity, so their concentrations are higher when salinity levels are lower. Since lower-salinity waters remain confined in the upper part of the water column, the higher nutrient concentrations are generally located in the surface layers. Pollutants follow a similar pattern. As a result, both substances are mainly dispersed by wind-driven currents and usually end up on the beaches, although they may also settle on the bottom.

In conclusion, the bay acts as a sink for waterborne particles (sediments, nutrients and pollutants), most of which remain trapped there. This harms water quality in the bay and may give rise to algal blooms.

Management policies aimed at reducing this environmental problem should focus on three aspects. First, a new marine outfall that discharges farther from the coast should be designed. Second, the amount of fertilizers and pesticides used in the region's agriculture should be reduced in order to diminish the nutrient load in the river and the amount of nutrients dumped into the bay. Finally, a continuous moni-

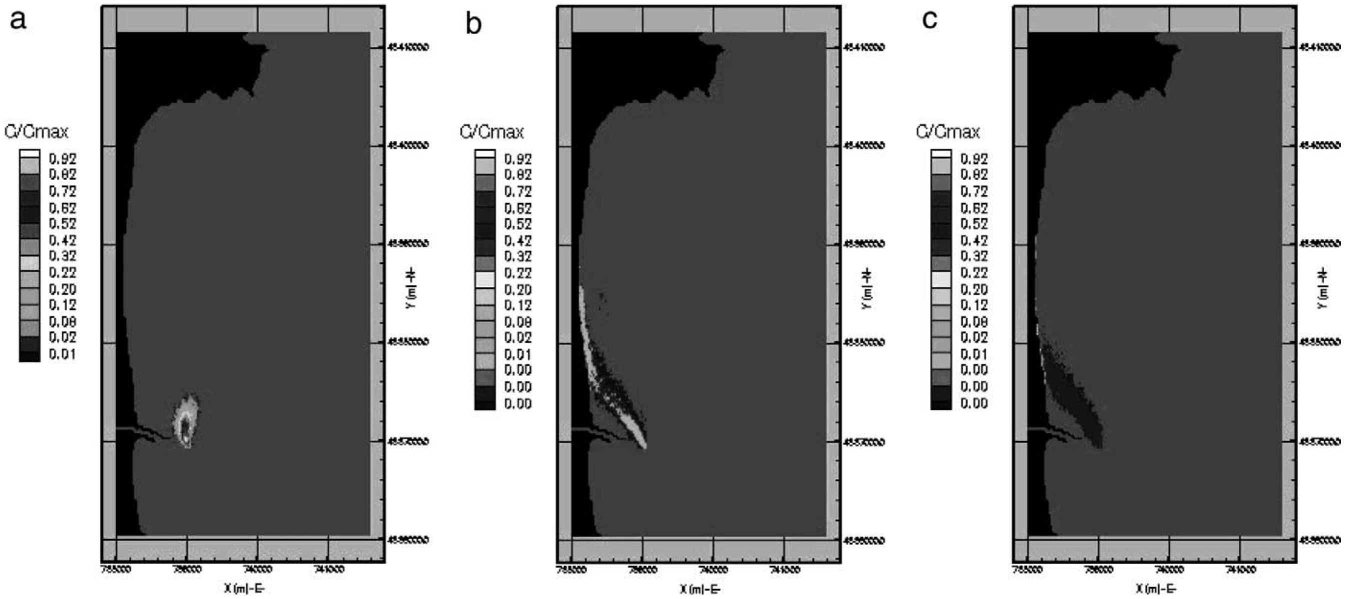

Figure 7. Modeled effluent plume under summer conditions.

toring program with periodic sampling should be designed to verify the suitability of the measures adopted and detect other possible sources of pollutants.

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