Coastal Bays as a Sink for Pollutants and Sediment

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ABSTRACT


Water quality in coastal and estuarine areas plays a very important role in both the ecological balance and the closely linked economic profitability and development. However, these areas have been progressively degraded in the last decades due to overexploitation of their natural resources; in semi-enclosed coastal basins, where the circulation is physically limited, particular problems associated to water quality degradation are enhanced, leading to possible eutrophication issues. This is the main aim of this paper, which focuses on coastal bays as traps for water-borne substances. The analysis is based on a comparison between the behavior of the river Júcar's freshwater plume and the plume of the Cullera marine outfall under typical wind conditions. Both plumes evolve within Cullera Bay, whose northern side is bounded by a cape. The obtained and simulated “actual” dynamics are compared to an hypothetical situation in which the cape has been removed. Numerical simulations of wind- and river-induced hydrodynamic fields and pollutant transport have been performed, and the results show that the presence of the cape is significant in determining the fate of the wastewater discharge, whereas the river plume, although affected also by the cape, shows a larger dependence on the wind speed.

ADDITIONAL INDEX WORDS: Numerical modeling, Cullera Bay, coastal pollution.

INTRODUCTION

The coastal zone is an important asset in the development of many countries. It hosts numerous economic and natural activities that lead to a progressive degradation of its water quality. This results in a loss of natural and economic productivity and is, therefore, a relevant issue that should be considered in the integrated management of the coastal area. The analysis of water quality in coastal regions is often based on pointwise measurements, and does not consider the past, present or future meteo-oceanographic conditions. The numerical simulations of hydrodynamics and water quality are commonly based on advanced models that have had little local validation with observations. Moreover, these numerical simulations use a “smooth” or simplified coastline and/or bathymetry that, thus, lose many of the nearshore features of simulations use a “smooth” or simplified coastline and/or bathymetry that, thus, lose many of the nearshore features of the coast.

Among such features, the accumulation of pollutants and sediments associated to stagnation areas plays an important role in the water quality and, particularly, in its degradation. This is related to the main goal of this paper, which is to assess the barrier efficiency of capes for water and waterborne substances, allowing an evaluation of coastal bays as sinks for pollutants and sediments. This is done by means of numerical simulations using models previously validated with field observations (MESTRES et al., 2003). The obtained results should allow a more efficient management of coastal areas, regulating river and outfall discharges as a function of the prevailing meteo-oceanographic conditions.

STUDY AREA

Cullera Bay is located on the Spanish coast, at a latitude of approximately 39°N (figure 1). It is a shallow basin, with maximum depths of the order of 15m. The Cape of Cullera, a rocky mass that protrudes into the sea, limits the bay on its northern side, whereas the southern end of the bay is open. The physical features of the bay largely determine the prevailing hydrodynamic pattern in the area, with a mesoscale flow in a general southward direction, and circulation within the north part of bay due mainly to the prevailing wind forcing and the presence of the cape.

The bay frequently presents nutrient-related problems due to the discharge within it of the highly nutrient-rich freshwater from the Júcar River and the presence of a shallow marine outfall that disposes of the local (occasionally untreated) domestic wastewater.

The combined effect of the freshwater discharge and the discharge from the marine outfall, together with the shallowness of the waterbody that allows the release into the watercolumn of benthic nutrients, cause important environmental problems related to the quality of the bay's waters. The frequent dense blooms of phytoplankton and red algae observed in Cullera over the past years are typical features of highly eutrophised coastal ecosystems (GONZÁLEZ del RÍO, 1987). At summertime, these negative effects are enhanced by the prevailing direction of the local wind, which blows from the SE during the day, pushing the river and outfall plumes towards the coast.

TOOLS AND METHODS

Numerical Models

For this work, two different numerical models have been used to simulate the hydrodynamic field and resulting transport.

Figure 1. Study Area.
induced by wind and river outflow inside Cullera Bay. The first one is the well-known COHERENS code (Luyten, 1999) to which a Lagrangian particle random-walk transport model (LIMMIX; Mestres, 2002) has been coupled.

The COHERENS Model

COHERENS is a 3-D hydrodynamic model developed to simulate mesoscale processes in coastal and estuarine waters, coupled to different modules that account for biological, resuspension and pollution processes (Luyten, 1999).

The model solves the equations of momentum and continuity in a (x,y,σ) reference system, assuming vertical hydrostatic equilibrium, and it includes also the equations for temperature and salinity. The complete set of equations can be found in Luyten (1999) or Luyten et al. (1999), and will therefore not be given here.

The mathematical model is discretized using conservative finite differences. In the horizontal plane, an Arakawa “C” grid is chosen, staggering currents and pressure/elevation nodes. The use of the σ coordinate allows for an accurate representation of surface and bottom boundary processes. A “mode-splitting” technique is used to solve the momentum equations, whereby the depth-integrated continuity and momentum equations are solved for the barotropic mode using a small timestep. A predictor-corrector step is applied to the horizontal momentum equations to guarantee that the depth-integrated currents obtained from the 2-D and the 3-D mode equations are identical. This model also includes the possibility of using different numerical schemes (upwind, Lax-Wendroff, TVD) for the advection of momentum and horizontal diffusion.

The LIMMIX Model

The transport model used to simulate the behavior of the outfall plume is based on a Lagrangian approach to the convection-diffusion equation

$$\frac{\partial C}{\partial t} + u_i \frac{\partial C}{\partial x_i} = - \frac{\partial}{\partial x_i}(K_{ij} C) + DS $$

(1)

where C is the concentration, $u_i$ are the components of the velocity, $K_{ij}$ are the components of the turbulent diffusivity tensor, and DS is a sink/source term, t is time and $x_i$ are spatial coordinates.

A Lagrangian particle formulation is suitable in this case because the freshwater plume will occupy only a fractional part of the computational domain and because the issues related to conservation of mass need not be explicitly considered, since it is implicit within the computational scheme. The numerical code solves a discretized version of the 3-D Fokker-Planck equation (Tompson and Gelhar, 1990):

$$r_n = r_{n-1} + A(r_{n-1}, t_{n-1}) \Delta t + B(r_{n-1}, t_{n-1}) \sqrt{\Delta t} Z_n$$

(2)

in which $r_n$ is the position of each Lagrangian element at time $r_n$, A is a deterministic forcing vector acting on each individual particle, B is a deterministic scaling matrix and Z is a vector of independent random numbers. The continuous form of (2) is equivalent to (1) when

$$A_i = u_i + \frac{\partial K_{ij}}{\partial x_j}, \quad B_{ik} = 2K_{ij}$$

(3)

Equation (2) can formally be written as

$$x_n' = x_{n-1} + u_{n-1}' \Delta t$$

(4)

where now $u_{n-1}'$ are the horizontal and vertical components of the “net velocities” responsible for the particle transport.

The turbulent part of these “net velocities” is computed using a random-walk algorithm,

$$u_n' = 2(R_{n-1}' - 1) \sqrt{6K_{ij}/\Delta t}$$

(5)

where $R_n$ are random numbers and $K_{ij}$ are the turbulent diffusion coefficients.

Particle concentration values at given positions are obtained by applying mapping methods to the cloud of discrete Lagrangian elements. A detailed description of the complete transport model and the implemented mapping algorithms can be found in Mestres (2002) or Sánchez-Arcilla et al. (1998).

Validation and Modeled Cases

The presented suite of models has been validated for Cullera Bay using observations from a series of field campaigns undertaken in the area during the years 2002 and 2003 (Møssø et al., 2002; Møssø et al., 2003).

To assess the barrier effect imposed on local hydrodynamics and substance transport by the presence of the Cullera Cape, two different sets (Table 1) of modeling cases were defined. In the first set, the actual physical configuration of the bay was considered, whereas in the second set the Cape was eliminated, and a longshore uniform coast was assumed instead. For both sets, the only hydrodynamic forcing agents considered were the freshwater discharge of the Júcar River ($Q = 9 \text{ m}^3/\text{s}$, annual mean) and a uniform wind blowing from the SE, with varying speed (0 m/s, 3 m/s, and 9 m/s). Due to the bay’s physical characteristics, SE winds lead to trapping near the cape and a decrease in water quality values in the northern part of the bay.

The hydrodynamic model was run during one day for each case (time enough to approach steady conditions) using the river flow value as the boundary condition for the western edge of the domain, whereas a zero normal gradient condition for the flow was imposed at the remaining open boundaries. The underlying mesoscale circulation was not considered, since the interest was focused on the region closest to the coast. No-slip and impermeability conditions were assumed at solid boundaries; at the bottom, a slip condition was considered, and the bottom shear was estimated using a conventional quadratic formulation (e.g., Mestres, 2002). The turbulent viscosity and diffusivity were parameterized using the 2.5-level scheme of Mellor and Yamada (1982).

Likewise, the transport of the outfall effluent was also modeled during one day for each case, using 86,400 particles and constant dispersion coefficients following Elder’s (1959) formulation. The discharged wastewater was assumed to hold a conservative pollutant, since this corresponds to the “worst” possible case in WQ terms.

RESULTS

From the modeled hydrodynamic fields (figure 2), it is evident that the importance of the cape effect on the bay’s hydrodynamics increases with growing wind speeds, as should be expected. Under no-wind conditions, the circulation patterns for both the “cape” and “no cape” cases are very similar, with a bulge in front of the river mouth and a coastal current in the direction of coastally trapped waves. In case SCV, however, the bulge extends farther to the North and decays slightly faster in the offshore direction.

Table 1: Summary of modeled cases.

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Case Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>ACV</td>
</tr>
<tr>
<td>3.0</td>
<td>AC0</td>
</tr>
<tr>
<td>9.0</td>
<td>AC1</td>
</tr>
<tr>
<td>0.0</td>
<td>SCV</td>
</tr>
<tr>
<td>3.0</td>
<td>SC0</td>
</tr>
<tr>
<td>9.0</td>
<td>SC1</td>
</tr>
</tbody>
</table>
The barrier effect of the cape becomes important when the wind speed increases to 3 m/s. Case SC0 shows a general NW current, following the coast, although density-driven effects are visible near the Júcar mouth. When the cape is considered (case AC0), the circulation in the northern part of the bay changes drastically, turning offshore towards the NE, and then hugging the cape coast to the NW. Stronger winds (cases SC1 and AC1) result in a clearly established wind-induced current along the coast, with little or no influence of the river’s momentum.

The evolution of the freshwater plume offers a different estimation of the importance of the cape, associated to the transport of river-borne nutrients, pollutants and sediment. Figure 2 also shows the plume’s boundary, defined here as the surface isopleth where the salinity anomaly $s$ takes a value of 0.03.

\[ s = \frac{S_S - S}{S_S - S_i} \]  

(6)

where $S$, $S_S$ and $S_i$ indicate the salinity, the ambient (sea) salinity, and the river’s discharge salinity, respectively. It is seen that, in the absence of wind, the river plume depends very lightly on the existence of the cape, which induces stronger offshore currents that increase the offshore extent of the plume in the AC cases. For larger wind speeds, the shape of the plume begins to vary from one configuration to the other. When $u = 3.0$ m/s, the plume still presents an upstream penetration, whereas north of the river mouth the plume for case AC0 shows a larger cross-shore extension, spreading farther to the North than the plume for case SC0. For $u = 9.0$ m/s, the strong longshore currents and the absence of the cape in case SC1 result in the spreading of the river plume over a long narrow band to the north of the rivermouth (extending approximately 4 km), whereas the combination of wind direction and the orientation of the coast leads the freshwater plume towards the coast after only half the distance in case AC1. The decrease in plume surface extension with growing wind is balanced by a larger efficiency of vertical mixing processes, so that for the stronger winds the watercolumn near the shore is almost uniform.

Results from the transport model show (figure 3) that the wastewater plume arising from the marine outfall behaves in a significantly different manner depending on whether the cape is considered or not. In all the AC cases (“with” cape), the plume becomes trapped in the bay, with only a small fraction (smaller than 5%) of the discharged mass exiting the semi-enclosed basin for mild wind conditions. On the other hand, the absence of the cape allows the wind-induced longshore currents to effectively drag the effluent plume away from the discharge point and along the coast. For the case of stronger winds associated to storm events ($u_w = 14$ m/s), the outfall discharge is dragged towards the shore.

**DISCUSSION AND CONCLUSIONS**

It is clear from the performed model simulations that the presence of the cape plays an important role in determining the water circulation and overall transport of water-borne substances in Cullera bay. Moreover, both the river plume and the effluent from the marine outfall may become trapped in the bay under given wind and freshwater input conditions.

To quantify the dependence of substance trapping on varying wind speeds, a “source-specific” retention index has been used. In the case of the river plume, this index $I_R$ has been defined as

\[ I_R = 100 \frac{Q_{in} - Q_{out}}{Q_{in}} \]  

(7)

where $Q_{in}$ and $Q_{out}$ are the total flux of water (salt) entering and exiting a given domain. In this case, the control region considered is that shown in figure 3.

The results obtained from calculating $I_R$ for water fluxes (using the modeled hydrodynamic fields) for all cases are plotted in figure 5. It is apparent that the variation of $I_R$ as the wind speed increases is different depending on whether Cullera Cape is considered or not in the simulations. When the cape is present, the data suggest that its main effect is to enhance the surface offshore currents in the northernmost region of the bay, therefore reducing the retention index as the wind becomes stronger. On the other hand, if the cape is “removed”, the initial retention index due only to the river-induced circulation decreases at first when a NW wind-induced current is established, and then increases with wind speed as the shore-normal (trapping) component of the wave field grows above a threshold.

However, this behavior of the water fluxes (summarized by the $I_R$ index) is not directly applicable to the river plume, since it does not exit the control volume in any of the performed AC simulations and the evolution of the salinity retention index simply mimics that of $I_R$. A different method to estimate the plume trapping in the bay is therefore required. For this purpose, the plume extension as a function of the wind speed has been considered. This is shown in figure 4, which plots the location of the maximum width of the plume for all the modeled cases. It can be seen that, for any fixed wind speed, the maximum plume width is found further North when the cape is considered than when it is “removed”. For weaker winds, the presence of the cape tends to yield wider plumes, due to the enhanced cross-shore currents in the northern part of the bay. As the wind speed increases above a threshold (in this case, around 3 m/s), the maximum plume width decreases, being found closer to the river mouth.

In the case of the marine outfall discharge, a similar retention index has been calculated using the pollutant mass flux into and out of the control volume. The obtained values (figure 6) reveal
a significant dependence on the wind speed in the cases when Cullera Cape is “removed”, with \( I_r \) initially decreasing as the wind becomes stronger (associated to the generated longshore current). After a wind threshold is reached, the effluent plume is dragged towards the coast, and the retention index increases. For the cases “with” the cape, although \( I_r \) depends also on the wind speed, it does so in a much weaker manner, and the retention index appears to be above 95% for all three wind situations.

It is obvious from comparing figures 5 and 6 that the water retention index is much smaller than the retention index computed for the outfall effluent plume. This is most likely due to the fact that the wastewater plume is transported by the uppermost layers of the watercolumn, and therefore is much more sensitive to wind characteristics. Since the calculation of \( I_r \) for water fluxes involves the whole watercolumn, the overall wind effect is less clear. Another reason could be the proximity of the marine outfall to the coast, suggesting further studies in order to evaluate the effect of the shore-to-outfall distance on the pollutant trapping inside the bay.

The results from the numerical simulations have shown that the Júcar freshwater plume extends offshore slightly further in the actual conditions (considering the cape) than when the cape is numerically “removed”; furthermore, the plume attains its maximum cross-shore size further to the north, nearer the actual Cullera Cape. On the other hand, the strength of the wind appears to be a key factor, as should be expected, in determining the cross-shore size of the freshwater plume and its vertical distribution, which is almost uniform for stronger winds and turns out to be surface bounded for weaker winds.

For the situation considered here, in which the prevailing winds blow from the E-SE, the trapping of river-borne sediments and pollutants in the northern part of Cullera Bay appears to be independent of the presence of the cape for weak winds, but depends on it significantly for medium and strong winds. The transport of outfall-borne pollutants, on the other hand, is significantly affected by the cape under any wind speed, therefore contributing decisively to the sink nature of the bay.

These conclusions suggest that the discharge and “beach use” policies should take into account the prevailing meteorological conditions. Moreover, the impact of the river and outfall discharges depends significantly on the barrier length. These results could be extended towards a practical methodology that would allow a more functional design of artificial barriers.

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LITERATURE CITED


