Bacterial pollution in Cullera Bay (Spanish Mediterranean coast)

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ABSTRACT


In coastal regions, ecological quality and economic development are highly sensitive to the quality of seawater, which often depends on the discharge of anthropogenic pollution through marine outfalls. This is the case of Cullera Bay (Spanish Mediterranean coast), where bacterial pollution problems are frequent during the tourist season due to its physical configuration, prevailing meteorological conditions, wastewater discharge from a shallow marine outfall, and the input from the Júcar River. The analysis of the data obtained during five field campaigns done in Cullera Bay between July 2002 and April 2003 to characterize the distribution of bacteria in the seawater along the coast show that, although the quality of the water is good (according to the EU Bathing Water Quality Directive on E. coli), bacteria counts can become very high at the stations closest to Cullera Cape. These concentration peaks appear to be due to the sporadic filtration through the karstic headland of untreated wastewater from ill-maintained domestic sewage systems, but also to the barrier effect exerted by the Cape upon the hydrodynamic circulation induced by S-ESE winds, as shown by numerical simulations. Further modeling suggests that the water quality in the northern part of the bay could be improved by lengthening the marine outfall, thus reducing the trapping effect induced by Cullera Cape.

ADITIONAL INDEX WORDS: Cullera Bay, fecal pollution, numerical modeling, water quality.

INTRODUCTION

Coastal zones are considered worldwide as important economic areas in which a number of activities are developed that depend directly on the quality of coastal waters, such as fisheries, tourism and industry.

However, the quality of coastal waters is often affected by the discharge of large volumes of domestic or industrial wastewater, resulting in the input of large quantities of pollutants, nutrients and pathogenic organisms. In fact, although the main source of general marine contamination is the output from rivers, the largest responsible for water pollution in coastal regions is the disposal of wastewater through marine outfalls. In spite of the increasing social awareness and the coming into force of updated and more restrictive legislation to ensure that the quality of nearshore waters is maintained or enhanced, still in many areas the discharge of wastewater induces a negative impact upon the local ecosystem.

This is particularly true in some tourist areas, in which the population varies significantly throughout the year. In these cases, the capacity of the local treatment plants may be insufficient to process the excess of domestic wastewater generated by seasonal inhabitants, and part of the residual water might be released untreated into nearshore waters through marine outfalls. The discharged effluents might contain high concentration levels of pollutants, including pathogenic bacteria, which can represent a threat to human health, especially if the discharge is not done in an appropriate manner. The improvement of outfall design in order to minimize the impact of wastewater discharges can be easily done using numerical models; in particular, these tools permit to optimize the discharge position to take full advantage of the typical meteorological and oceanographic conditions in the area.

The bacterial pollution of coastal waterbodies has been the subject of a large number of studies. CARUSO et al. (2000) analyzed the fecal contamination of Messina coastal waters; HASSAN et al. (1996) assessed bacterial pollution along the eastern coast of the United Arab Emirates; DABY et al., (2002) studied the microbial pollution of coastal bathing waters in Mauritius; PASCUAL et al. (2008) have focused their studies in the area of the Valencian coast and, in particular, Cullera Bay.

Several studies have been conducted to model the discharge of effluents or to optimize the design of marine outfalls. MESTRES et al. (2006), for example, have modeled the dispersion of effluents from marine outfalls in coastal waters. On the other hand, AKYARLI and ARISOY (1995) and AL-MUZAINI et al. (1999) analyzed the effects of modifying different marine outfalls. NOUTSOPULOS et al. (1999) studied the effects of three potential discharge points for a marine outfall on the water quality in the Gulf of Saronicus (Greece). More recently, ALVAREZ-VAZQUEZ et al. (2008) addressed the optimal design of a wastewater treatment system focusing also on the potential outfall locations.

In this paper, the water quality near the beaches of Cullera Bay is analyzed using the data of two field campaigns and considering the wastewater input from the marine outfall. A numerical analysis is also performed, evaluating the operation of the actual outfall, and assessing different alternative discharge positions which could improve the quality of the bathing waters in the bay.
Bacterial Pollution in Cullera Bay

STUDY AREA

Cullera Bay is located on the Mediterranean Spanish coast (figure 1). It is a shallow gulf with sandy beaches, open to the south and limited to the north by the karstic Cullera Cape. Approximately 6 km to the south of the cape there is the mouth of the river Júcar, whose freshwater outflow is typical of Mediterranean climate (SÁNCHEZ-ARCILLA et al., 2007), with larger mean flows during the winter (16 m$^3$/s in February) and smaller ones during the summer (4 m$^3$/s in July). The river waters are characterized by their high content of nutrients coming from the pesticides and fertilizers used upriver. A further source of nutrients is the wastewater discharged into the bay through a marine outfall located close to the river mouth. Cullera is a touristic area, and the population of the town of Cullera can grow from about 21,500 to above 150,000 in the height of the summer season. As a result, there is a strong increase of domestic wastewater generation that often exceeds the capacity of the local treatment plant. Under these conditions, the surplus may be discharged untreated either through the marine outfall or directly into the last stretch of the river. Therefore, the recreational use of the bay’s waters might be limited by the discharge of pathogenic loads which could be nocuous to human health.

METHODS

Field data

Surface water was sampled four times in 2002 (July 9th and 24th, August 5th and September 4th) and once in 2003 (April 23rd) at eleven stations distributed along the northern coast of Cullera Bay, from the mouth of the river Júcar to Cullera Cape (points P in figure 1). During these five campaigns, samples of water at the surface and at different depths were also obtained with the Superficial Water Sampling (MÖSSO et al., 2008) instrument close to the marine outfall (station M11 in figure 1). The APHA (1998) membrane filtration method was used to obtain the colony forming units per 100 ml of fecal coliforms (FC), enterococci and Escherichia coli, which were the indicators used at the time by the European Directive to determine the microbiological quality of bathing waters.

This coastal sampling was part of a larger data collection effort extending from June 2002 to July 2003 undertaken to improve the knowledge of the most relevant hydrodynamic forcing mechanisms in the area, the dispersion of nutrients and pollutants, and the physical and biochemical processes that are associated with the quality of seawater. The data acquisition included time series of wind speed and direction near the river mouth and hydrodynamic currents at several positions. Water temperature and salinity, suspended solids, and nutrient and chlorophyll a concentrations were obtained from samples taken at several river and sea stations. A complete description of the whole set of field campaigns can be found in MÖSSO et al. (2002).

Numerical models

Two different models have been used to simulate the hydrodynamic field and the outfall plume dispersion within Cullera Bay.

COHERENS (LUYTEN et al., 1999) is a 3D hydrodynamic code that solves the momentum and continuity equations in a sigma-coordinate system, including the transport equations for salinity and temperature to take into account baroclinic effects. This model has been used to obtain the circulation pattern inside the bay induced by different oceanographic and meteorological forcing mechanisms.

The numerical results supplied by COHERENS have been used to feed the pollutant dispersion code LIMMIX (MESTRES, 2002), which has been applied to obtain the evolution of the wastewater plume generated by the marine outfall discharge. This model is based on a Lagrangian particle approach to the general transport (advection-diffusion) equation and incorporates a decay module to reproduce microbiological mortality.

The hydrodynamic simulations have been fed with the meteorological and hydrological data corresponding to the July campaign. During this survey, the measured wind data reproduced the typical summer breezes pattern, with weak winds between 0.5 and 3 m/s blowing from the NW during the late afternoon and the night, and stronger southeasterlies, with 9 m/s peaks, during the morning and early afternoon (MÖSSO et al., 2007). During this summer campaign, the river freshwater discharge rate was close to zero (SIERRA et al., 2007). In addition to the actual wastewater discharge position, at about 910 m from the shoreline and at a 6 m depth, two alternative options were analyzed. The first one consisted in lengthening the outfall 425 m, up to a discharge depth of 8 m, and in the second one the length of the outfall pipe was doubled, discharging the wastewater at a depth of about 10 m. The three outfall positions considered herein are shown in figure 1.

RESULTS

For the purposes of this study, only the bacteria concentration data obtained during the July 9th and September 4th, 2002 campaigns have been analyzed, and the results have been evaluated following the EUROPEAN WATER FRAMEWORK DIRECTIVE (2000, which in turn refers to the EUROPEAN BATHING WATER DIRECTIVE, 1976) that establishes guideline and maximum permissible mandatory values in order to classify bathing waters as “good” or “excellent”, respectively. The values of indicator concentration and the corresponding water classification are shown in table 1.

The spatial distribution of the indicator organisms along the coast of the bay are shown in figure 2, whereas the vertical profiles of FC, E. coli and enterococci obtained close to the marine outfall (station M11) can be seen in figure 3. The data obtained during the July survey reflect the typical conditions...
during a heavy tourist period, while the September data correspond to a month with less tourism and smaller population.

The results for the three outfall positions considered in the numerical simulations are shown in figure 4. For the actual outfall position (figure 4a), the surface wastewater plume is dragged by the wind-induced currents towards the north, affecting the beaches between the rivermouth and Cape Cullera. This behavior broadly coincides with the bacterial counts obtained during the summer campaigns. For the first alternative (figure 4b), the effluent also reaches the shoreline, although its dilution is somewhat larger because of the deeper discharge. Finally, for the second alternative (figure 4c), the wastewater plume is dragged out of the bay by the circulation induced by the wind and deflected by the cape.

**DISCUSSION**

The analysis of the July data shows that, although in all the sampling positions the concentrations of FC throughout the bay were smaller than the mandatory values imposed by the European Directive for Bathing Waters, almost all the bacteria counts were larger than the recommended guidelines. Near the beaches, where pathogenic pollution can be more harmful, fecal coliform concentrations varied between 140 and 184 CFU/100ml, except at P3 (66 CFU/100ml) and P1 (1800 CFU/100ml). The pattern for enterococci is very similar, with very high concentrations at station P1 and, in general, larger values at the stations closest to the cape, although they comply with the guideline values established by the European Union. In both surveys, the concentration of *E. coli* at the beach stations was negligible.

The bacteria concentrations measured during the September survey are smaller than those found in July, as was expected. All the fecal coliform values obtained in the beach samples are smaller than the European guideline value, except at station P11, close to the marine outfall, with concentrations of 113 CFU/100ml, and again at station P1 (1030 CFU/100ml). The enterococci concentration distribution for September is almost identical to the distribution obtained in July, although the value at P1 is about twice as small.

The persistence of large fecal microorganism concentration values near the cape, about 4 km from the wastewater injection point close to the river mouth, cannot be explained neither by direct transport of the wastewater plume nor by the accumulation over time of wastewater in the northern part of the bay. Although it has been shown (MESTRES et al., 2006; SÁNCHEZ-ARCILLA et al., 2007) that, under the typical local wind regime, the cape acts effectively as a barrier for the coastal hydrodynamics, converting the northern part of Cullera Bay in a virtual trap for pollutants discharged both by the marine outfall and the freshwater output of the Júcar River, it is likely that the population of fecal bacteria will be reduced by biological mortality processes mainly linked to solar radiation, and that concentrations as high as those observed will not be found.

The bacteria concentration values around the cape suggest that additional sources of fecal pollution other than the marine outfall and the river exist. The karstic nature of Cullera Cape allows runoff to filter through the rock, washing the frequent wastewater leaks from the old and ill-maintained sewage system existing on the cape. This could explain the large spatial variation in fecal coliform and enterococci concentrations observed in both surveys, and the persistence of the large values at station P1.

Close to the marine outfall, in the wastewater plume, the analysis show relatively high concentrations of FC during both surveys, with larger values occurring in July. For this campaign, coliform concentrations ranged from about 130 CFU/100ml at 5 m depth to around 250 CFU/100ml close to the surface, whereas in September the lowest concentrations were around 40 CFU/100ml at deeper levels and the highest about 200 CFU/100ml again close to the surface. For this latter campaign, only the upper 0.5 m of the water column showed coliform concentrations in excess of the guideline value. Neither the enterococci nor the *E. coli* concentrations exceeded the European guideline value that determines the excellent quality of seawater for bathing purposes.

The vertical distribution of all three indicators confirm that the wastewater plume resulting from the Cullera outfall discharge becomes rapidly surface-bound, as indicated by the visual observation of the surface plume boil during several of the campaigns (SÁNCHEZ-ARCILLA et al., 2007). This, which is due in part to the shallowness of the outfall diffuser, contributes an additional aesthetic contamination issue that cannot be lightly treated in a touristic area.

The numerical simulations show that, for typical summer meteorological conditions, the actual design of the marine outfall is not the most adequate to guarantee good water quality in the beaches of Cullera Bay, since the wind-induced circulation tends to drive the surface wastewater plume towards the shore. The alternatives considered, based on increasing the depth of the discharge point, confirm this conclusion. Shifting the marine

**Table 1: Bacterial concentration values for the quality of bathing waters (EUROPEAN WATER FRAMEWORK DIRECTIVE, 2000).**

<table>
<thead>
<tr>
<th>Indicator organism</th>
<th>Maximum permissible values (CFU/100ml)</th>
<th>Guideline values (CFU/100ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal coliforms</td>
<td>2000</td>
<td>100</td>
</tr>
<tr>
<td><em>E. coli</em></td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Enterococci</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Water quality</td>
<td>Good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

**Figure 2. Spatial distribution of FC (top) and enterococci (bottom) in Cullera Bay.**
outfall diffuser seawards to a depth of 8 m reduces the concentration of pathogenic bacteria near the beaches, although the wastewater plume still remains confined within the bay and, therefore, continues to represent a potential source of pathogenic hazard for bathers. By lengthening the outfall up to a depth of 10 m, the effluent plume is dragged out of the bay by the surface wind-induced current that is deflected northeastwards by Cullera Cape. Under this outfall design, the bacteria concentrations in the area of the Cullera beaches would be negligible, even for the most unfavorable summer conditions (i.e., large wastewater outflows and predominant southeasterly winds), and the quality of the bathing waters in the Bay would improve significantly. This would also reduce the visual impact of the wastewater boil close to the outfall and the surface wastewater plume. However, and because of the gentle bottom slope in the bay, this solution implies that the length of the outfall must be drastically increased. Due to the economic effort involved, other less costly designs focused on reducing the initial dilution (number of diffusers, diffuser shapes or orientation, etc.), rather than on the overall plume transport should also be considered.

CONCLUSIONS

Cullera Bay is an eminently touristic zone located in the Spanish Mediterranean coast. During the summer months, mainly July and August, its population grows one order of magnitude, originating a similar increase of the volume of domestic wastewater generated and discharged into the bay waters through a shallow outfall. Due to the limited capacity of the local treatment plant, part of the wastewater can be discharged untreated. The pollution by fecal microorganisms in the bay has been analyzed using numerical simulations and data obtained during several field campaigns. The measured data show that the beaches between the mouth of the Júcar river and Cullera Cape are moderately contaminated -according to the criteria defined in the European Water Framework Directive-, during the summer, when outfall discharges are greater and the typical wind patterns favor the transport of effluent towards the shore. Nevertheless, the data presented here is insufficient to classify the quality of Cullera Bay’s bathing waters, since the categorization defined in the Directive is based on the statistical analysis of the results from a large number of surveys. A diffuse source of pollution not related to the marine outfall has been located, although not clearly identified, close to Cullera Cape, probably linked to the filtration of polluted runoff through the karstic cape.

The numerical simulation of the outfall effluent dispersion under the actual conditions is consistent with, and explains, the bacterial distribution observed in the bay. The results show that the actual design of the marine outfall is inadequate since it contributes to increase bacterial pollution in the bay. Two alternatives to the outfall position have been analyzed to reduce...
the pollution of Cullera’s bathing waters. The first one, which extends the actual outfall a further 425 m, does not completely solve the problem, since the wastewater plume still reaches the beaches, although with a slightly larger dilution. The second alternative, doubling the length of the existing outfall and discharging at a depth of 10 m, generates a dispersion pattern that transports the effluent out of the bay, thus reducing the impact of the wastewater discharge upon the bathing areas. The visual impact of the surface boil and wastewater plume would also be reduced with a deeper outfall.

In any case, to obtain a good bacterial quality of bathing waters in Cullera Bay, the modification of the marine outfall should be complemented by the identification and repairing of the leaks in the sewage system of Cullera Cape, thus impeding the filtration of wastewater through the karstic rock, and eliminating the points of high bacteria concentrations observed near the cape.

**LITERATURE CITED**


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