A Design Methodology for Combined Sewer System Elements with Overflows in Coastal Zones

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ABSTRACT ▆

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The European Community Directive (ECD) referring to bathing water quality establishes its admissibility as a function of the results obtained in control samples.

This procedure is convenient to establish a monitoring and control program but presents serious difficulties in designing elements of combined sewer systems with overflow discharges in the coastal zones. These difficulties appear when it is necessary to design according to unknown future random control results which are obtained with also unknown sampling frequency.

This uncertainty is usually solved by identifying the percentage of samples that do not comply with water quality criteria with the percentage of time that water quality does not satisfy the regulation which, strictly speaking, is not correct from the point of view of ECD.

In this paper, a methodology is presented to analyze, in probabilistic terms, the influence of overflow from sewer systems on the quality of bathing water and on the design of the capacity of sewer system elements.

This methodology includes some concepts as the return period of no compliance time and shows the possibility of using regression equations between overflow parameters and no compliance time, this being useful to handle the large amount of data for the probabilistic study. All this being in strict accordance with 76/160/EEC.

Finally, the design procedure for the coastal interceptor of Gijón (Spain) is presented as an example of the application of this methodology.

ADDITIONAL INDEX WORDS: *Bathing water quality, water quality control, littoral zones modeling, return period.*

INTRODUCTION

The European Community Directive (ECD) for bathing water quality (COUNCIL OF EUROPEAN COMMUNITIES 1975) establishes its admissibility as a function of the results obtained in control sampling. ECD gives the minimum sample frequency, the critical concentrations, and the percentage of the samples that can exceed these concentrations.

These specifications are suitable for a control monitoring program, but they are difficult to interpret when designing different combined sewer system (CSS) elements. A particular case is the design of the capacity of CSS versus bathing water quality, when overflows from CSS are produced. The problem arises in the design procedure because a future random sampling is carried out every year with an unknown sample size.

This problem is usually solved incorrectly by

identifying the percentage of samples that exceed the concentration limits with percentage of time in which the bathing water criteria is not met. Some countries, members of the European Community, have developed their directives in terms of incompliance time (MINISTRY OF THE ENVIRONMENT, 1985) without justifying the correspondence between theirs and the ECD.

In recent years, the problem to design the CSS capacity versus the quality of marine environment when overflows from CSS are produced is attracting much attention (HEAD, *et al.,* 1992; DELO and KELLAGER, 1992; JENSEN and LINDE-JENSEN, 1991). Different approaches have been used by different authors to solve the problem, but the probabilistic interpretation of the phenomenon have only been considered in rare cases.

It is apparent that the CSS overflows and their impact on the bathing water quality depend on a number of random variables such as: rain inten-

Table 1. *Bathing water quality criteria after 76/160/ECD for fecal coliforms.*

	Percentage of Samples that Exceeds the Maximum Concentration	Maximum Concentration (fecal coliforms per 100 ml)	Minimum Sampling Frequency
Imperative values	95	2.000	Bimonthly
Guidance values	80	100	Bimonthly

sity and duration, wind direction and intensity, tide stage and amplitude at the time of overflow, light intensity, *etcetera*.

In this paper, the relation between the percentage of the exceedance time of limit concentration and the probability of certain percentage of samples with overconcentration being exceeded is studied.

Also, a methodology for design of CSS capacity versus bathing water quality when overflows are produced is presented in probabilistic terms, this strictly in accordance with 76/160/EEC.

Finally, a case study for the design of interceptor of Gijón (Spain) is presented as an example of the application of this methodology.

CONSIDERATIONS AND ANALYSIS OF THE BATHING WATER QUALITY CRITERIA (76/160/EEC)

Without loosing the generality, we will only discuss the part of 76/160/EEC concerning fecal coliforms.

For these bacterias, the directive establishes two criteria which are presented in Table 1.

This directive clearly states imperative values, but is ambiguous concerning the obligational level of the guidance values and the definition of exceptional meteorological event.

Nevertheless, the main problem appears when these criteria are used to design, because the directive does not offer any probabilistic interpretation of the control results in spite of the probabilistic nature of the sampling results and the whole phenomenon implied in the process to be studied.

Nowadays, it is usual practice to study the pollutant transport in the marine environment with mathematical models, thus obtaining the time in which a given pollutant concentration has been exceeded. This time is the parameter that is usually calculated when elements of CSS are designed. Then the question arises: What is the re-

lation between the percentage of time for which a given concentration is exceeded and the probability of exceeding a given percentage of samples with overconcentration, when the samples are randomly taken?

Note that the random nature of all the phenomena involved imply that there is always nonzero probability (in the case of overflows) to exceed the given percentage of time (no matter how large it is) for which the limit concentration is surpassed. Thus, it is sensible to design in terms of this probability, that is, in terms of return period.

Relation between Exceedance Time of Maximum Concentration Permitted and the Probability of no Compliance of ECD

It is clear that if bathing water exceeds the maximum concentrations permitted, 5% and 20% of the time of the bathing period depending on whether imperative or guidance values are being referred to and if the control sampling is continuous, these percentages will coincide with the percentage of samples with concentrations over the limit.

However, nobody does continuous sampling. The sampling frequency can vary between daily and bimonthly (minimum value indicated in the ECD), although it is more common to adopt a frequency between weekly and biweekly. However, it is possible to simulate the processes involved in the studied phenomena and obtain the exceedance of the limit concentrations with any discretization level (hour, minute, second).

Then one can compute (for the imperative values for example) the probability that more than 5% of the samples from all the samples taken from one point during the whole bathing season has concentrations of more than 2,000 fecal coliforms/100 ml, when the real (or simulated) exceedance time of this concentration is given (a similar task can be solved for the guidance values). This probability can be called rejection probability.

Suppose that the concentration of fecal coliforms in a given sample is representative for the biological state of the bathing water at the point of sampling, say for one hour. (It is possible to choose another interval without changing the conclusions.) Then, the probability of obtaining X defective samples (with concentration over the limit) when M samples are taken (number of samples taken during the bathing season) from one

population of N individuals (number of hours in the bathing season) with m defective samples (number of hours in which during the bathing season the limit concentration is exceeded) can be readily computed using the hypergeometric distribution:

$$P_r[X = x] = \frac{\binom{m}{x}\binom{N - m}{M - x}}{\binom{N}{M}}.$$

Now, it is possible to obtain the probability of no admissibility of bathing water according to (the rejection probability) with the following expressions:

Imperative values:

$$P_r[X > \text{intg}(0'05\,M)] = \sum_{\text{intg}(0'05\,M)+1}^{M} \frac{\binom{m}{X}\binom{N - m}{M - x}}{\binom{N}{M}}$$

Guidance values:

$$P_r[X > \text{intg}(0'2\,M)] = \sum_{X = \text{intg}(0'2\,M)+1}^{M} \frac{\binom{m}{x}\binom{N - m}{M - x}}{\binom{N}{M}}$$

Figures 1 and 2 show these probabilities for different sample numbers (M) and different exceedance times of the limit concentration (m, as percentage of total time N) for the imperative and guidance values, respectively. In the remaining text, we will only consider imperative values, the application of the results to guidance values being analogous.

Figure 1 demonstrates the fact, which has been commented upon and related to the methodology developed, that the usual identification between percentage of time with percentage of the samples with excess concentration is not correct. From this figure, it is apparent that the probability to fail the bathing water quality criteria is too high, even with a very low percentage of time in which the limit concentration is exceeded, and that this probability strongly depends on the sample size. It can be appreciated from this figure that relatively low rejection probabilities can only be obtained if the portion of time with concentration over the limit is very small and the sample size is at least 20 (or a multiple of 20).
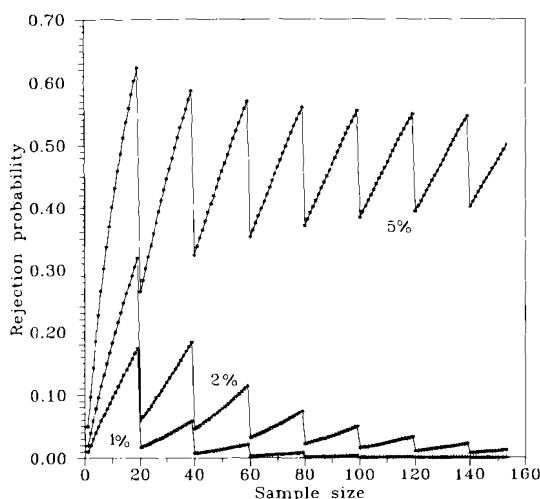

Figure 1. Probability that more than 5% of the samples have a concentration over the limit, as a function of the total sample size for different percentages of exceedance time of limit concentration.

Return Period of the Exceedance Time of the Limit Concentration

As mentioned previously, the random nature of the impact to the marine environment when overflows from CSS are produced implies that there is a non-zero probability for both the percentage of the exceedance time and the percentage of the samples with overconcentration to exceed a given value, no matter how big this value is. This is why it is sensible to design the elements of CSS according to the probability of violating the directive at a certain moment.

Consequently, a return period can be defined which reveals the fact that in a certain bathing season and at a certain point, the limit concentrations can be surpassed for a time equal or bigger than that admitted in the design.

DATA, MODELS AND METHODOLOGY PROPOSED

The study of the pollution resultant in a littoral zone by the overflows from CSS requires data and models which permit reliable simulation of all the phenomena involved in the process.

Basic data are the geometrical configuration of the sewer system, the discharges in dry periods with urban and industrial origin, and also the discharges in rainy periods drained from the catchment area by CSS (these being well defined with
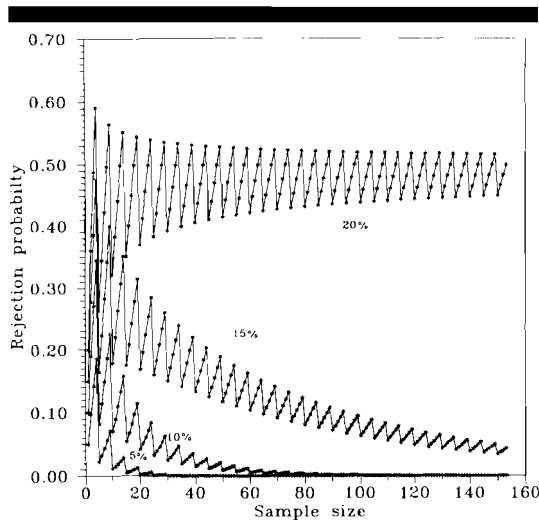
Figure 2. Probability that more than 20% of the samples have a concentration over the limit, as a function of the total sample size for different percentages of exceedance time of limit concentration.

their runoff hydrographs of the subcatchment areas). Data from the marine environment, as tidal data, wind statistics, density profiles, light intensities, light properties of the water, *etcetera* are also necessary.

The following phenomena have to be modeled:

(1) Transference rain-discharge to obtain a reliable estimation of the hydrograph at each point of incorporation to the sewer system.
(2) Circulation of the water in the sewer system to find an estimate of the overflow regime in each overflow structure.
(3) Current field in the marine region of interest.
(4) Dispersion-advection of the pollutant introduced in the sea.
(5) Bacterial die-off

The available numerical models are relatively complex and require much computer time for the simulation of each rain event.

The probabilistic study of the overflow impact on the marine environment according to previous considerations can be undertaken in different ways, depending on available rain data for the zone. Even when there is a good data base of rain series, one should use every one of the rain episodes in order not to lose information.

However, because the simulation of each rain episode is expensive in computer time, the sim-

ulation of one representative rain series (with perhaps thousands of rain events and hundreds of overflows) can be a very difficult or impossible task with PC computers commonly used nowadays. Although the simulation of both the "land" and "marine" part of the process is costly, the latter is more expensive.

One way to solve this problem is to accomplish "full" simulation of limited but representative rain episodes, obtaining for each of them the exceedance time of limit concentration in the point of interest. Then, one can look for a regression equation from the following type:

EXCEEDANCE TIME = F (overflow parameters, marine parameters).

A good correlation coefficient between independent and dependent variables in an adequately chosen regression equation can be expected because the cause-effect relation is strong and physically consistent. A case study is presented in the next section which shows that if the independent variables are correctly chosen, the correlation coefficient is close enough to one. In other similar case studies, good correlation coefficients have also been obtained.

After simulating the rest of the rain events with the "land" models and making use of the regression equation, the exceedance times of the limit concentrations for the whole rain series can be obtained. In this fashion from one random and representative sample (parameters of the overflows, for example overflow volume and duration), another random and representative sample is obtained (the exceedance time) which can be studied statistically. The regression equation acts as a transference formula.

Obviously, for each geometric configuration of the sewer system and for the same rain series, different regimes of overflows, exceedance times and, of course, statistical characteristics of the new random variable result; but, if the overflow points are maintained, the regression equation is the same. Therefore, this methodology is a low cost versatile way of studying different alternatives for the sewer system using only a simple transformation formula, instead of time consuming numerical simulations.

Note that the design procedure is directed toward attaining two main objectives:

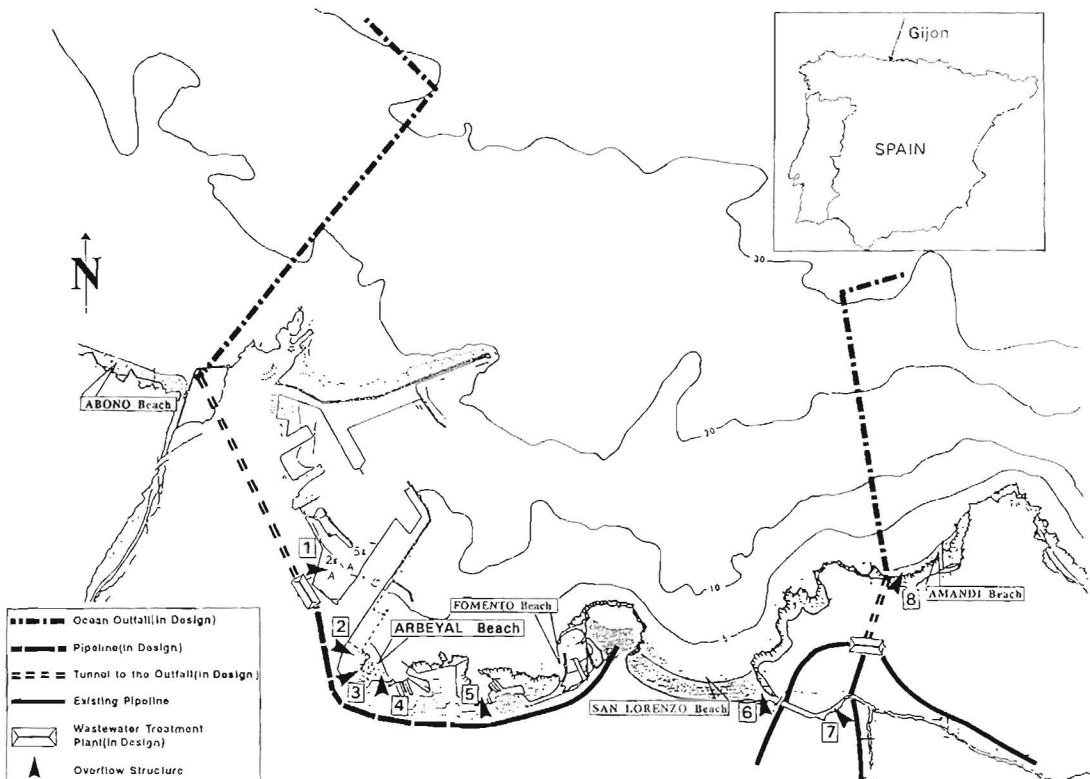(1) To obtain a relation between a sewer system

Figure 3. Gijón, Spain. General scheme of the CSS with proposed coastal interceptors, treatment plant, and ocean outfalls.

configuration and the return period of the percentage of the exceedance time, which might coincide with a flooding return period of the sewer system.

(2) To comply a chosen percentage of exceedance time of the limit concentration, according to Figures 1 and 2 in order to ensure low rejection probability.

CASE STUDY

The methodology presented has been used to study CSS overflows in the city of Gijón (Spain) when the coastal interceptor was designed. This zone is an important industrial and recreational center. At present, the industrial and urban residual waters are discharged into the sea without any treatment. The construction of a coastal interceptor, sewer system treatment plants, and two ocean outfalls are planned (see Figure 3). There are some overflow points whose influence on bathing water quality have been studied and these are presented later.

In order to simulate the phenomenon, several models have been used which are as follows:

(1) Runoff model based on time-area curves.
(2) Hydrodynamic model to study the circulation of the water in the sewer system, based on Saint Venant's equations in one dimension, solved by the method of characteristic or simple cinematic wave model. These two models have been used alternatively depending on the precision required, and the former has often been used to validate and calibrate the latter. The cinematic wave model has been used to calculate the large amount of rain events and to determine the overflow parameters for each of them.
(3) Quasi three dimensional marine model for tidal and wind flow computations solved using A.D.I. scheme.
(4) Advection-Dispersion three dimensional Lagragian model.
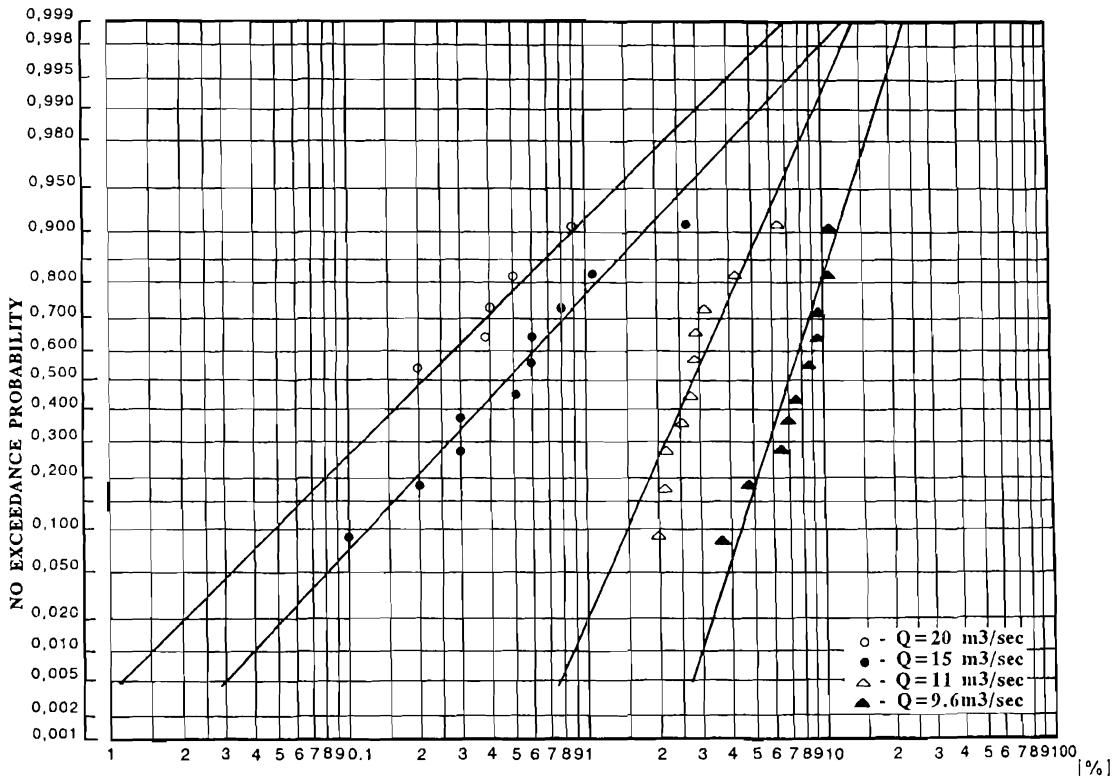(5) Bacterial die-off model which contemplates

Figure 4. Log normal empirical distribution of the percentage of the exceedance time of the limit concentrations for different capacities of a coastal interceptor.

temperature, salinity and light variations in the water column.

The values of the main parameters in the marine models are adopted as a result of calibration, previous experience, and specialized bibliography as follows:

(1) Manning coefficient = 0.030
(2) Eddy viscosity [m^2/sec] = 20
(3) Dispersion coefficients [m^2/sec]: longitudinal = (0.3 ÷ 0.01) $u^2\Delta t$, transversal and vertical- one and two orders of magnitude smaller than the longitudinal.

Here u is the longitudinal velocity and Δt the time step.

The population of Gijón is approximately 375,000 habitants. This becomes 467,000 equivalent habitants, on account of industry. Figure 3 shows the general scheme of the sewer system of Gijón.

To demonstrate the methodology previously described, we present the design procedure for the capacity of the coastal interceptor versus bathing water quality of the Arbeyal beach, where most overflow points are concentrated.

The capacity of the coastal interceptor has been studied for four maximum discharges (9.6, 11, 15 and 20 m^3/sec) and for each of them, all the 1,277 rain events corresponding to the bathing seasons of the decade 1981–1990 have been simulated by means of runoff and hydrodynamic sewer system models. The results of these simulations are the hydrograph and pollutograph for each overflow point when the simulation is done with dynamic wave model and the volume and the duration of the overflow when the simulation is done with cinematic wave model. With the dynamic wave model, only fifteen rain events have been simulated. These results have been used later to obtain the regression equation.

As previously mentioned, the marine simula-

tions have been undertaken for only fifteen of the overflows produced in the marine environment by means of the hydrodynamical marine model, the advection-dispersion model and bacterial die-off model, obtaining for different points of the Arbeyal beach the exceedance time of the limit concentrations.

With the results of these fifteen simulations with the "lands" and the "marine" models, a regression equation has been obtained between the exceedance time for the most damaged point in the Arbeyal beach and the overflow parameters:

$$t = 5.678 \ (VD)^{0.014},$$

where t [h] = the exceedance time of 2,000 fecal coliforms/100 ml, V [m³] = sum of the overflow volumes in structures 2, 3 and 4, and D [h] = mean duration of the overflows in structures 2, 3 and 4. The regression coefficient is 0.96.

For all of the marine simulations, a 3.5 m tide range, a north-northwest wind of 5 m/sec (49.5 % of overflows occurs with wind from this direction and intensity equal to or less than 5 m/sec), mean summer values for the temperature, salinity and light variation, have been used. All overflows have been initiated at low tide; as in this case, this is the most unfavorable stage of the tide.

Using the regression relationship, the exceedance time for each capacity of the coastal interceptor and for each overflow have been obtained. Then for each bathing season studied and each capacity of the interceptor, the percentage of the exceedance time has been found.

With this data, empirical log normal distributions of the percentage of exceedance time for each capacity of the interceptor has been constructed (Figure 4).

According to the climatic conditions and bearing in mind the local habits, the pollution has not been evaluated between 8 p.m. and 8 a.m. or on days in which the rain duration exceeds 5 hours.

From the empirical distributions and Figure 1, a design graph can be constructed which relates the percentage of the exceedance time versus the capacity of the interceptor for different return periods, and separately the percentage of the exceedance time versus the rejection probability for different sample sizes (see Figure 5). For example, for a 3% exceedance time and a 10 years return period, the capacity of the interceptor must be 13 m³/sec. If 20 samples are taken for quality control, the rejection probability is 0.13.
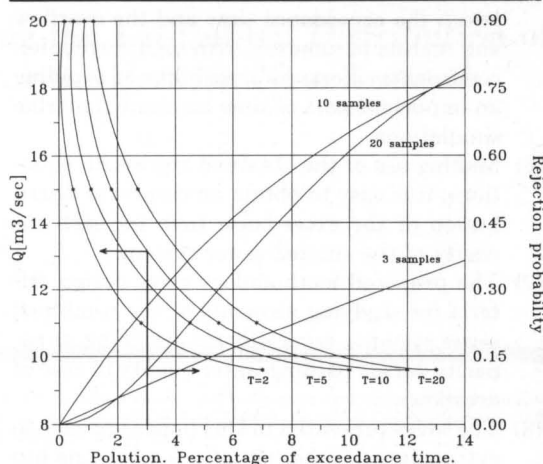

Figure 5. Design graph for the coastal interceptor of Gijónwest: (1) Exceedance time versus interceptor capacity for different return periods. (2) Exceedance time versus rejection probability for different sample sizes.

CONCLUSIONS

In the present paper, the following conclusions can be drawn:

(1) The water quality criteria for bathing waters stated in the 76/170/EEC is difficult to include directly in the design procedures of CSS in coastal areas.
(2) The common identification between the percentage of samples with concentration over the limit with the percentage of exceedance time of the limit concentration is not correct. This assumption normally yields high rejection probabilities.
(3) The ECD for bathing water quality should define accurately the control sampling scheme with a double purpose: (A) To avoid the increasing rejection probability when the sample is not a multiple of 20 for the imperative values and 5 for the guidance values. (B) To facilitate the design procedure by making it possible to calculate the rejection probability beforehand.
(4) As the exceedance time of the limit concentration is a random variable because of its dependence on random meteorological and oceanographical factors, it is sensible to design the elements of the CSS in terms of a return period for this variable (the exceedance time).

(5) The existence of regression relationships between the exceedance time and the overflow and marine parameters with high correlation coefficients offers the possibility of avoiding an important part of time consuming marine simulations.

(6) Making use of the obtained regression equations, it is easy to obtain an empirical distribution of the exceedance time for each capacity of the studied sewer system.

(7) The proposed methodology gives design criteria for studying elements of the combined sewer systems, especially for designing its capacity versus bathing water quality in case of overflows.

(8) The ideas presented in this paper are easy to extrapolate to other situations when one has to design elements of the sewer system versus water quality in the region of discharge(s).

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